

Sensor Trends 2030



**Engineering
our
future**

**Study by AMA Association for Sensors and
Measurement in co-operation with VDI**

Management Summary

The rapid evolution of sensor technology is set to redefine industries and drive innovation across multiple sectors. By 2030, sensors will play a crucial role in enabling smarter, more efficient, and sustainable solutions in fields such as healthcare, automotive, industrial automation, and environmental monitoring and consumer market, and thereby form the backbone of the transformation to an information society and a digital age.

Key Trends

1. Accuracy of measurement

The long-lasting trend to more and more accurate and precise sensors is ongoing and is nurtured by both technology improvements and by new technologies.

2. Miniaturization

Advances in precision and microelectronics will enable smaller, more efficient, and cost-effective sensors. But economics and physical limitations more and more often set limits to further miniaturization. Hence, miniaturization goes on but loses momentum.

3. Smart Sensor Systems

Artificial intelligence and machine learning will enable sensors to process data at the edge, reducing latency and increasing real-time decision-making capabilities. Self-learning sensors will improve predictive maintenance and automation across industries. And sensors will learn to cooperate in sensor networks.

4. Sensors designed for making decisions

While, initially, sensors were often designed to provide a value for a physical or chemical parameter, a class of sensors emerges that does not provide such values but information on how best to decide. This development goes hand in hand with application and customer-specific sensing solutions.

5. Emerging new sensors

Emerging quantum sensor technologies will revolutionize precision measurement, particularly in fields such as medical diagnostics, navigation, and geophysics. Biosensors will advance personalized medicine, early disease detection, and environmental health monitoring. Higher frequency electronics especially for radar will generate new options.

6. Sustainability and Circular Economy

The future of sensor technology will emphasize eco-friendly materials, recyclability, and reduced energy consumption. Regulations and industry standards will encourage sustainable sensor design and manufacturing processes.

Impact on Industries

- **Healthcare:** enhanced diagnostics, real-time patient monitoring, and personalized medicine solutions
- **Automotive:** advanced driver assistance systems (ADAS), autonomous vehicles, and enhanced vehicle-to-everything (V2X) communication
- **Manufacturing:** predictive maintenance, increased automation, and improved supply chain efficiency
- **Environmental monitoring:** improved air and water quality monitoring, climate change adaptation, and smart agriculture solutions
- **Consumer market:** enabled by sensors, end-user products will get smarter.

As we approach 2030, these sensor trends will shape a more connected, intelligent, and sustainable future. Businesses and policymakers must stay ahead by investing in research, fostering innovation, and adapting to the evolving sensor ecosystem.

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1 Global Overview

(Drese, K. S.; Gerlach, G.; Krause, P.; Simmons, C. T.)

1.1 Introductory Remarks, Scope of the Report

(Peter Krause, Chairman of the AMA Executive Board)

Sensor technology is the heart and driving force of modern industry and, as a key technology, is driving digitization and automation in almost all areas. The increasing networking of machines and systems in the context of Industry 4.0 and the rapid spread of the Internet of Things (IoT) are creating a growing demand for powerful, reliable, and intelligent sensors. Miniaturization, precision, and the integration of new technologies such as artificial intelligence (AI) play a crucial role here.

In this new edition of the AMA Sensor Study, published by the AMA Association for Sensors and Measurement together with the Association of German Engineers (VDI), more than 50 experts highlight current innovations and future developments in sensor technology. They analyze the latest trends, the decisive progress, and the challenges that the industry must overcome in order to further advance industrial transformation.

The contributions to this study impressively show how deeply sensor technology is integrated into almost all industrial sectors. From optimizing production processes and increasing energy efficiency to developing safe and autonomous systems – sensors are the basis for data-based decisions and innovations.

In addition to technological developments, political support is also crucial for the further development of sensor and measurement technology. Government funding programs and political frameworks play a significant role in creating an innovation-friendly environment. They not only enable investments in research and development, but also help to ensure that the German industry remains competitive in the global market. Close cooperation between politics, science, and industry is therefore essential to sus-

tainably strengthen the innovative power of the sensor industry.

This study also places a special focus on the multifunctional sensors of the future, the role of quantum sensors, and the growing importance of data security. These topics not only create technical challenges, but also open new opportunities for industry to remain competitive by developing smarter and more secure systems.

This sensor study is intended not only to serve as a guide for research and development, but also to provide impetus for practical application and for new collaborations between industry, science, and politics. We invite you to discover the diverse perspectives and solutions presented by the authors and to actively shape the future of sensor technology together.

We would like to thank all authors and contributors for their valuable input, and we hope that this study will make a significant contribution to the further development of sensor and measuring technology.

1.2 Patent Analysis Insights to Sensor Technology

Patents are the key tool for securing the rights to a new technology for a limited time. Therefore, patents are as essential for industry as peer-reviewed publishing is for academia. Patents do not provide information on the market size for different fields, but they are a reasonable indicator of what industry is putting its focus on for future innovation. Hence, we extract and examine international patent publication data by statistical and data mining analyses and gain information about how much effort different sensor topics have received worldwide, which topics are the hottest, and how patenting intensity is distributed over the different countries.

Demand for sensors is growing across all industries, from healthcare to consumer products, as they help to enhance functionality, performance, and energy efficiency. This fuels rapid advancements in the sensor industry, including new

measurement principles, miniaturization, and smart features for IoT and Industry 4.0. For innovative award-winning examples, see Chapter 6.

The industry for sensor and measurement technology is very innovation oriented. While sustaining a 6.3 % annual growth rate in sales, it reinvests 11 % of its revenue into R&D (Figures 1.1 and 1.2).

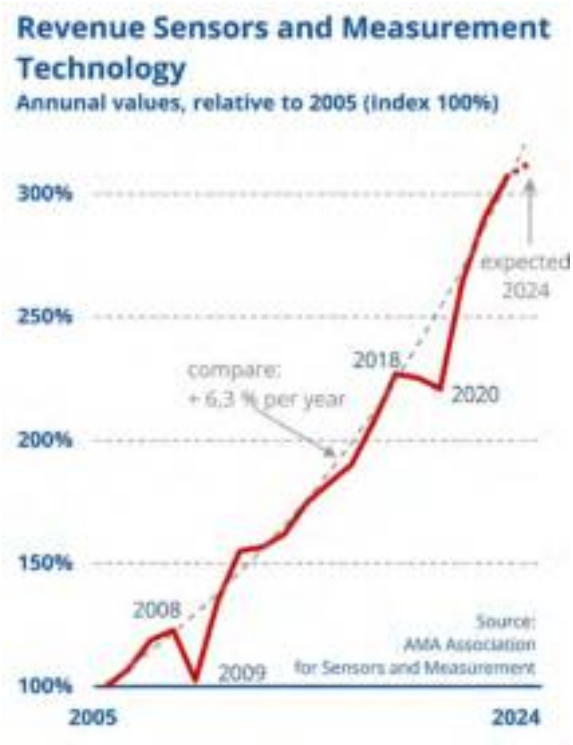


Figure 1.1 Revenue, sensors and measurement technology. Annual values relative to 2005, index 100 %.

To illustrate how R&D intensive sensor technology is, Table 1.1 lists the top ten technology fields by rate of patent publication under the Patent Cooperation Treaty (PCT). Here, measurement reaches sixth place out of 35 technology fields. [WIPO 2024 PCT]

For any market participant developing a market strategy, reliable information on industry trends is crucial. While economists and innovation researchers may not agree on the quantitative interpretation of patent statistics, they recognize their qualitative value, including insights into R&D activities and upcoming technological changes. Thus, we analyze patent activities to gauge the sensor industry’s R&D allocation across different technologies.

In the following, international patent publications are examined in two ways. First, by database access operated by the World Intellectual Property Organization (WIPO) to Patent Cooperation Treaty (PCT) data using the International Patent Classification (IPC) system, and second, with an additional approach based on the Google Scholar search engine. In all cases, the data is visualized as time series [WIPO 2024; Google Scholar 2024]. The analysis begins with the superclass that captures all patents from sensing and measuring technology: class “G01 Measuring; Testing”. This is followed on the next level by differentiating its five most used subclasses. Finally, statistics independent of the IPC classification scheme are included for four fields which are hotly discussed on conferences lately by using free text terms, namely “hydrogen sensors”, “quantum sensors”, “smart sensors”, and “sensors with artificial intelligence”.

PCT publications by technology

Rank	Technology	No. of PCT publications in 2023
1	Computer technology	27 281
2	Digital communication	25 124
3	Electrical machinery, apparatus, energy	21 087
4	Medical technology	17 871
5	Pharmaceuticals	12 430
6	Measurement	11 830
7	Transport	10 841
8	Biotechnology	9 694
9	Audio-visual technology	9 500
10	Semiconductors	9 413

Source: WIPO statistics database. Last updated: October 2024

Table 1.1 Top 10 list of the 35 technologies, as ranked by WIPO. Source C.T. Simmons, AMA Data:[WIPO 2024]

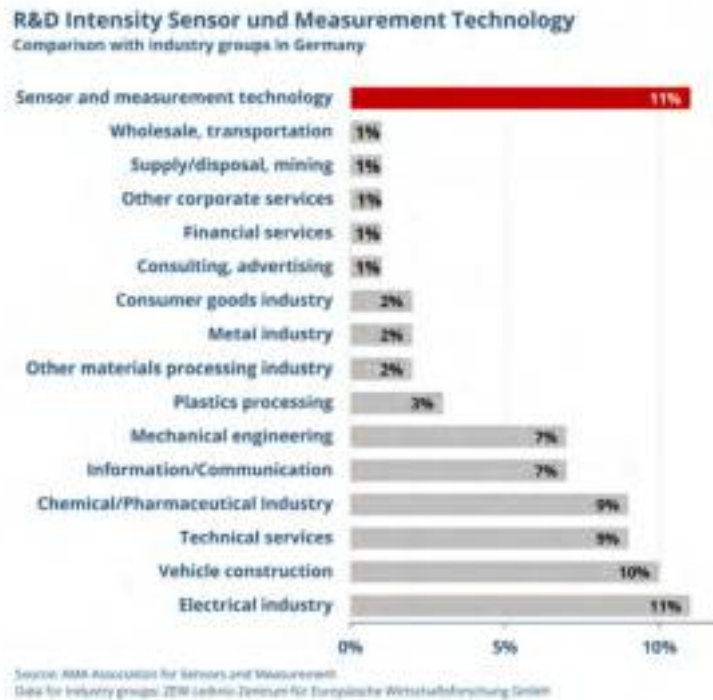


Figure 1.2 R&D-intensity, sensor and measurement technology compared with other industry groups in Germany. Data: AMA and [ZEW 2022]

1.2.1 Analysis of PCT Statistical Data

In the following sections, international patent publications under the Patent Cooperation Treaty are examined using the International Patent Classification (IPC) system. The IPC provides a hierarchical framework for classifying patents by technology. The focus lies on class G01 – “Measuring; Testing” and its subclasses. The World Intellectual Property Organization (WIPO) manages the IPC and has supplied the data for this analysis. For more details, visit the WIPO portal [WIPO 2024] and the PCT webpages [WIPO 2024 IPC].

Figure 1.3 shows the annual publication rate for IPC superclass “G01 Measuring; Testing” since 2010, currently at a level of around 23,000 PCT publications per year globally, growing linearly at approximately 750 publications per year. Europe and North America each contribute 6,000 patents per year, and Asia about 11,500. Since 2014, Asia has been on top, conducting as much patent work as North America and Europe combined, even despite a plateau caused by COVID. Other regions play a comparatively insignificant role in world patenting.



Figure 1.3 PCT publications and their regional origin. (Source: C.T. Simmons, AMA Association for Sensors and Measurement. Data: [WIPO 2024])

IPC class “G01 Measurement; Testing” has 18 subclasses, G01B to G01W. Figure 1.4 shows these subclasses in descending order by publication count. For the purposes of this study, we focus on trends involving the top five by publication count, to identify possible trends.

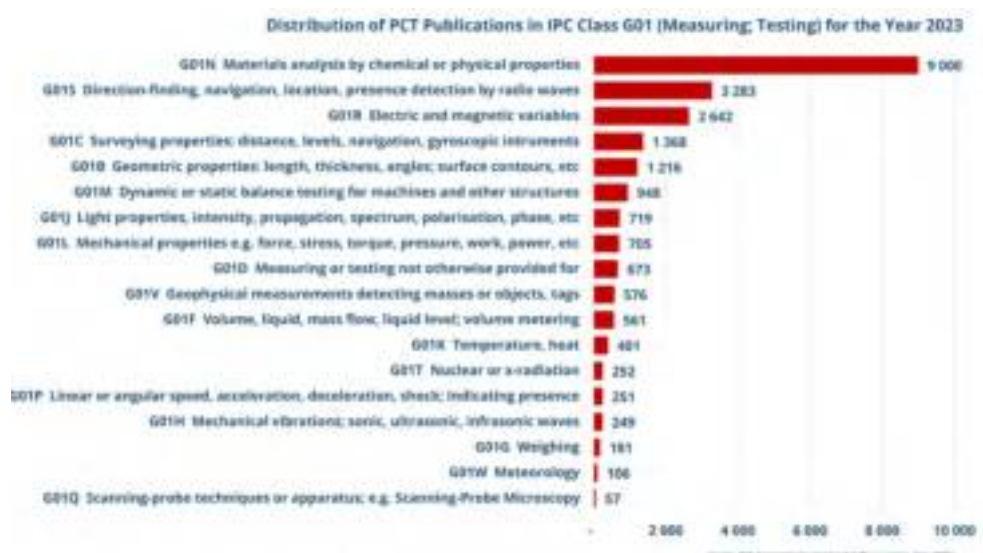


Figure 1.4 PCT Publications of the 18 subcategories of “G01 Measuring; Testing” in 2023.

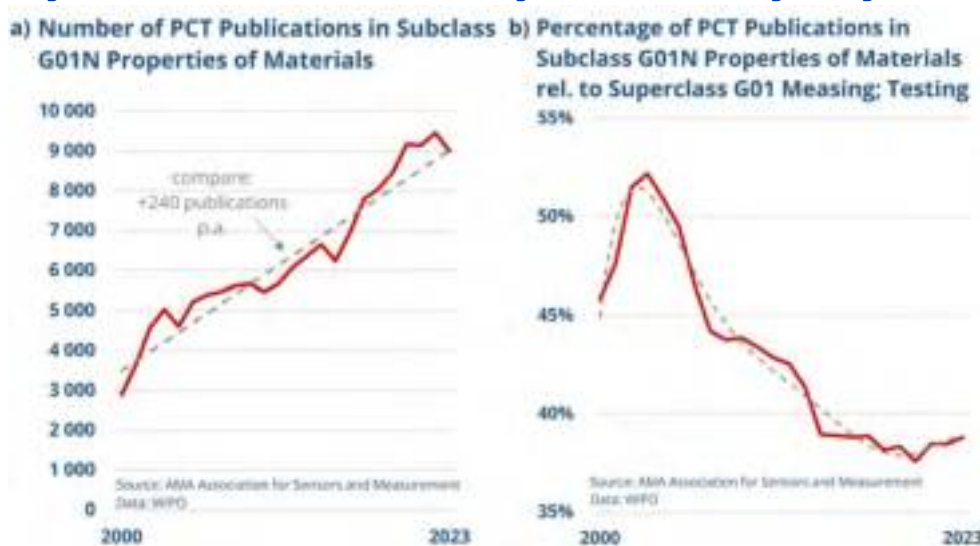


Figure 1.5 PCT publications under “G01N Measuring geometric properties”, where a) shows the absolute number of publications under G01N Materials analysis, b) the relative percentage of publications compared to all of G01. The dashed lines are a guide for the eye. (Source: C.T. Simmons, AMA Association for Sensors and Measurement. Data: [WIPO 2024])

The field is led by **Material Analysis**. Although the proportion of the sum of all R&D effort going into measuring has been receding since 2003, the industry continues to invest very strongly into R&D for analyzing materials. This is the area with currently the most R&D effort of all measuring and testing parameters.

The class “G01N Investigating or analyzing materials by determining their chemical or physical properties” had 9,000 publications in 2023, accounting for over one-third of superclass “G01 Measuring; Testing”. Significant R&D efforts are focused on materials analysis. Figure 1.5 a) shows a steady rise in PCT publications for this subclass at a level close to 240 additional pub-

lications per year. Figure 1.5 b) reveals that, while absolute numbers have increased, the relative share within G01 since peaking in 2003 has been declining. Meaning the growth of the number of publications under G01N is slowing down in comparison with the growth of its superclass G01. Where it once comprised half of all G01 publications it now comprises just under 40 %. The graph of Figure 1.5 b) is remotely reminiscent of a portion of the Gartner style hype cycle course [Gartner 2024] with its “Peak of Inflated Expectations” followed by a “Trough of Disillusionment”, now possibly headed for the “Slope of Enlightenment”. Judged simply by the sheer volume of patents being produced on

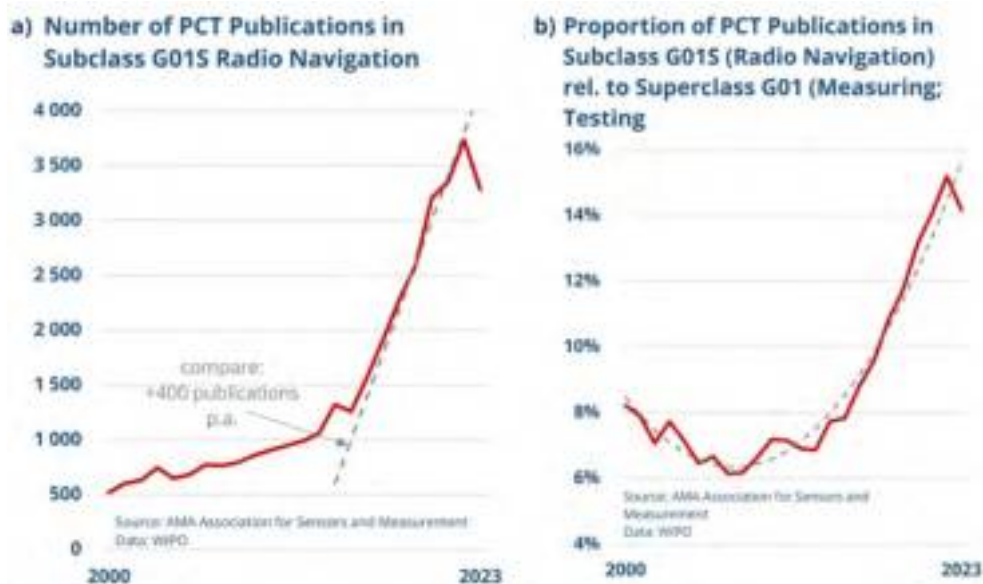


Figure 1.6 PCT publications under “G01S Radio navigation”, a) absolute number, b) relative percentage of patents compared to G01. (Source: C.T. Simmons, AMA. Data: [WIPO 2024])

this subject, it surely demonstrates that materials are a key topic in sensors.

The second largest field in patenting activity is **Radio Navigation**. As can be seen in Figure 1.6, it grows constantly.

The class “G01S Radio direction-finding; Radio navigation; Determining distance or velocity by use of radio waves; Locating or presence-detecting by use of the reflection or reradiation of radio waves” with 3,283 PCT publications in

2023 accounts for more than 14 % of all PCT publications under G01 Measuring; Testing.

Despite the absolute growth in Figure 1.6 a), the shape of the graph in b) shows that until 2008, G01S was in relative decline, but has since returned to growing strongly.

On third rank follows **Electromagnetic Variables**. After a slight temporary dip in R&D efforts into measuring electromagnetic variables around 2017, the level of R&D remains substantial and growing, see Figure 1.7.

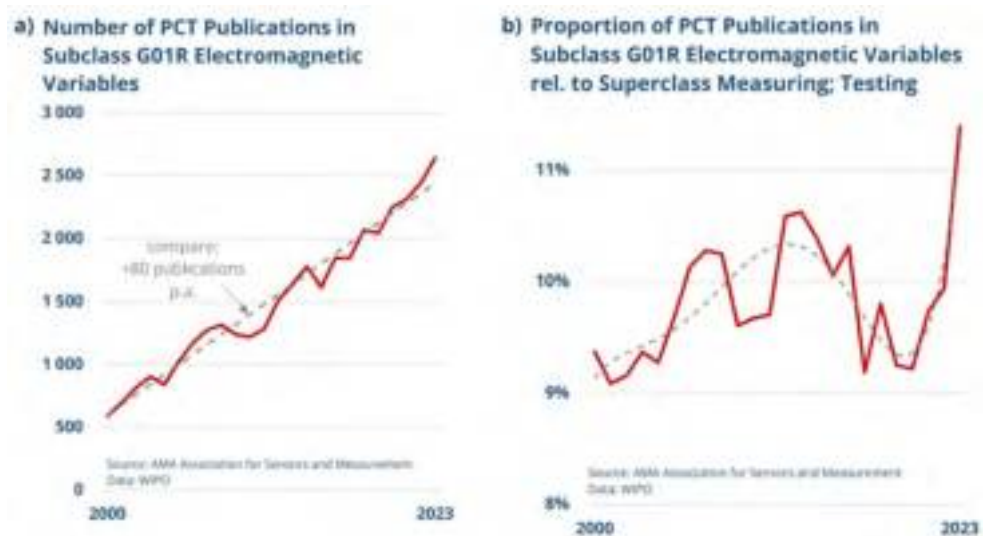


Figure 1.7 PCT publications under “G01R electromagnetic variables”, a) absolute number, b) relative percentage of patents compared to G01. (Source: C.T. Simmons, AMA. Data: [WIPO 2024])

The subclass “G01R-Measuring electric variables; Measuring magnetic variables” has had 2,642 PCT publications in 2023, accounting for more than 11 % of all PCT publications under “Measuring; Testing”. The R&D activity for electromagnetic variables is growing at a high level relative to superclass G01 (Figure 1.7b), and both curves point upwards. Time will tell whether the 2023 data of graph b) is an outlier or part of an upswing.

The upwards trend both in absolute number of publications and in relative comparison with the growth rate is also found in the fourth field, namely **Measuring Related to Distances, Levels, Bearings, Surveying, etc.**, as can be seen from Figure 1.8. This data may be related to G01S “Radio direction-finding; radio navigation”.

The subclass “G01C Measuring distances, levels or bearings; Surveying; Navigation; Gyroscopic instruments; Photogrammetry or videogrammetry” has had 1,368 PCT publications in 2023, accounting for nearly 6 % of all publications under G01 “Measuring; Testing”. Comparison with graph b) in Figure 1.8 shows this class clearly growing faster than its superclass.

The R&D activity level for measuring geometric properties is trending upwards while, since about 2015, its relative proportion compared to all of measuring and testing has been slowly

falling behind the general development. The subclass “G01B Measuring length, thickness or similar linear dimensions; Measuring angles; Measuring areas; Measuring irregularities of surfaces or contours” ranks fifth in publication frequency, with 1,216 publications in 2023, accounting for currently just over 5 % of all PCT publications under “G01 Measuring; Testing”. In the long term, geometric properties are gaining in PCT publications, at a rate of + 50 publications per year, while in proportion to the entire field of measuring, a peak around 2015 is followed by a downward tendency, see graphs a) and b) in Figure 1.9.

The course of graph b) in Figure 1.9 can be interpreted as R&D activity in the realm of geometric properties being headed for Gartner’s “Trough of Disillusionment”.

A short-term tendency is difficult to discern, due to data fluctuations. In any case, the development outside of the last three years has been positive, see Figure 1.9 a). However, the same data relative to superclass “G01 Measuring; Testing” indicates that the number of patent publications on measuring geometric properties is slowly falling behind the general development of publication numbers for “G01 Measuring; Testing”.

Details of the above analysis of PCT data results are summarized in Table 1.2.

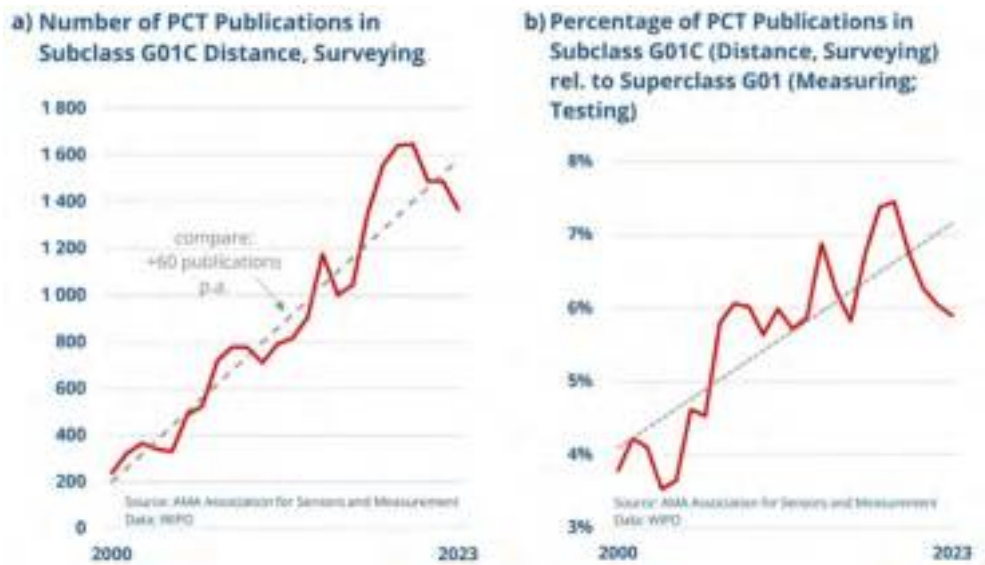


Figure 1.8 PCT publications under “G01C Distance, levels or bearings, surveying, etc.”, a) absolute number, b) relative percentage of patents compared to G01. (Source: C.T. Simmons, AMA. Data: [WIPO 2024])

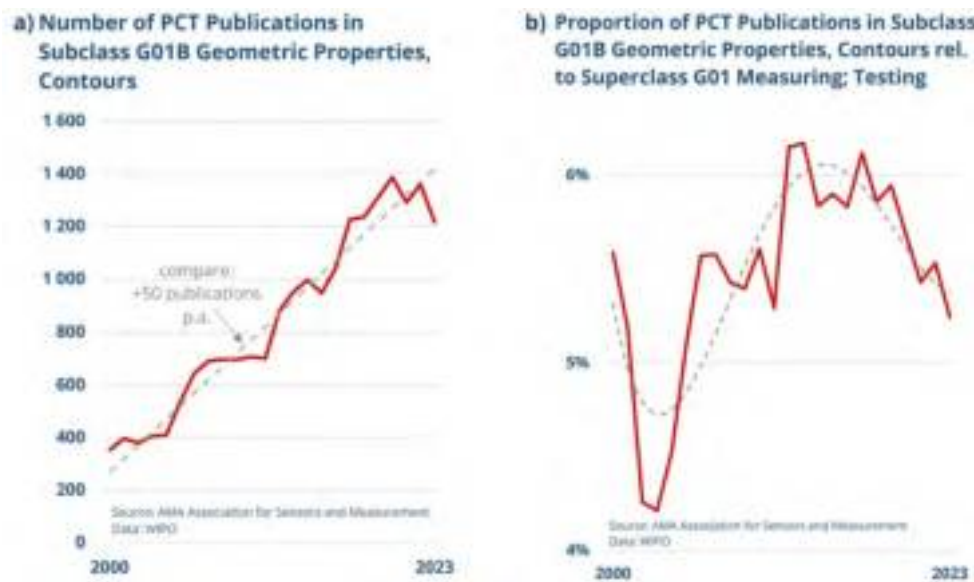


Figure 1.9 PCT publications under “G01B Measuring geometric properties”, a) absolute number, b) relative percentage of patents compared to G01. (Source: C.T. Simmons, AMA. Data: [WIPO 2024])

Key Findings in PCT Database

Classification	Class	Patent publications in 2023	Recent growth rate – linear [additional annual publications p.a.]
Measuring: Testing	G01	23 188	+750
Materials analysis	G01N	9 000	+230
Radio navigation	G01S	3 283	+400
electromagnetic variables	G01R	2 642	+ 80
Measuring distances, levels, bearings, surveying, etc.	G01C	1 368	+ 60
Geometric properties	G01B	1 216	+ 50

Table 1.2 Summarized details of the PCT data analysis.

1.2.2 Analysis of specific sensing fields

This approach uses Google Scholar to search and aggregate patent titles and is therefore independent of the IPC classification. It is not based on hierarchical context information as in the case of IPC data, but instead provides flexible, unstructured analysis of any text. The queries used in the following were case-insensitive and restricted to patent titles only, and options were set to the appropriate time periods, and to alternately include and exclude patents. [Google Scholar 2024]

Due to changes in energy supply, one could expect that numbers around **Hydrogen and Sens-**

ing are growing. However, judged by the number of patent titles concerned with measuring hydrogen, R&D into measuring hydrogen is at a comparatively low level and has been growing quite slowly.

The current level lies about 25 patents per year, increasing beyond this rate at a slow linear pace of one additional patent every two years (Figure 1.10) [Google 2024_1]

Number of Patents Concerned with Hydrogen Sensors

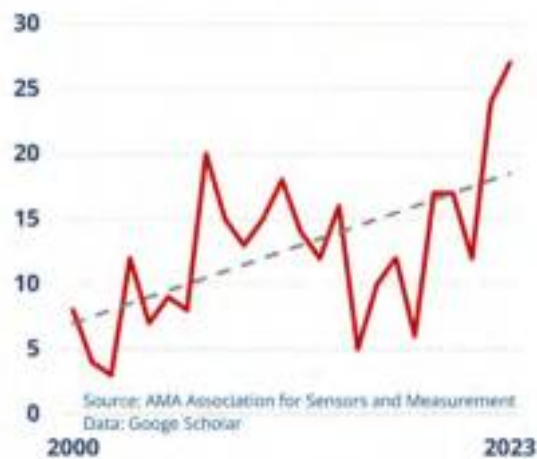


Figure 1.10 PCT titles containing “Hydrogen Sensors”. (Source: C.T. Simmons, AMA. Data: Google)

Another field that gets quite a lot of academic attention is **Quantum Sensing**. Judging by the number of patent titles concerned with quantum sensors, R&D into this subject is currently at a relatively low level but is rapidly gaining momentum (Figure 1.11). [Google 2024_2]

Number of Patents Concerning Quantum Sensors

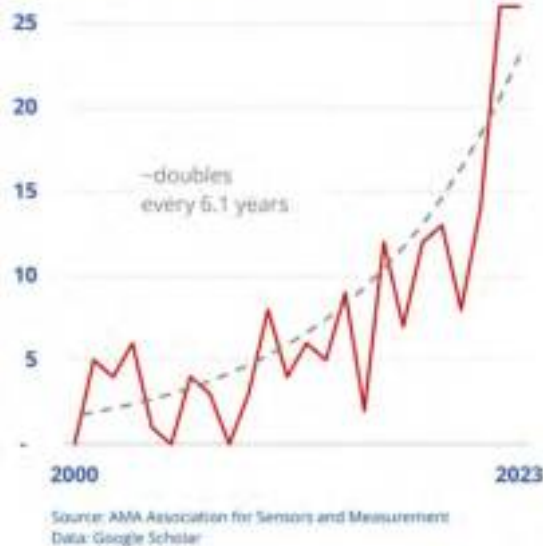


Figure 1.11 PCT titles containing “quantum sensors”. Searched and counted: patent titles containing “quantum” and (“sensor” or “sensors” or “sensing”). (Source: C.T. Simmons, AMA. Data: Google)

The situation is slightly different for **Smart Sensors**. From the number and yearly development of patents concerned with smart sensors, it can

be judged that the R&D into this subject is currently at a moderate level but growing exponentially at a rate of about doubling every six years [Google 2024_3]. The current level is at about 70 patents per year in 2023 (Figure 1.12).

Number of Patents Concerned With Smart Sensors

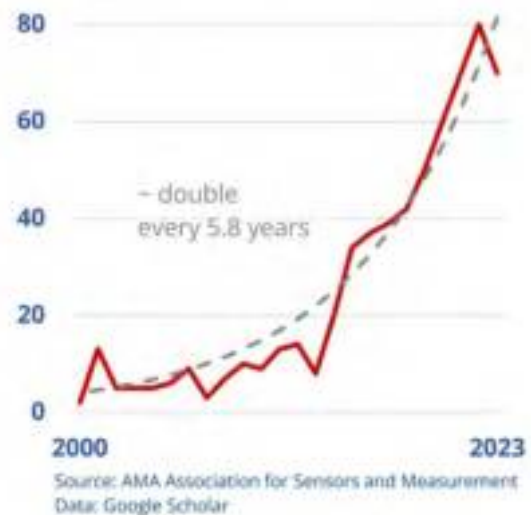


Figure 1.12 PCT titles containing “smart sensors”. Searched and counted: patent titles containing “smart” and (“sensor” or “sensors” or “sensing”) (Source: C.T. Simmons, AMA. Data: Google)

A much more extreme development is found with **Sensors with Artificial Intelligence**. Starting extremely low, the growth rate has lately been the highest in the specific sensors investigated. (Figure 1.13) [Google 2024_4].

Details of the above analysis of search results are summarized in Table 1.3.

Several conclusions can be drawn from this patent analysis:

- The sensor and measurement technology industry is highly active in R&D, with Asia leading in the sheer number of patent publications.
- Material Properties is by far the most active R&D area but is losing momentum.
- Radio Navigation Technology, while being slightly smaller, is growing significantly.

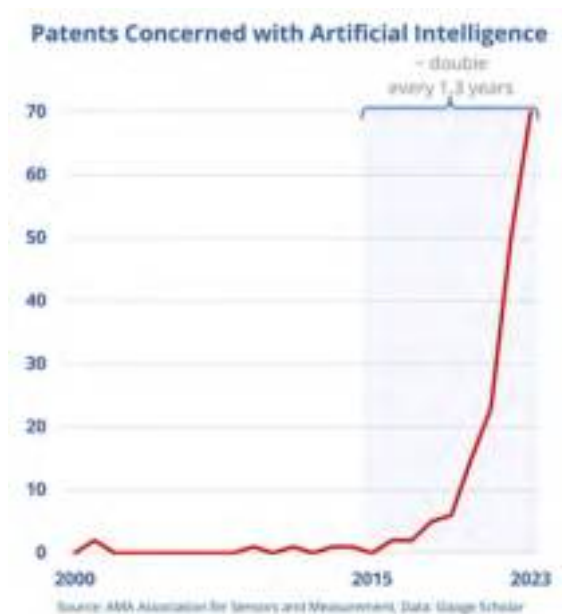


Figure 1.13 PCT titles containing “sensor” and “artificial intelligence”. Searched and counted patent titles containing “sensor” and (“neural networks” or “neural network” or “machine learning” or “deep learning” or “artificial intelligence” or “AI”) (Source: C.T. Simmons, AMA. Data: Google)

- Technology for measuring distances, levels, and bearings in surveying is on the rise.
- R&D efforts are also growing in measuring electromagnetic variables and geometric properties like length, thickness, and angles.
- Judging by the rate of patent publication, “Hydrogen Sensors” are currently the subject of only few patent publications and are growing comparatively slow.

- Patent publications on “Quantum Sensors” are few but growing moderately.
- “Smart Sensors” are gaining ground in patent titles, but at a moderate growth rate.
- By growth rate of R&D patent publications, Sensors with Artificial Intelligence are the hottest topic in sensor technology.

1.3 Trends in Sensor Technology

Humanity is in the transition to an age of information. This has many implications which find a straightforward expression in mega trends like digitization, AI, Industry 4.0/5.0 (Industrial Internet of Things), etc., but also indirect implications on megatrends like the shortening of innovation cycles. Most of the time, discussion focuses only on how to deal with information, how to process it and perhaps how to create value from it. However, the key question of where the information is coming from is often forgotten or at least does not stand in the limelight. It is comparable to studying the relevance of metals without dealing with the ores and the mining from where the metals are coming. Sensors are the devices which do the mining of information. Following this logic, we use the term sensors not in the academic definition in which a sensor only responds to a stimulus and transmits a signal, but understand a sensor as a device that picks up a stimulus and transmits information about the stimulus picked up.

Key Findings from Patent Title Search

Term Searched for in Patent Titles	Patent publications in 2023	Recent growth rate (additional annual publications p.a.)	Remarks
Hydrogen sensor	27	<1	absolute growth patents per year
Quantum sensor	20	+15%	relative growth per year, exponential
smart sensor	70	+14%	relative growth per year, exponential
Sensor with artificial intelligence	70	+20%	relative growth per year, exponential

Table 1.3 Summarized details of the patent search data analysis.



Figure 1.14 Schematics of a sensor

A sensor is a man-made device to acquire information on a process or an object that picks up a stimulus and transmits information about the stimulus picked up

Figure 1.14 underlines this understanding of sensors, as sensors are typically part of a decision-making chain where the information obtained is used to influence (control or regulate) processes regarding predefined criteria (target function). Sensors are man-made devices that react in particular to a physical or chemical variable, provide corresponding information about this variable mostly in the form of an electrical output (Figure 1.4) but are usually also influenced by other, interfering variables (temperature, humidity, light, etc.). These relationships between the measured variable, the output carrying the information and the disturbance lead to important requirements for the properties of sensors, which are summarized in Table 1.4, and which are also discussed in the different parts of this study.

The above-mentioned difference between “transmits a signal” and “transmits information” sounds minute, but lays the basis for the smart sensor discussed in detail in Chapter 4. It also happens more and more often that one asks for a sensor, but what is actually expected is a sensor module that can be integrated with ease in the application at hand. And finally, it also makes it easier to give an overview of the general trends in sensorics.

Table 1.4 The six S that describe the success of sensors (Source: [Gerlach 2021, Gerlach 2023])

Sensitivity: Sufficiently high sensitivity (relationship between output signal as carrier of the information and stimulus)
Selectivity: Output signal should only depend on the stimulus as measuring quantity.
Stability: Properties of the sensor should be constant.
Settling time/speed of response: Sensor must react sufficiently fast in order to influence processes at a sufficiently fast rate.
Signal-to-noise ratio/Limit of detection: Noise in/by the sensor must be sufficiently low compared to the signal to deduce significant and reliable information.
Sales aspect: New sensors have to provide higher value by improved properties and/or functionalities (e.g., better long-term stability, smaller limit of detection, faster sensor response) and/or have price advantages due to simpler or more efficient manufacturing technologies, if they want to establish themselves on the market.

1.3.1 Classification of Sensors

Sensors can be classified according to different aspects, e.g., from the point of view of the input variable to be measured, with regard to the mostly electrical form of the sensor signal, with respect to the physical conversion mechanism or in relation to the manufacturing technology.

Which stimulus is sensed? As energy is involved in all natural processes (including living organisms), thermodynamics is particularly important. Accordingly, pressure and temperature sensors are the most commonly used technical sensors. The same applies to volume-characterizing sensors for level and flow. However, sensors for other mechanical (and acoustic) variables as well as electrical, optical/radiation and magnetic sensors and chemical and biochemical sensors are also widely used. All these sensors are considered in Chapters 2 (physical sensors) and 3 (chemical and biochemical sensors).

What is the electrical interpretation of the resulting information? As shown in Fig. 1.1, the information about the quantity to be measured can be represented in various forms: as a change in resistance, capacitance or inductance, as a self-generated or electrically modulated (e.g., frequency-modulated) signal [Middelhoeck], analog or digital, as a standardized signal, without or with signal or data processing. This is addressed in this study in Chapter 4.

Fabrication aspects of the sensor. An important issue for the properties, but even more for the cost of the sensors, are questions related to the production, integration and packaging of sensors, which are closely linked to the number of units to be produced. These current developments are examined in detail in Chapter 5.

1.3.2 General Trends

Increasing accuracy, decreasing uncertainty of measurement. The first general trend which is found here and which is also found in virtually any report on sensors is the increasing precision and accuracy that sensing and measuring devices are achieving. The trend is one that some authors claim to be persistent through the whole development of humanity, e.g., when studying how time, length or weight measurements developed. The rate at which the measurement uncertainty is improving is very technology-dependent and ranges from 26 % for time measurement to 6 to 14 % for length measurement. This trend in measurement uncertainties has many implications, e.g., it enables miniaturization which is one of the key reasons why computation power experienced exponential growth over the previous decades. This trend is also the basis for why the technology gap in the frequencies between high frequency electronics and infrared is continuously closing. On the one side, one sees how frequencies in communication, radar technology, etc. are rising, and on the other, there are optical solutions for increasing wavelengths. There is no indication that the continuous race to growing accuracy will end in the foreseeable future. The rates might change as has been the case with time measurements lately with the switch from microwave to light-driven clocks, but a termination cannot be foreseen.

Miniaturization. In contrast to the trend towards ever smaller measurement uncertainty, the trend towards ever smaller dimensions has increasingly clear limits. It is therefore left to the reader if one really wants to put miniaturization on the list of trends. While some sensors will keep on shrinking, other technologies will reach or have been reaching their reasonable limit due to physical limitations. For instance, microelectronics is limited by atomic scale, microfluidics is limited by cell size (for cellular assays) and low concentration (there must be a sufficient number of molecules to meet the quantification precision set), and limitations in optics are caused by the diffraction limit. The latter example also underlines in an excellent way that by "changing the rules", once set limits can be broken, e.g., nearfield optics and STED microscopy overcome the diffraction limit. The trend for miniaturization hence has to be looked at in a differentiated way. Another reason for this is that miniaturization very often goes hand in hand with higher challenges to reach good signal-to-noise levels or measurement effects, and with increased processing/manufacturing costs (per manufacturing run). One should also mention that, sometimes, devices stop shrinking because humans still have to be able to handle them, e.g., point-of-care testing solutions. Hence, for all of the reasons given above, miniaturization increasingly has to be motivated by matching markets, which leads to the next major trend.

Exponential demand on information in our information society. The third trend is that the ranges and areas in which sensors are used are growing. This is true not only in a global sense, but very often even for all individual technologies. The reason for this can be found on different levels. One aspect is surely that an information society requires more information input. Also, the increasing automatization of all aspects of life requires information about the situation one is in to allow to control it and to appropriately react to it as quickly as possible. How sensors are an integral part of such control circuits can be seen in Figure 1.15.

A second reason might lie in the nature of innovation as outlined by Drucker as long as 40 years ago [see Drucker 1985; Drucker 1986; Drucker 2002]. It is a lot easier and less risky to find innovative applications for established

technologies than to bring forward new high-tech technologies.



Figure 1.15 Sensors as a part of control circuit
(Source: Gerlach 2021)

This corresponds with the frequent requirement to guarantee a sufficiently accurate measurement over years or even decades, and this often under harsh conditions. This extreme demand for reliability of technical systems and, hence, of sensors often causes sensor manufacturers to act in a very conservative way.

A last reason might be purely economic: that companies, but also academic research groups, try to expand their business by establishing new markets and new applications. In contrast to other sensor trend studies, we name this trend here in a very abstract way, but we ought to mention that it can be found more specifically elsewhere, e.g., the trend for MEMS for gaming, MEMS for medical applications, smart textiles, etc. However, since the trend of broadening the application range is more driven by economic and societal trends, it is hard to make predictions from a technology standpoint.

Sensor systems replace sensors. The fourth trend is towards more complex sensor systems. To grasp this trend, one has to jump back to the understanding that a sensor is a device that provides information about the state or properties of an object or process and its environment. The value of this information is increasing the better it allows to draw conclusions and to act accordingly. In a traditional way of thinking, this means that one has to decrease the measurement uncertainty, increase the selectivity, increase the sensitivity and minimize the effect of nuisance factors. sensors will develop to have not only a single transducer that allows only to read a single value, but they will have many element both in hardware and in the process they are operated to allow for multiple value readings. Prominent examples are self-X, smart sensors and multi-sensor systems. More examples

can be found in Chapters 2 to 4. A closer look shows an interplay of many elements which is more and more often no longer linear. Once the interacting elements rise above a critical level, such a system can no longer be understood as just a complicated system, but the behaviors get complex and thus requires new ways in dealing with them. The interplay of a growing number of elements which sometimes have a very intricate inner life can also be seen in manufacturing trends such as different types of integration, e.g., system on chip. Hence, the trend to complex systems is found in virtually all levels of sensors, i.e., system design, transducer interplay, operation, signal processing and manufacturing.

Making decisions instead of just measuring a quantity. A striking point in this trend is that there is a growing number of cases where the information is no longer mediated via a high-quality number of a physical or chemical quantity, but via a qualitative or quantitative output like OK/not OK or high/medium/low, directed more towards a reaction on the measurement rather than on a value of a single parameter. In medicine, it is common practice to use surrogate parameters to make treatment decisions, and there is a high likelihood that AI-based data evaluation can achieve that as well. Also, not all decisions to be taken need high-quality measurement results. And, finally, with the help of statistics, the evaluation of many low/medium results can also lead to a high-quality outcome. The use of multiple sensors that were originally not intended for such a purpose and that still lead to good decisions shows that the way to results might get more complex and might be reached differently from how it was done in the past. This trend is feasible for three main reasons: improvements in manufacturing (e.g., system on chip), growing computation power, and falling prices of sensors and transducers which allows for using more than just one sensing element.

Falling costs and decreasing energy consumption. The reason why these two trends are named together is that both trends are only visible if one compares sensors with exactly the same performance. When comparing sensors at the state-of-the-art level, these trends are less

obvious or it might even seem that both energy consumption and prices are rising.

Sustainability. It has to be mentioned that there are further developments which are not sensor specific. One is lowering the environmental impact, e.g., by removing lead from electronics and, lately, by eliminating per- and polyfluoroalkyl substances (PFAS). It is likely that requirements for recyclability will raise and that further sustainability requirements will arise. A similar development is that interfaces are standardized to enable high ease of integration of sensors.

Solutions for every demand. A final note has to be made that there are also several developments which are divergent. Examples of such developments are the use of edge or cloud computing. Also, the last sensor trend report already showed that there is an increasing number of “low cost/moderate performance” sensors that are vastly used, and at the same time “high cost/high performance” sensors are used for non-mass applications. These diametral developments show that specialized sensors will be needed to make it possible to pick the most appropriate sensor solution for the challenges at hand. This will require a good overview of available solutions and deep insight into the requirements of the applications. Chances are high that in the future, the best solution will in more and more cases no longer be the obvious and most trivial one.

High reliability and low measurement uncertainty of sensors cause continuous advancement rather than disruptive development. Since most of the above trends reflect very continuous changes, the reader might ask which surprises are to be expected. One has to admit that abrupt changes are either due to inventions that show how things can be done totally different, e.g., nano-pore sequencing of DNA or new gas sensing materials, or that a technology slowly but steadily develops up to the point where it is ready to be applied widely, e.g., AI due to increasing computation power and availability of data. The curious reader is invited to visualize such claimed disruptive innovations. For the most part, one does find a kind of step function (market introduction of new sensor solutions) on a linear scale and a linear one on a logarithmic

scale. Hence, the later ones can be predicted, but very often it is unclear when they will go viral, because the critical level is unclear. AI and 3D printing, to name only two examples, had a (several) decades-long history prior to the point when they became a megatrend.

1.3.3 Technological Readiness of Sensors

Two laws on sensors have been postulated:

The number of sensors fabricated annually doubles about every five years [Simmons]. This trend is driven mainly by the larger and larger demand on sensors in all areas of industry and technology as mentioned above.

The number of scientific publications on sensors doubles about every four years [Gerlach 2021]. Analogous to Moore's law, this describes an observation and projection of a historical trend and is therefore by no means a law of physics. Interestingly, it has been shown that this current exponential growth in publications is in no way coupled with a corresponding increase in innovations, but is caused by the ever-increasing pressure to publish in academia. In order to realistically speak of a “sensor”, the influence of possible interfering variables (selectivity) and the reproducibility of the sensor properties would have to be thoroughly investigated not only in terms of sensitivity but also over sufficiently long measurement times (long-term stability).

The maturity of a particular technology during its development process can be judged by Technology Readiness Levels [Heder 2017]. In 2013, the TRL scale was canonized by the Standard ISO 16290:2013. To reliably achieve this for the commercially usable sensors with respect to the six S mentioned in Table 1.1, both the sensor principle and the fabrication technology must be mastered extremely well, as already stated above [see Gerlach 2021]. For completely new sensor solutions, the development time from the lab R&D phase to a marketable product and then to a mass product has shortened significantly in recent decades, but still amounts to about 10 years [see Eloy 2014]. It is difficult to estimate the extent to which this period could be shortened in the future.

References Chapter 1

Drucker, P. F. (1986). Innovation and Entrepreneurship (1st edition). First Perennial Library.

Drucker, P. F. (2002). The discipline of innovation. Harvard Business Review, 80(8), 95–102.

Drucker, P. F. (1985). Principles of successful innovation. Research Management, 28(5), 10–12.

Gerlach, G. (2021). How to bridge the gap between academic and industry-oriented sensor research. IEEE Sensors Journal, 21 (11), 12344–12351.

Gerlach, G. (2023). The long and rocky road from academic sensor research to industrial mass production. In: M. R. Rzasny (Ed.): Metrologia. Opole: Politechnika Opolska. 99–106.

Middelhoek, S. (1998). The sensor cube revisited. Sensors and Materials, 10(7), 397–404.

Simmons, C.T. (2015). Sensor opportunities for the industrial IoT. Presented at 7th International Workshop on Novel Developments and Applications in Sensor and Actuator Technology, Coburg, 16.–17.09.2015.

Héder, M. (2017). From NASA to EU: the evolution of the TRL scale in Public Sector Innovation, Innovation Journal 22(2), article 3.

Eloy, J.C. (2014). What are the business and technology trends that are impacting the MEMS business for the next 5 years?, presented at the General Meeting of the AMA Association on Sensors and Measurement Technology, Nuremberg, Germany, June 2014.

[ZEW 2022] Innovationen in der deutschen Wirtschaft, ZEW – Leibniz-Zentrum für Europäische Wirtschaftsforschung GmbH (Publisher), Mannheim, 2022.

[WIPO 2024] World Intellectual Property Organization (WIPO) web portal <https://www.wipo.int/portal/en/> (accessed on: March 11th 2025)

[WIPO 2024 IPC] International Patent Classification system (IPC) <https://www.wipo.int/classifications/ipc/en/> (accessed on: March 11th 2025)

[WIPO 2024 PCT] World Intellectual Property Organization (WIPO). Patent Cooperation Treaty (PCT) Statistics. Retrieved from <https://www.wipo.int/ipstats/en/statistics/pct/> (accessed on: March 11th 2025)

[Gartner 2024] URL: <https://www.gartner.com/en/information-technology/glossary/hype-cycle> (accessed on: March 11th 2025)

[Google Scholar 2024] URL: <https://scholar.google.com>

[Google 2024_1] Google Scholar. Search results for “(sensor OR sensors) (hydrogen OR H2)”. Retrieved October 2024 from <https://scholar.google.com>.

[Google 2024_2] Google Scholar. Search results for “allintitle: quantum sensor OR sensors OR sensing”. Retrieved October 2024 from <https://scholar.google.com>

[Google 2024_3] Google Scholar. Search results for “allintitle: smart (sensor OR sensors OR sensing)”. Retrieved October 2024 from <https://scholar.google.com>

[Google 2024_1] Google Scholar. Search results for “allintitle: sensor “neural networks” OR “neural network” OR “machine learning” OR “deep learning” OR “artificial intelligence” OR “AI”. Retrieved October 2024 from <https://scholar.google.com>

2 Physical Measurands

(Stöckel, C.; Zimmermann, S.)

Sensors measuring physical quantities are a fundamental cornerstone of modern technology. They convert physical parameters such as temperature, pressure, force, inertial signals, sound, ultrasound, and magnetic fields into electrical signals that can be analyzed and processed. This data is crucial for a wide range of applications in industry, medicine, environmental monitoring, and everyday life, providing precise and reliable information necessary for the control, monitoring, and optimization of processes and systems. Also, they are the most prominent parameter since everyone uses them daily in the omnipresent technical devices like smartphones. Within this chapter, a tour through these different properties is taken.

2.1 Mechanical Measurement Quantities

(Schäfer, A.; Stöckel, C.; Stoppel, F.; Uebbing, J.; Zeller, H.; Fischer, M.; Hampel, T.; Lehmann, T.)

Mechanical measurement quantities have always been closely connected to the development of mechanical engineering, machine manufacturing and particularly of automotive industry [Bonfig 1988].

In many measuring tasks, mechanical quantities on solids like strain in general, force, pressure, torque, vibration, acceleration and number of revolutions (rpm) are of interest besides geometrical quantities for the coordinate measuring technology (such as length, displacement, thickness, angle, tilt, and position).

What are the commonly used physical pick-up principles for sensors of mechanical measured quantities? Two basic principles are dominating:

Out of the pick-up principles used, the electrical foil-type strain gauge is the longest available, reliable and very accurate principle, which is based on resistance change by strain (resistive principle) [Hoffmann 1987]. Furthermore, the strain gauge sensor and device technology are well developed and have been commercially

available for a long time. In many fields of measurement, the theoretical and technological issues of this principle have largely been clarified at a high level. This is also the reason why strain gauges are used widely in the worldwide traceability system as transfer standards (to trace back force, torque or pressure back to national standard). For force, torque and pressure sensors a well dimensioned measuring body is required to get a sufficient signal.

With the strain gauge principle, the change of the resistance is based on the geometric change of the conductor (which dominates for the most strain gauges) and the piezoresistive effect at semiconductor strain gauges.

The latter is the change of the resistivity of a material (metal, silicon) when mechanical strain is applied.

The second pick-up principle is based on the piezoelectric effect, which is the ability of certain solids to generate an electrical charge in response to mechanical stress. The charge produced in the piezoelectric material is proportional to the force applied and can be used as a measurement signal in a charge amplifier. Since the development of the first charge amplifier in 1950, this principle can be used for highly-accurate dynamic and quasi-static measurements of mechanical quantities.

Strain Measurement in General

In the fields of structural analysis, material characterization and validation of computational models, strain measurement is frequently required. The most commonly principle used is the foil strain gauge as introduced above. Precision strain gauges of various designs and applications are available for this purpose [Schäfer, 2023]. Piezoelectric strain sensors are applied for industrial applications, e.g., the monitoring of different types of machinery such as presses and automatic assembly machines.

Another strain measurement principle worth mentioning, which is increasingly being used, is fiber optic sensor technology (Figure 2.1), e.g.,

fiber Bragg gratings and distributed fiber-optic sensors.



Figure 2.1: Strain gauge, Strain meter, Rosette and Accelerometer can all be realized in fiber optic sensor technology (Source: HBK)

Force Sensors

Sensors for force measurement are mainly based on the two different measurement principles: the strain gauge (foil-type strain gauge, Figure 2.2) and the piezoelectric principle. The first one is suitable for static and dynamic measurements while the piezoelectric principle is dedicated in particular for dynamic measurements.

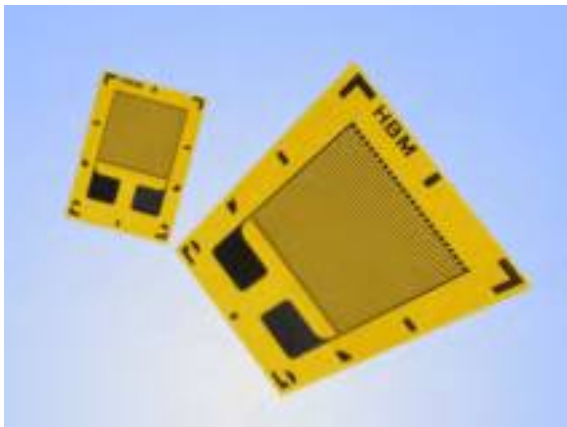


Figure 2.2: Strain Gauges (Source: HBK)



Figure 2.3: Force Sensor U10M (Source: HBK)

Strain gauges are not only the basis for force transducers (Figure 2.3), but also for load cells calibrated in kg (Figure 2.4).



Figure 2.4: Load cell of PW Series (Source: HBK)

Piezoelectric force sensors, respectively piezoelectric force transducers or load cells, are perfectly suited for the precise measurement of compressive and tensile forces, both in highly dynamic applications and in quasi-static processes. One of the most important piezoelectric materials is quartz (SiO_2) (Figure 2.5). Other synthetic crystals are used for applications where high-temperature stability or high sensitivity is required (see Chapter 5.2).



Figure 2.5: Quartz crystals and transduction elements, (Source © 2024 Kistler Group)

Depending on the direction of the applied force and the position with respect to the polar axes of the crystal, the piezoelectric effect occurs longitudinally (in the direction of the force), transversely (with respect to the force) or as a shear effect. Piezoelectric sensors can, therefore, be integrated in a variety of ways (Figure 2.7). Due to the combination of small displacements and the high stiffness of the crystal structure, extremely rigid structures can be realized featuring high natural frequencies. This is ideal for capturing very fast or high-frequency events up to the 1 MHz range. Figure 2.6 shows a force transducer for compressive nominal force of 50 kN, with a compact stainless design, for op-

eration with a charge amplifier. Quite common in industrial applications are the so called Integrated Electronics Piezo Electric (IEPES) transducers (Figure 2.7). This describes an industry standard for piezoelectric sensors with built-in impedance converter electronics. For a comprehensive overview on piezoelectric sensors see [Gautschi 2002].



Figure 2.6: Piezoelectric Force Sensor CFT+/50kN
(Source: HBK)



Figure 2.7: Piezoelectric Force Sensors for (highly) dynamic measurements with IEPE or charge output
(Source © 2024 Kistler Group)

Pressure Sensors

Piezoresistive pressure sensors (Figure 2.8) especially in their miniaturized form are based on silicon semiconductors and mostly realized as a MEMS (micro-electromechanical system). For the larger sensors, however, the sensor principle is most frequently based on metallic strain gauges using the resistive principle. Pressure MEMS are usually based on a membrane principle. For high-temperature applications, silicon-on-insulator (SOI) technology is applied.



Figure 2.8 Miniaturized barometric pressure sensor, based on Piezoresistive principle (Source: CiS Forschungsinstitut für Mikrosensorik, Nadin Jurisch)

Pressure sensors based on the piezoelectric principle (as explained above) are used for quasi-static and in particular dynamic measurements. Sensors like the ones in Figure 2.9 exhibit a high natural frequency of more than 500 kHz and are thus ideal for applications where fast pressure rise times of up to 1 μ s have to be measured. Additionally, piezoelectric pressure sensors like the one in Figure 2.10 are ideal for the measurement of very small pressure changes (pressure pulsations) at high static pressure levels. These enable the long-term measurement of very small pressure pulsations with high resolution and excellent signal-to-noise ratio for a frequency range of over 100 kHz.



Figure 2.9: Left: Pressure Sensor 2200C (Source: Dytran Instruments); **right: Kistler Pressure Sensor 603C**, featuring a rise time < 0.4 μ s within a temperature range of -196 to 200 °C (Source © 2024 Kistler Group).



Figure 2.10: Piezoelectric pressure sensor Type 6635A1 for closed-loop cylinder pressure control (Source © 2024 Kistler Group)

For the measurement of high pressures (> 2 kbar resp. 200 MPa), improvements are continued to be made in the different pick-up principles, i.e. piezoelectric, piezoresistive, or foil type strain gauge elements (Figure 2.11).



Figure 2.11: Left: High Pressure sensor foil type strain gauge: Pressure Sensor P3 Top Class BlueLine (Source: HBK); right: piezoelectric high pressure sensor 6213B for dynamic measurements up to 10 kbar (Source © 2024 Kistler Group)

Accelerometers

Basically, an accelerometer is a dynamic force sensor on which a seismic mass is attached. The measuring signal is proportional to the occurring acceleration. The constant mass m , also called seismic mass, evokes a force F due to the mass inertia when it is accelerated. Calibration determines the relationship between acceleration a and force F . Accelerometers are extremely common in dynamic testing. Microelectromechanical system (MEMS) accelerometers based on a capacitive measuring principle are used for static and low-frequency measurements (Figures 2.12, 2.13).



Figure 2.12: left: Dytran 7500 Series Super compact Single Axis Variable Capacitance MEMS Accelerometer 8S (Source: HBK); right: high-sensitivity, low-noise, single-axis accelerometer K-Beam 8316A (Source © 2024 Kistler Group)

Shown below is a piezoresistive strain gauge accelerometer realization (Figure 2.13). This combines two advantages: on the one hand, it is able to measure static acceleration, and on the other, it is able to measure velocity by integration of accelerometer value by means of electronics, a real smart-sensor (see Chapter 4) application.



Figure 2.13 Microstrain 3DM-GQ7-GNSS/INS, Accelerometers covering an enormously wide measuring range, in some cases up to more than 100'000 g. (Source: HBK)

The third alternative approach is to use piezoelectric effect (Figures 2.14, 2.15, 2.16) which can have robustness and sensitivity advantages and feature a wide measuring range.



Figure 2.14: Left: HBK Type 4383 HS Accelerometer (Source: HBK); right: ultra low-noise triaxial accelerometer 8788A featuring a noise level of only 42 μg in the 5 g range (Source © 2024 Kistler Group)



Figure 2.15: Dytran 3215 Series Accelerometer, particularly suitable for both aircraft applications and the space industry; the measuring body is made of titanium, hermetically sealed. (Source: HBK)

Torque Sensors

For torque sensors, the commonly used pick-up principle is the strain gauge principle (Figure 2.17). Generally, they can satisfy even very



Figure 2.16: World's smallest triaxial accelerometer which measure vibration in three orthogonal axes, weighing only 0.9 grams (Source © 2024 Kistler Group)

demanding requirements in terms of measurement uncertainty. Basis for this extraordinary performance of this kind of torque sensors is that temperature dependency can be neglected anyway and even humidity is no problem as the rotor is a firmly encapsulated block. Such torque sensors can also run a very high turning speed, such as 20,000 or even 30,000 rpm, and can be found over a wide range of nominal torque.



Figure 2.17: left: Flange type torque transducer T12HP (Source: HBK); right: Shaft type sensor 4503B, for high-speed torque measurements, both based on foil type strain gauges (Source © 2024 Kistler Group)

Classified according to their shape, there are two types of designs for torque transducers. The traditional one is the shaft transducer, i.e. measuring shaft, and there is the more recent and more up-to-date design: the measuring flange.

Users may find the shafts easier to integrate into their machine design, especially if it is about measurement of small torques. At the same time, shaft sensors are also more elastic than the measuring flange and suited for easy integration for fast and dynamic measurements.

If the task is to measure larger values of torque, then the measuring flange is clearly the preferable design. In automotive engineering, it can be assumed that more than 90 % of the transducers used to measure torque are measuring flanges, because this makes it possible to build up much shorter test benches.

Torque measurement origins from the need of automotive industry for power and efficiency determination and the need for further optimization of these two quantities. An application example in renewable power generation is the efficiency estimation of a wind turbine. Regarding the newly arising electromobility, if one wants to improve the efficiency evaluation of an electric motor, one has to deal with the mechanical power generated by the motor as well as for the electrical power put in. Electrical power is calculated by the mathematical product of current and voltage. For further progress, the cross-connection of the mechanical and electrical power determination must be strengthened to further reduce the overall measurement uncertainty [Schäfer 2019].

In addition, non-contact torque sensors based on magnetostriction have opened completely new areas of application in torque measurement technology (Figure 2.18).



Figure 2.18: Non-contact torque measurement (Source: NCTE AG)

In magnetostriction, the length of a body changes under the influence of an external magnetic field. The reverse principle is the so-called inverse magnetostrictive effect: When a force acts on a magnetically encoded component, the magnetic field changes are used to measure torque. The change in the magnetic field can be observed and measured directly, very accurately and reproducibly even under difficult external conditions. The sensors work at very low field strengths; the component itself does not become a magnet.

Every steel component, such as a drive shaft, can be encoded in such a way that an electrical component can measure mechanical forces such as torque and shear precisely without contact. This magnetic coding is long-term stable (remanent). The discrete secondary sensor is easy to integrate in various applications. An example where this contactless technology is essential for success is the e-bike boom: the precise measurement of the forces applied by the rider on the rotating shaft is the basis for a harmonious riding experience. Other areas of application that torque sensor technology has advanced in recent years are agricultural engineering and robots.

Superlatives Needed

In both force and torque measurement, with the development of mechanical engineering, the measurement of very high nominal values, such as meganewton (MN) and meganewtonmeter (MN·m) is required. The reason is that in many pioneering applications such as rolling stock as well as wind energy generation by wind turbines, highest torque values and forces occur (Figure 2.19).



Figure 2.19: Torque transducer capable of measuring in the kN·m/MN·m range have an impressive size. (Source: HBK)

Although such sensors are quite expensive, they are considered necessary for further progress. Thus, several metrology research projects with different National Metrology Institutes (NMIs) and partners from industry aim for the development of torque transfer standards even in the higher MN·m range. They come with an integrated, modularized digital architecture as a platform for mechanical performance measure-

ment in nacelle test benches [Schäfer 2024] (Figure 2.20).



Figure 2.20: 400 kN·m Torque calibration device, (Source: HBK)

Reference Torque Sensors

For the sake of completeness, a further group of torque sensors should also be mentioned: the torque reference transducers, serving as transfer standards for the mechanical quantity torque and usually also based on strain-gauge technology. Torque transfer standards are meant for inter-laboratory comparisons such as between different countries. According to this purpose, it is a non-rotating, shaft-type reference torque transducer, specifically for use as transfer standard in calibration labs in compliance with DIN 51309. An example is the Torque Transfer Standard type TN of HBK, covering nominal ranges from 100 N·m to 20 kN·m. As mentioned before, it is part of the equipment used in NMIs for the quantity torque but also in secondary laboratories of accredited bodies such as DAkkS, the national accreditation authority of the Federal Republic of Germany.

Turning speed (RPM)

In connection with efficiency determination, also torque has to be determined, since mechanical power is torque times rpm (revolutions per minute). Accurate measurement of such large torques is still critical and not sufficiently investigated yet.

Therefore, traceability of rotational speed is a subject which also needs further attention, as for rotational speed, there is no accredited standard with actual rotation at the moment. Presently, speed measurement is listed together with frequency measurement in measurement class “K03” [Accreditation Advisory Board 2015], using an electrical or optical stimulus generated by a calibrated frequency generator and the relevant procedure described in the appendix of accreditation certificates. This is a problem, as in contrast to reality, there is no actual rotation here. Therefore, substantial progress is required soon in order to properly represent this measurement quantity.

2.2 Acoustic Sensing

(Stoppel, F.; Schäfer, A.; Betz, B.; Nooshin, S.; Woeckel, S.)

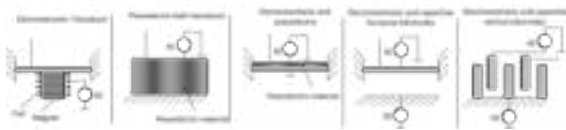


Figure 2.21: Overview of the operating principles for the production of sound and ultrasonic transducers

Acoustic sensors are ubiquitous in our everyday lives as microphones and ultrasonic transducers use a wide range of operating principles (Figure 2.21). Microphones are defined as acoustic sensors that operate in the audible frequency range, which is usually set in a range of around 20 Hz to 20 kHz. The frequencies above 20 kHz are called ultrasound.

A typical application of microphones is the acousto-electrical conversion of signals in communication. Microphones are also used for the presence detection of people and objects [Barjatia 2016] as well as for sound or noise monitoring.

Ultrasonic transducers operate in higher frequency ranges to perform a variety of measurement tasks in gases and liquids. This includes distance measurement, material detection and testing, and acoustic imaging. To perform these functions, the ultrasonic transducers are usually actuators and sensors at the same time (Figure 2.21). The higher the frequency, the shorter the wavelength and the higher the spatial resolution. The acoustic components for ultrasound

are acousto-electric transducers, which are mostly used as actuators and sensors. They generate a sound signal that is radiated into the environment. In this environment, the signal is reflected, scattered and absorbed. The same or a different transducer then picks up the acoustic signal and generates an electrical signal from it. Optoacoustics is a special form of acoustic conversion chain [Chen 2014]. Here, an object is irradiated with light. The resulting thermal-expansion in the material generates a sound signal that is picked up by the ultrasonic transducer. This principle is used in gas analysis or medical technology.

The first industrial products were the condenser measuring microphones of the company HBK (formerly Brüel & Kjaer) from the 1960s. The latest generation of these sound measurement units (HBK 4180 or HBK 4966) still set the standard in the field of sound measurements. The application of acoustic sensors ranges from laboratory standard microphones as a measurement standard to free-field microphones which are used for sound pressure measurement in a frequency range of usually 1 Hz to 20 kHz. Today, these meters are sometimes available wirelessly as hand-held devices (Figure 2.22).

All acoustic sensors are acousto-electric transducers in their field of application and frequency range. This means that the systems have to convert acoustic energy into mechanical energy (strain or mechanical stress) and then into electrical energy. In the case of acoustic transmitters, the transducer works reciprocally. Various change principles are used for electromechanical conversion. These include electrodynamics or electromagnetics, electrostatics or piezoelectricity (Figure 2.21).



Figure 2.22: Example of a wireless sound level meter HBK 2255 (Source: HBK)

Electrodynamic transducers are usually membranes that are connected to a magnet. The magnet, in turn, is wrapped with a coil. Due to the Lorentz force, an electrical signal is generated when moving. By using a magnet as a solid, only limited miniaturization is possible, making these converters not suitable for higher frequency ranges. Typically, these electrodynamic sensors are used in microphones. This transducer principle and the technologies associated with it are well known. New sensor trends can be expected through the use of microtechnologies that enable the production of micromagnets.

Acoustic sensors can also work on the basis of electrostatics. In this process, an electric field is applied between plate capacitors. One or both electrodes are suspended in a mechanically movable manner. The acoustic wave generates a deflection of the moving components, which leads to a change in the capacitance, or the dielectric flux. This electrical signal is equivalent to sound pressure. A sensor trend in capacitive acoustic sensors is the use of microtechnologies for the cost-effective, reliable and scalable production of microphones and ultrasonic transducers. The miniaturization of the individual capacitive components makes it possible to generate high sensitivities of the transducers, as even the smallest sound amplitudes cause a significant change in capacitance. Technologically, two approaches are used for the production of plate capacitors. The components can be applied horizontally or vertically to the substrate surface (Figure 2.23). In the frequency range of ultrasound, horizontal membranes are usually integrated using microtechnology. These sensors are called CMUTs (capacitive micromachined ultrasonic transducers).

The third transducer principle for the use of acoustic sensors is piezoelectricity. A piezoelectric crystal undergoes strain or mechanical stress from a sound wave and intrinsically generates an electrical charge. This is the most frequently used operating principle for acoustic sensors in the field of medical ultrasound or industrial sensor technology. Traditionally, bulk converters made of lead-zirconate-titanate (PZT) have been used to manufacture these sensors.

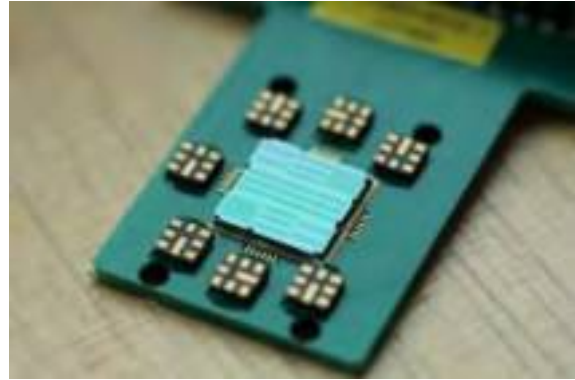


Figure 2.23: Micromechanical MUTs based on vertical comb electrodes for microphones and loudspeakers (Source: Fraunhofer IPMS)

The high piezoelectric coefficients lead to a very high sensitivity. The technology is mature. In the case of bulk converters, there is an increasing trend towards new materials to replace lead-containing PZT and thus comply with an expiring EU special regulation on RoHS-compliant resources. An example of this new class of materials are KNN-based transducer elements [Zhang 2020]. These are also characterized by excellent piezoelectric coefficients, but currently still have to prove their reliability in the temperature range of the respective application. As with the other two converter principles, there is also a major trend in piezoelectricity towards the use of microtechnologies in manufacturing. In addition to the already mentioned advantages of scalability, cost-efficiency and reliability, PMUTs (piezoelectric micromachined ultrasonic transducers) show other significant advantages over bulk converters. In bulk transducers, the piezoelectric material is both an electromechanical transducer and an electroacoustic transducer. PMUTs (as well as CMUTs) separate these two converters into two devices. A silicon diaphragm acts as an acoustomechanical transducer and determines the resonant frequency (operating frequency). The piezoelectric element defines the electromechanical conversion. As a result, the operating frequency is determined by the design of the movable silicon element, and the piezoelectric transducer can be carried out according to the requirements of the electrical system components. For example, piezoelectric transducers in PMUTs are usually 500 nm to 2 μm thin, which leads to a high electric field per strain, or mechanical stress.

Bulk converters, on the other hand, are geometrically designed based on the operating frequency and have much higher material thicknesses. In addition to PZT, aluminum nitride (AlN) and aluminum scandium nitride (AlScN) are also present as transducer materials in the field of PMUTs. The small dielectric constant compared to PZT results in a lower capacitance and this, in turn, allows for a higher electrical voltage for an identical generation of charge carriers. PZT, on the other hand, has the advantage of higher piezoelectric coefficients, which generates higher amounts of charge carriers. Piezoelectric transducers enable zero-power systems. The transducers generate their charge carriers intrinsically during an acoustic event. This means that the sensor does not require an extra electrical power supply to switch an electronic circuit from a passive energy-saving mode to an active mode [Pop 2019], but can use the power generated by the PZT in event that triggers the PZT based transducer. This trend can be seen in a number of products that are already available in industry, such as MEMS microphones.

In addition to the strong miniaturizability, MEMS technology offers the possibility of integrating a large number of acoustic sensors on a compact chip [Stoeckel 2018] regardless of the transducer principle (see Figure 2.24). This is mainly used in the ultrasound range where spatially resolved measurements and high-resolution imaging are possible via arrays.

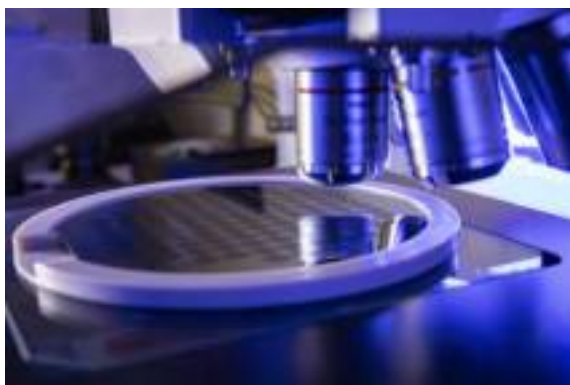


Figure 2.24: Example of scalable production of a large number of ultrasonic transducers using silicon microtechnologies (Source: TU Chemnitz)

New fields of application for acoustic sensor technology and trends are manifold. One example is the measurement of gases in potentially explosive environments, especially in hydrogen

technologies [Hashwan 2023]. However, the non-invasive nature of the sensors also enables new applications in gas analysis in medical technology [Marshall 2015].

For gas and fluid measurements (level, flow, distance, etc.), the use of microtechnology offers the possibility to build up dozens to tens of thousands of individual elements per sensor, which enables sound field manipulation (focusing, beam shaping). By using high operating frequencies, the resolution of time-of-flight (ToF) signals is greatly increased (see Figure 2.25).

In auditory sound, microphones are increasingly being designed as MEMS components. The use of silicon single crystals in microtechnology makes the devices robust and stable over the long term. The power requirement is low and zero-power applications are made possible.

In medical ultrasound and sonography, there is a major trend towards micromechanical components made of capacitive or piezoelectric MUTs, as high operating frequencies with high sensitivity are possible at low production costs [Wang et al. 2020].

One area of application for acoustic sensing acoustic is optoacoustics, in which the optical excitation of fluids is used. This enables wavelength-specific gas analysis in materials testing. In medical technology, this technology promises to greatly increase the contrast in organic material compared to sonography [Dangi et al. 2020].

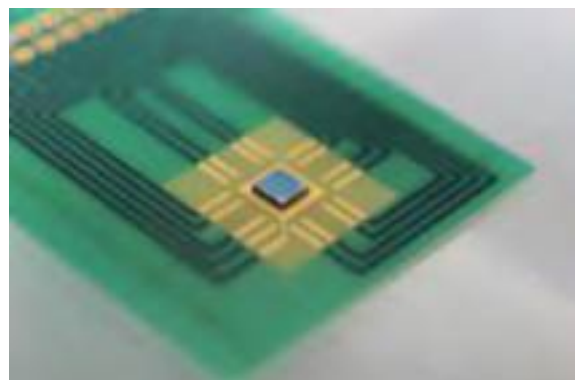


Figure 2.25: Single-channel CMUT with an array of electromechanical membranes on a chip for highly accurate and highly sensitive measurement of ToF signals (Source: Nooshin Saeidi)

PMUTs are also established sensors for fingerprint scanners, as microtechnologies enable small channel geometries and the sensors also work reliably behind a surface, such as displays [Jiang et al. 2017].

Another trend is the use of acoustic transducers for non-contact motion detection, such as gesture control (see Figure 2.26). In addition to data processing and analysis, the challenge in this application is the high signal attenuation due to the acoustic medium (air) and the high operating frequencies.



Figure 2.26: MUTconverter array for non-contact gesture recognition (Source: Bodo Schmidt)

2.3 Electrical Measurement Quantities - Electrical Current Measurement

(Kirk, A.; Schäfer, A.; Spasic, S.; Zimmermann, S.)

Measuring electrical quantities has a twofold importance in sensors and measurement technology. On the one hand, the electrical quantity such as a voltage, current or power can be the measurand of interest itself. On the other hand, many, if not practically all modern sensor principles convert the physical, chemical or mechanical measurand to an electrical quantity. Typically, at the end of each signal chain, there is an analog-to-digital converter (ADC) that converts voltages of a few millivolts or volts to digital signals. The challenge, however, is that many sensors inherently output electrical currents, requiring specialized electronics that convert them into suitable voltages.

In sensor or optical applications with low currents from femtoamperes to a few milliamperes, transimpedance amplifiers (TIA) are the most common choice. For higher currents from

milliamperes to several hundred amperes, such as in power metering, shunt resistor amplifiers are more suitable. If the current is even larger or the conductor not accessible for inserting a resistor, magnetic current sensing offers a non-contact alternative. High current applications include measuring parameters of electrical machines, where a big boost came with electromobility. However, main markets more and more shift to aerospace and newly arising applications such as wind energy as the most important branch of renewable energy generation.

Transimpedance Amplifier

Figure 2.27 shows the general setup of a TIA. In order to amplify the small currents to be measured, a large resistor is placed in the current path. As the voltage across such a large impedance would create significant disturbance at the sensor, an operational amplifier is used to regulate the input to ground. Thus, despite the high feedback impedance, the input impedance of the circuit in Figure 2.27 is close to zero. This has the major advantages that the burden voltage at the sensor remains low and the capacitance of the sensor does not affect the bandwidth of the circuit directly. The major limitation is that the entire electrical current needs to be supplied by the operational amplifier, limiting the feasible current range to usually a few ten milliamperes.

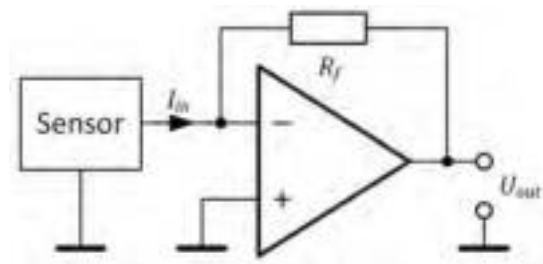


Figure 2.27: General setup of a transimpedance amplifier (TIA). The operational amplifier keeps the input at ground. (Source: ACKISION GmbH)

For optical applications, for example high speed fiber receivers, feedback resistances of a few kilohms are typical, allowing measurements between a few hundred nanoamperes and a few milliamperes with a bandwidth of several gigahertz. For various low current sensor applications, the resistances may reach gigaohms or even teraohms, allowing measurements between a few femtoamperes and a few microam-

peres with a bandwidth in the range from hertz to kilohertz.

Current research for low-current applications focuses on lower noise and better stability to measure smallest currents faster. In 2018, a team from the PTB (Physikalisch-Technische Bundesanstalt) received the Helmholtz Prize for their resistive TIA “ULCA-1” [Drung et al. 2015; Krause et al., 2019]. It acts both as a TIA for converting current to voltage and as a current source for calibrating other current meters, thus serving as a transfer standard for bringing improved accuracy to the lab without requiring cryogenic cooling.

In 2022, a team from the ACKISION GmbH and the Leibniz University Hannover was nominated for the AMA Innovation Award (see Chapter 6) and won the “Young Enterprise” Award for the current meter “FUSE” shown in Figure 2.28, utilizing a capacitive TIA [Wendt et al., 2022]. By using a capacitor as feedback element combined with a special reset scheme, an order of magnitude faster low-noise current measurements become possible compared to a resistive TIA.



Figure 2.28: Capacitive TIA/current meter “FUSE” [Wendt et al., 2022] (Source: ACKISION GmbH)

Shunt/Current Sense Amplifier

For measuring higher electrical currents in the range from a few hundred microamperes to several hundred amperes, so-called shunt resistor amplifiers or current sense amplifiers are used. Such currents typically occur in power measurement applications, not as sensor outputs. The typical setup is shown in Figure 2.29. Here, the voltage across the resistor is only measured, but not actively regulated. Thus, the output current of the operational amplifier does

not limit the maximum current as it does in a TIA. However, now there is a burden voltage creating a disturbance at the load, necessitating the use of smaller resistances. Furthermore, the resistance values are also limited by the power dissipation, often resulting in the use of physically large resistor constructions or even cooling.

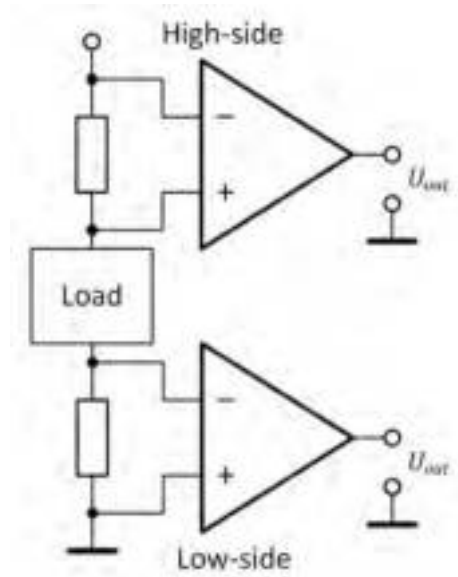


Figure 2.29: General setup of shunt amplifiers on the high side and the low side of the load (Source: ACKISION GmbH)

The shunt and sense amplifier can be placed either in the power supply line (“high-side current sensing”) or in the ground line (“low-side current sensing”). Due to the offset voltage, high-side current sensing requires instrumentation amplifiers with high common mode rejection. Low-side current sensing is often simpler to implement, but potentially creates grounding issues.

Many specialized integrated circuits for these applications exist, with constantly improving rejection of both static and dynamic common mode voltages and higher isolation voltages. Typical bandwidths extend to a few hundred kilohertz or even a megahertz.

Magnetic current sensing



Figure 2.30: General setup of core-less magnetic current sensing. No changes in the circuit carrying the electrical current are required, but instead the external magnetic field is measured. (Source: SENIS AG)

In applications where the current to be measured would result in too much power dissipation in the shunt resistor, the common mode voltage is too high or inserting a shunt is simply impractical, using magnetic field measurements around the current-carrying conductor as shown in Figure 2.30 for current sensing is more feasible. The magnetic field created by a passing current through a primary conductor is proportional to the applied current and therefore carries the information about the current amplitude. Current measurement by using the generated magnetic field has the advantage of being a non-contact i.e. isolated current measurement so that the primary circuit does not need to be interrupted.

Both Hall sensors and inductive coils may be used to pick up the magnetic field of the electrical current. While Hall sensors typically operate in the lower frequency range up to a few kilohertz, inductive coils have a gain proportional to frequency and thus only operate in the higher frequency range. Through a combination of both sensor types, a wide range from DC up to MHz may be covered with a flat frequency response. The sensors used for current measurement must have a sufficiently high bandwidth to detect switching frequency harmonics injected by the power converter but also be capable of measuring DC.

By combining complex magnetic performance with advanced electronics, the fluxgate technology

allows it to measure current with a very high accuracy.



Figure 2.31: Fluxgate current transducer Hottinger Brüel Kjaer CTS200ID, manufactured by DaniSense, (Source: HBK)

In general, the fluxgate principle is to use an excited magnetic material coil as a probe. Thanks to a saturation/desaturation cycle and signal processing, this coil is able to measure the magnetic field proportionally. From there, multiple options are possible to design a current transducer. It can simply replace a Hall effect probe in the air gap or the coil could have the shape of a tore. For this second option, the current transducer can achieve really high accuracy (few ppm) and a strong EMC robustness.

In the European metrology EMPIR project 19ENG08 WinEFCY “Traceable mechanical and electrical power measurement for efficiency determination of wind turbines” e.g., the DL2000ID current transducer from Danisense (Figure 2.31) using fluxgate technology has been found an ultra-stable, high precision (ppm class) current transducer with the measurement staying linear (1 ppm linearity) within the whole frequency and current range (DC ... 100 kHz) [Blaser, 2023].

One prime example where a TIA or a shunt amplifier cannot be used are currents inside structural elements. Within a European project, the Swiss SENIS AG combined Hall-based and inductive sensors for monitoring DC and AC currents and thus the contact resistance on an aircraft structure [Blagojevic et al., 2023]. These components have been integrated in a single CMOS chip for measuring currents up to several megahertz in a wide current range and with very high resolution (Figure 2.32).



Figure 2.32: Structural current sensor with both Hall and inductive current sensing on an aircraft structural beam [Blagojevic et al., 2023] (Source: SENIS AG).

2.4 Magnetic measurement quantities

(Popovic Renella, D.; Kamrani, S.; Prediger, M.; Wurz, M.)

Magnetic sensors are sensors that measure the magnetic field to determine magnetic properties such as field strength, direction, and flux. The magnetic signal is then commonly converted in a magnetic sensor microsystem into an electrical signal, and, after processing, the output is transferred to further systems [Popovic et al, 1996]. Whether a magnetic sensor measures the entire magnetic field or only its vector components changes its categorization and thus its scope of application. Magnetic sensors represent a very robust and reliable technology that requires no maintenance and are widely used in automotive, industrial, medical, biological, and various other applications [Lenz et al, 2006]. The main types of magnetic sensors are Hall sensors as well as magnetoresistive (MR) sensors. The demand for sensitive and miniaturized MR sensors increases continuously in various fields of application. However, their measuring range is very restricted with less than 10 mT [Žurauskiene, 2023]. Researchers are therefore continuously investigating how to expand and improve it and overcome the limitations. Some of the most important magnetic sensors are briefly described below, including Hall devices and magnetoresistive sensors (AMR, GMR, TMR).

Hall Sensors

Hall magnetic field sensors play a crucial role in various industries, including robotics, automotive, and medical applications, where precise measurement of magnetic fields is essential. Traditional Hall-effect sensors, also known as horizontal Hall sensors, are widely used but are limited in capturing magnetic fields in all three dimensions simultaneously and at the same point. Since magnetic fields are vector fields with both strength and direction, measuring them accurately requires advanced sensors capable of capturing this multidimensional information. To address this challenge, modern applications utilize 3D Hall sensors, which enable concurrent measurement of all three magnetic field components (B_x , B_y , and B_z) at virtually a single point. These sensors integrate both vertical and horizontal Hall elements, ensuring compact field sensitive volume and orthogonality of the three measurement axes (Figure 2.33).

Horizontal and Vertical Hall Sensors

A classical horizontal Hall plate, as illustrated in Figure 2.34, measures only the perpendicular component of the magnetic field. But for some applications, it is important to also have Hall sensors that measure the in-plane component of the magnetic field which is parallel to the chip surface, the so-called vertical Hall sensors. This idea was first introduced by Popovic [Popovic 2003] over 20 years ago and has been further developed using CMOS silicon technology.

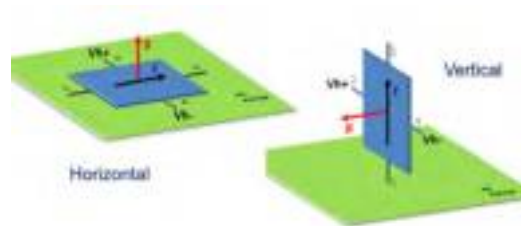


Figure 2.33: Horizontal and Vertical Hall sensor (Source: SENIS AG)

Integrated Horizontal and Vertical Hall Sensors

The latest published results of a patented Vertical Hall sensor in silicon CMOS technology demonstrate the highest noise voltage spectral density of $0.8 \mu\text{V}/\text{Hz}$ at 1kHz after signal processing [Popovic and Dimirijevic, 2014]. It is the first published and implemented vertical Hall sensor on the market to exhibit such a high signal-to-noise ratio and to have the same excellent performance as a horizontal Hall sensor.

Vertical and horizontal Hall elements can be combined in integrated CMOS technology to create various magnetic sensors for a wide range of applications. These include compact 3D Hall sensors for providing a complete picture of the magnetic field environment, 2D sensors for magnetic angle measurement, Hall sensors for electric current measurements, or a matrix of 3D sensors, building a 3D magnetic field camera for magnet inspection.

3D Hall Sensors

3D Hall sensors are capable of measuring all three magnetic field components simultaneously in a field-sensitive volume (FSV). The size of the FSV is crucial for measurement accuracy, particularly in high-gradient magnetic fields. Errors attributed to the size of the FSV were analyzed, emphasizing the importance of a small FSV for accurately characterizing magnetic structures and minimizing measurement errors [Stuck et al, 2023].

Integrated 3D Hall sensors combine horizontal and vertical Hall elements to provide accurate measurements with high spatial resolution. Currently, the 3D Hall sensor with the smallest FSV on the market is the 3D Hall sensor SENM3Dx [SENIS AG, 2024a]. The sensor is capable of measuring all three components of the magnetic field (B_x , B_y , and B_z) at a single location simultaneously. The sensor is designed with three groups of mutually orthogonal Hall-effect elements, each of which has its dedicated biasing circuits and amplifiers, enabling the sensor to have a high spatial resolution of only $100 \mu\text{m} \times 100 \mu\text{m}$, see Figure 2.35. For example, the 3D sensor has been implemented in the inspec-

tion robot ANYmal [Popovic Renella et al, 2023].

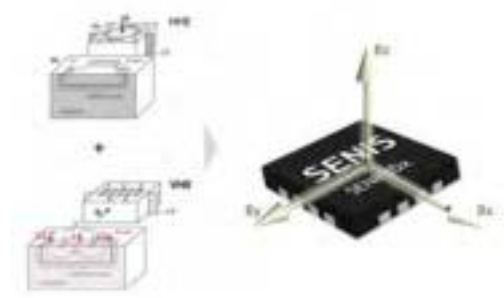


Figure 2.34: 3D Hall sensor consisting of integrated horizontal and vertical Hall elements (Source: SENIS AG)

The World's First True 3D Magnetic Field Camera

To capture the magnetic field quickly and precisely, a matrix of 3D sensors is utilized, also known as a magnetic field camera. There are cameras consisting of single packaged 3D Hall sensors, or there is a newly developed camera with integrated 3D Hall sensors.

Figure 2.35 shows the SENIS 3D Magnetic Camera (SENIS AG 2024b), which has been nominated for the AMA Innovation Award 2024 [AMA, 2024] (see Chapter 6). The camera features a compact chip positioned within its small head. The camera simultaneously measures all three magnetic field components (B_x , B_y , B_z), providing comprehensive and accurate pictures of magnetic fields in three dimensions. With a spatial resolution of $100 \mu\text{m}$ and a tiny measurement volume of $27 \mu\text{m} \times 9 \mu\text{m} \times 4 \mu\text{m}$ in each pixel, the camera offers unprecedented precision in magnetic field measurement. This is particularly important when measuring complex fields with high field gradients. With 16,000 pixels, the camera can acquire seven full magnetic images within one second, making it ideal for both inline and offline inspection of magnetic systems.



Figure 2.35: 3D Magnetic Field Camera (Source: SENIS AG)

Magnetoresistive Sensors

Magnetoresistive effect is the phenomenon of changing the intrinsic electrical resistance when an external magnetic field is applied [Žurauskiene, 2023]. The magnetoresistance can be measured in a short and wide probe with minimal Hall voltage. Magnetoresistance is generally defined as the percentage ratio between the resistivity change due to an external magnetic field B and the resistivity without a magnetic field $\rho(0)$, as shown in the equation below [Žurauskiene, 2023]:

$$MR = \frac{\rho(B) - \rho(0)}{\rho(0)}$$

According to the equation, the MR can be positive or negative. Magnetoresistive (MR) sensors composed of layers of magnetic material have a great sensitivity which makes them particularly suitable for small magnetic fields in the range between 10^{-9} T and 10^{-2} T. They are also ideal for low-cost applications with low power consumption [Zheng et al., 2019]. Just by applying a constant current, the resulting voltage represents a measure of the magnetic field [Lenz et al., 2006]. A further attractive aspect of MR sensors is their small size and their compatibility with IC technology, to which they can be easily connected [Elzwawy et al., 2021]. Moreover, microfabrication technology can be applied to produce many types of XMR sensors on large Si wafers [Oogane, 2023]. MR sensors have a wide range of application, including navigation and transportation, biomedicine, storage technology, non-destructive monitoring of power grids, aerospace fields, etc. [Chen et al., 2023], which can be categorized into three main types depending on the strength of the magnetic field measured: measurement in the range of the Earth's magnetic field (μ T), μ T to nT, and below nT. The main applications of XMR sensors rely on the anisotropic MR (AMR), giant MR (GMR)

and tunnel MR (TMR), as briefly described below.

Anisotropic Magnetoresistive Sensors

Anisotropic magnetoresistance is a characteristic that some materials reveal. These materials exhibit the dependency of the resistance on the angle between the direction of the material magnetization and the direction of the electric current flow. Sensors based on this material property are referred to as anisotropic magnetoresistance or AMR sensors [Lenz et al, 2006; Elzwawy et al, 2021]. For the first time, anisotropic magnetoresistance was observed in ferromagnetic metals (Fe and Ni) [Zhang et al, 2022]. When an external magnetic field approaches, the intrinsic material magnetization rotates in the direction of the field. Therefore, the initial angle between the direction of the magnetization and the current flow and thus the material resistance changes depending on the strength of the external magnetic field. The further the angle is from 0° (magnetization and current flow in parallel), the lower the resistance, and it is lowest at 90° , i.e., with the magnetization perpendicular to the current flow. The resistance varies approximately in proportion to the square of the cosine of this angle (Figure 2.36). Not only ferromagnetic bulk materials (Ni, Co, Fe, etc. and their alloys) but also thin films exhibit the AMR effect [Elzwawy et al, 2021]. The AMR sensors can be manufactured on both hard substrates such as silicon and insulating glass as well as on flexible substrates such as polyimide or the thermoplastic compound polyether etherketone (PEEK) for various applications [Chen et al, 2023; Wurz et al, 2023]. These lightweight, tiny sensors consume about 0.1 mW to 0.5 mW and cover a wide temperature range between 55°C and 200°C . Despite the very low effect initially noticed (at a few m Ω), the application potential of AMR was recognized due to its easy accessibility and high magnetic sensitivity and was exploited in many fields, e.g., in the innovation and development of nanoscale material measuring devices, magnetic sensors and transducers as well as spintronic devices [Li et al., 2022].

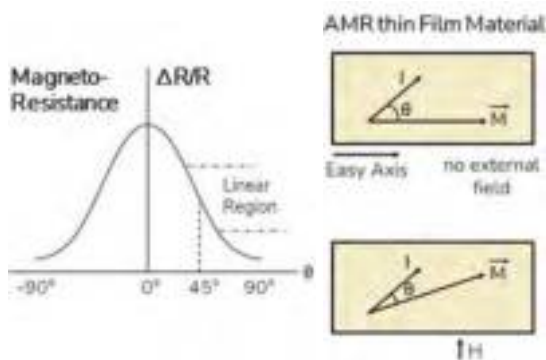


Figure 2.36: Left: AMR sensor resistance as a function of the angle θ between the direction of current I and magnetization M ; Right: Change in θ by applying an external magnetic field H . (Source: Modified from [Lenz et al, 2006])

Giant Magnetoresistive Sensors

The most basic form of a GMR is a so-called spin valve, which consists of four layers, including a conductive layer between two thin ferromagnets. One ferromagnet, also called a hard ferromagnet, has a pinned magnetization due to its adjacent antiferromagnet layer, while the magnetization of the other ferromagnet, also called a soft ferromagnet, is unpinned. It is important to produce very thin layers (about a nanometer thick) with very small deviation to achieve the best possible effect. With parallel magnetizations, the electrons can move most easily between the ferromagnets and the resistance is the lowest, whereas with antiparallel magnetizations the resistance is the highest. The electrons are less scattered at the interfaces and in the ferromagnetic layers as they move between similar or identical electronic band structure states in ferromagnets [Lenz et al, 2006; Elzwawy et al., 2021]. However, changing the direction of the magnetization of the soft ferromagnet from antiparallel to parallel by approaching an external magnetic field leads to a decrease in resistance. A sufficiently strong magnetic field can even unpin the pinned ferromagnet. Figure 2.37 shows the influence of an external magnetic field on the alignment of the magnetization of the ferromagnets in a GMR spin valve.

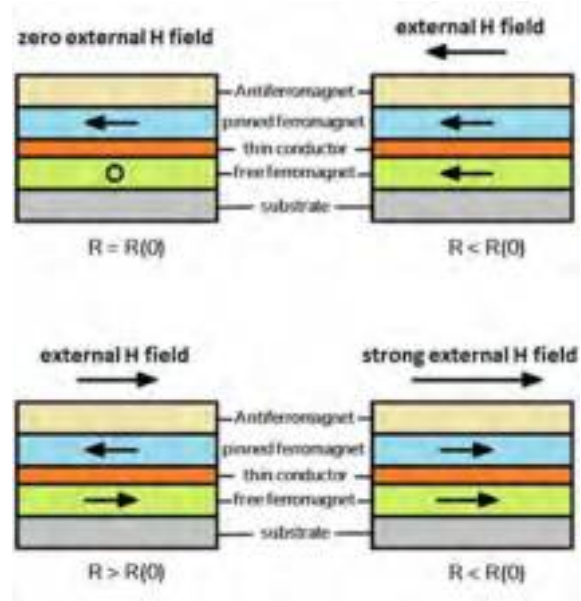


Figure 2.37. Influence of an external magnetic field on the alignment of the magnetization of the ferromagnets in a GMR spin valve. Modified from [Lenz et al, 2006]

A multilayer geometry made from the repetition of this fundamental four-layer structure exhibits increased percentage change in resistance. In addition to their original application in hard drive read heads, GMR sensors are also widely used in navigation and transportation systems, position sensing, mechanically flexible electronic devices, non-destructive evaluation and monitoring systems, biomedicine, and many other fields of application such as biotechnology and microelectronics for measuring small magnetic fields utilizing miniaturized equipment [Zheng et al, 2019; Reig et al, 2013].

Tunnel Magnetoresistive Sensors

Tunnel magnetoresistance (TMR) appears in magnetic tunnel junctions (MTJs). The structure resembles that of GMR spin valves, except that the conductive layer is substituted by an extremely thin insulator (approx. 1 nm). The most commonly used insulating layers are Al_2O_3 , MgO or TiOx [Reig et al, 2013; Knudde et al., 2017]. According to theory, magnetoresistance grows with the thickness of the barrier. The TMR effect is due to the tunneling of electrons across the insulating barrier, which leads to conduction. However, it is determined by the relative alignment of the magnetizations of the ferromagnets. The TMR effect achieves an MR ratio of over 200 % at room temperature. Djaya-

prawira et al. reported a TMR effect of 230 % at RT with CoFeB/MgO/CoFeB structure on an Si substrate [Djayaprawira et al, 2005].

TMR sensors generally exhibit a higher magnetoresistance than GMRs. They also have a higher impedance and therefore consume less power compared to GMR sensors. Due to these features and the planar geometry, TMR sensors represent energy-efficient, miniaturized, and highly sensitive magnetic sensors with low power consumption and low cost that offer a wide potential for use [Zhou et al, 2022]. However, a long measurement time is necessary to overcome the inherent noise of these devices, which is significantly higher than the Johnson noise limit, to detect very low magnetic moments. The fields of application of MTJ structures are diverse and wide, including magnetic sensors, biomedicine, and the detection of bio-magnetic fields and magnetic markers, as well as spin tunnel read heads. TMR sensors are also applied to control the electric current for electric vehicle batteries as well as infrastructures in a non-destructive way [Oogane, 2023].

2.5 Temperature

(Gebhardt, J.; Simon, M.; Budzier, H.)

Temperature is one of the seven base units comprising the international system of units. [Bernhard 2014] Every day, we are observing and experiencing temperature, we discuss about temperature and temperature changes, we heat or cool our homes or production sites, we measure temperature to make decisions or to control processes, and we try to reduce risks by monitoring temperatures. For our world and our climate, it is of utmost importance that we can limit the global temperature increase to 1.5 K or to 2 K. And during the pandemic, it became of vital importance to measure the body temperature of infected persons and at the same time keep a certain distance to them.

In medicine, the body temperature is one of the most important parameters to assess the course of a disease. Ear and forehead thermometers for consumer use are a big and interesting market for sensor companies.

The temperature of a medium in process industry or of a part in manufacturing industry is one

of the most common and vital measured state quantities. T-measurement here is often standardized and treated as a commodity. Nevertheless, measurement tasks are often challenging, e.g., if they are necessary to control the process, to optimize results, to avoid dangerous situations or to shut down appliances before reaching a critical situation.

Building automation is a further relevant area: since live beings usually differ in temperature from the background, remote temperature measurement can be used for movement and presence detection. If it is known how many people are in a building and where they are, light switching, heating, ventilation and climate control can be optimized and consequently energy waste can be reduced.

Physical Working Principles

Temperature measurement can be done in contact with the object or medium which is to be measured or remote by detecting the thermal radiation of the object in question.

Contact thermometers use either mechanical changes, like volume expansion as in mercury or alcohol thermometers or electrical changes or phase change effects related to tabulated temperatures. Classical electrical type T-measurement devices include sensor elements such as resistance temperature detectors (RTD), NTC thermistors, thermocouples and semiconductor-based temperature sensors (PTAT).

Fiber Optic sensors use light guided through the glass core of optical fiber to measure changes in length. Fiber Segment Interferometry (FSI) is a novel technology using the phase of coherent light from a laser to make precise measurements [James et al. 2022; Kissinger et al. 2022]. Strain sensors take the form of a coated optical fiber bonded directly to the surface under test. FSI temperature sensors house the optical fiber within an outer structure, such as a polymer tube, designed to screen the sensor from mechanical strain and friction. Fully dielectric sensor construction is particularly well suited to high voltage environments, such as in battery packs or electric motors (Figure 2.38). Similarly, optical fiber measurement is inherently immune to electrical interference.



Figure 2.38: a) Glass fiber sensor mounted on a battery pack; b) fiber optic sensor. Kistler Fiber Optic Technology (Source © 2024 Kistler Group)

A topic closely connected to contact thermometers which recently raised particular interest, is surface temperature measurement [Augustin et al., 2023], since it can be used as an intermediate step for non-invasive temperature measurement [Gebhardt et al., 2020].

Remote temperature measurement is advantageous when contact measurements become difficult because of high temperature, difficult access, moving parts, or because the measurement itself would disturb the process or the temperature equilibrium. In remote temperature measurement, the radiation from the object is usually absorbed by a sensor element and a resulting internal heat change causes a change of electrical parameters, like resistance changes in bolometers or generating voltages as in pyroelectric or thermoelectric sensors.

In recent decades, the main trends in microbolometer technology were improved thermal and geometric resolution, reduced pixel pitch (see Figure 2.39), new and improved sensor technologies, low power consumption, miniaturization and significant cost reduction [Cortial et al. 2023]. Improvement in the a-Si and VOx materials primarily used in microbolometers has led to higher sensitivities and a significant reduction in $1/f$ noise. [Guillaumont et al. 2021; Yu et al. 2020]. Advances in MEMS technology in the production of microbolometer pixels increase the thermal insulation of the microbolometers and the optical fill factor. Up to 1280×1024 pixels are available for geometrically high-resolution thermal images. The pixel pitch of today's microbolometer arrays is usually between $17 \mu\text{m}$ and $12 \mu\text{m}$. Arrays with pixel pitches smaller than $10 \mu\text{m}$ have already been presented. The power consumption is essentially determined by the readout circuit (CMOS IC). Advances in analog CMOS technology, such as smaller structure widths, have greatly reduced power consumption. Improvements in vacuum

packaging, such as wafer-level vacuum packaging and pixel-level vacuum packaging, allow miniaturized packages, e.g., Quad Flat Package and Ball Grid Array Package. Developments in microbolometer technology have been accompanied by major advances in uncooled thermal imaging technology. Miniaturization and a reduction in power consumption enable small, portable and battery-powered thermal imaging cameras (Figure 2.39). Thumbnail-sized camera modules allow use in all conceivable scenarios. Improved image processing and integrated image analysis make it easier to interpret thermal images and simplify operation. All this goes hand in hand with a significant reduction in costs [Budzier et al., 2021].

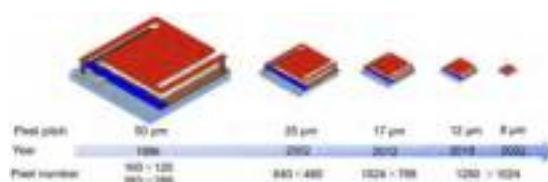


Figure 2.39: Development of the minimum of pitch and the maximum number of pixels for bolometer cameras in recent years (Source: Dr.-Ing. Habil. Helmut Butzer)

Remote temperature measurement is an optical method, so usually there is no contamination nor does the sensor or measurement process contaminate or disturb the object or media. But optical methods measure only the surface of the object, and the emissivity of the surface is of great importance for the achievable accuracy. Also, stray light and reflections can cause error signals in the temperature measurement. For remote temperature measurement, typical accuracy is around $\pm 2^\circ\text{C}$ or $\pm 2\%$ of the measured temperature range, whichever is greater. This accuracy is connected to object radiation calculation, sensor sensitivity variation and accuracy of the calibration process. Repeatability of the temperature measurements is usually better than the physical accuracy. And NETD (noise equivalent temperature difference) or MRTD (minimum resolvable temperature difference) is typically specified in the mK range. Thus, remote temperature measurements can resolve very small temperature differences while the absolute accuracy might be less than the accuracy of contact measurement.

Non-contact Measurement

Infrared array sensors or image sensors offer much more information than a single temperature of a specified point (Figure 2.40). If they are used to monitor varying and complex situations, for example people moving in public buildings, people living in hotel rooms, elderly people living alone in their home, monitor the cooking of different kind of food in a microwave oven, survey temperatures in electrical cabinets, prevent kitchen fires or fires in storage areas or monitor industrial processes for critical temperatures, then the information of the thermal image has to be analyzed and artificial intelligence becomes a valuable tool to determine necessary actions. After sensors measuring a complete thermal scene became easily affordable, it is nevertheless still difficult to extract meaningful information from that scene and determine which actions are sensible in response to the observed infrared scene. This is where in future, AI will play an important role for the application of smart temperature measurements.

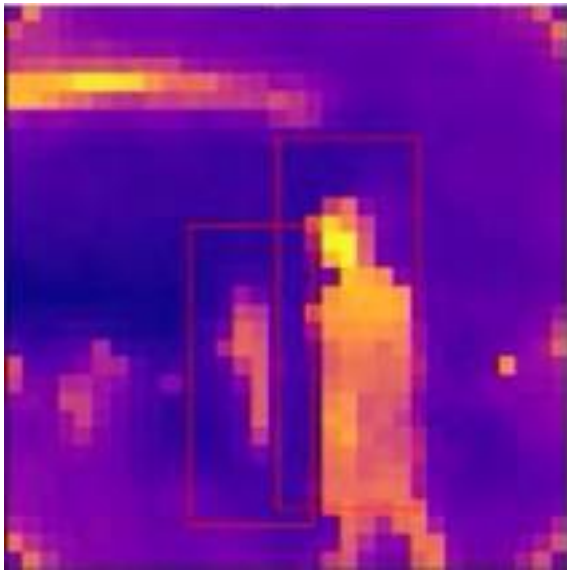


Figure 2.40: Person detection with a thermopile infrared 32x32 sensor (Source: Heimann Sensor GmbH)

Another newly emerging application is monitoring of the body temperature by wearable devices and obtaining personal health data from the measured temperatures [e.g., Melexis, 2023].

Operating and monitoring of electrical equipment for power networks from high to low volt-

age also requires accurate, reliable, and cost-effective T-measurement solutions. Such preventive maintenance is an important element for the stability of electrical supply infrastructure.

Optical sensors such as thermopile sensors do not need regular recalibration. If conditions like ambient temperatures or steady state conditions and cleanliness of the optics are closely monitored, the sensors can be operated with the same calibration parameters for many years.

In recent years, Heimann Sensor has developed a wide range of thermopile array sensors [Schieferdecker et al. 2023] (Figure 2.41). The thermopile sensor chips are manufactured in semiconductor foundries on 200 mm wafers and digital readout electronic circuits are monolithically integrated on the same chip. A subsequent micromachining of these wafers increases the thermal sensitivity of the sensor chip. Microsystem technology processes are used to assemble the MEMS sensor chips in standard TO or in SMD type packages. Optical elements like lenses, apertures and optical filters are integrated in the same housing.



Figure 2.41: Heimann Sensor Infrared Thermopile Arrays (Source: Heimann Sensor GmbH)

Starting from single element sensors for pyrometer application, there are nowadays small and cost-effective infrared array sensors available to measure complete infrared images. Sensors in TO46 package with less than 5.5 mm diameter offer 8×8 elements resolution. In a TO39 can, with base diameter 9.1 mm, sensors are available with 256 pixels (16×16) or 1024 pixels (32×32) or even 2400 (60×40) pixels. In TO8 packages, resolutions up to 160×120 pixels fill the gap to higher-resolution bolometer cameras. The integrated optics offer field of view options ranging from $12^\circ \times 9^\circ$

to wide angle up to $120^\circ \times 120^\circ$ default frame rates range between 8 Hz and 37 Hz. Low-cost sensors with a small form factor enable the user to take an infrared image, measure temperature fields, temperature variations, moving objects, count people or prevent fires.

Challenges in Process Industry

Due to the importance and large number of measurement points, temperature is in the focus of many research activities, often closely related to digitization and Industry 4.0.

From the major use cases, we mention two examples:

- a. monitoring and optimization (M+O) measurements
- b. automatized calibration management

Here, new opportunities are opened, e.g., by artificial intelligence. However, this often requires large amounts of data, much more than what can be provided by today's instrumentation of industrial processes. Even when not using "big data" concepts, many questions on process optimality or asset management in a plant require additional measurement points.

Retrofitting existing processes with additional sensors has not been an easy task in the past. Mechanical installation as well as integration of additional sensors into operating systems involved considerable cost and effort. For some installations, it would even be necessary to shut down the process.

Point b) is a natural consequence of a): if a large number of sensing devices are added to industrial facilities, it will obviously be a challenge to maintain and calibrate them for achieving a given data quality.

Flexible, reliable, and potentially ubiquitous measurement is not easy to achieve, but there are new offerings to customers, in particular in the case of temperature measurement.

Noninvasive Temperature Measurement

For the important use case of pipes conveying liquids or gases in process industries, recently established noninvasive concepts offer many

new opportunities. The combination of a reliable surface temperature measurement with a model-based inference of the temperature of media inside the pipes can be used as alternative [Gebhardt et al., 2020] to standard invasive thermowell measurements (Figure 2.42).

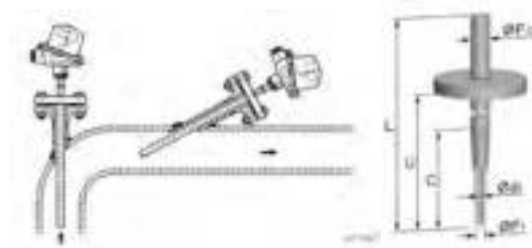


Figure 2.42: a) Typical thermowell installations, as recommended for small nominal diameter pipes; b) Flange thermowell according to DIN 43772 form 4F, with some of its parameters to be chosen in engineering (Source ABB)

For a few years now, offerings have been developed to measure the medium temperature in process pipes without violating the pipe wall, e.g., the Rosemount X-Well [Morrison2023] or the ABB NINVA-T [Gebhardt et al., 2020]. Commissioning and deciding if non-invasive is a reasonable option for a measurement point can be done by web tools [e.g., ABB Ltd., 2023].

The idea behind the concepts is model-based: extrapolation of the temperature field based on two or more external T-measurements and knowledge on the thermal situation at the measurement point. Details of the device designs, however, are crucial for performance, such as primary and secondary sensor positioning and reproducibility of thermal couplings. These can result in quite different accuracies and response times.

As an example, the ABB device (Figure 2.43) contains two sensors positioned very close to the surface installation point. This leads to short response times, often comparable to those of invasive devices, and accuracies of 1 K to 2 K for many relevant applications. In particular, such model-based designs usually outperform by far simple clamp-on-probe approaches.



Figure 2.43: ABB Ninva-T (Source ABB)

Maintenance Concepts

For the very important use case of calibration and verification in large, digitalized plants, there are new developments to be mentioned. In part, these are connected to the non-invasive technologies mentioned above.

Flexible noninvasive solutions can be used to calibrate or verify existing invasive T-sensors in many applications [Gebhardt et al. 2022]. A non-invasive device can be clamped on and used as a reference for an existing invasive instrument as shown in Figure 2.44. The device under test does not need to be detached from the pipe, nor from the operating system. The process remains uninterrupted. From the two temperature time series, a calibration statement can be deduced. Due to the different, independent measurement principles, even effects like deposits on the pipe wall or on the thermowell can be detected.

An alternative approach is offered by Labom [Labom, 2023], where the measurement insert of an invasive thermometer is equipped with a hollow pipe for temporary insertion of a reference (e.g., a resistance) sensor. Such an invasive instrument, therefore, also offers an in-situ verification or calibration option without detaching the device from the process.

Furthermore, Endress+Hauser offers specific instruments with inbuilt fixed-point cells. The devices can calibrate themselves under certain conditions when the process crosses phase transition temperatures (in this case the Curie temperature) of the media chosen in the fixed-point cell [Endress+Hauser, 2022]. The ap-

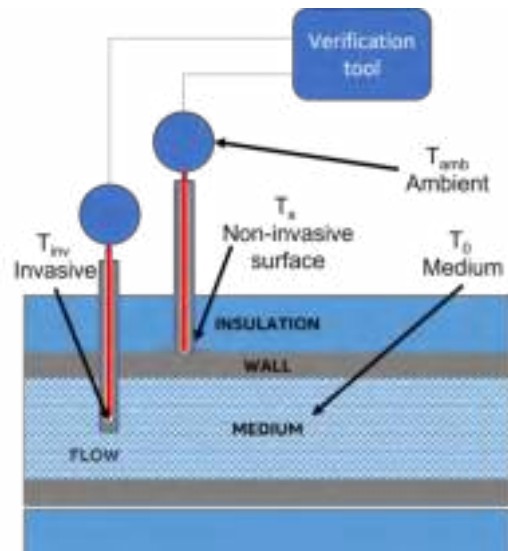


Figure 2.44: In situ verification/calibration by a non-invasive measurement [Gebhardt, 2022]

proach can, e.g., be used in hygienic applications where the process pipes are regularly heated up to high temperatures for cleaning.

Trends for Temperature Sensing

More applications will become accessible if the costs of infrared sensors can be lowered further. One major cost factor for sensors are optical materials like Germanium, needed for the fabrication of infrared lenses. New material developments which enable batch manufacturing of optical components will be another essential step for future lowering of production costs.

The trend for smaller sensors with higher pixel numbers and more integrated functions follows technology steps in semiconductor manufacturing, and smaller element sizes and higher integration will require more sophisticated assembly and packaging processes. It is to be expected that for remote infrared temperature sensors, the trend for miniaturization will continue.

Noninvasive temperature measurements and new calibration/maintenance concepts are now an attractive alternative for many measurement points. The enhanced flexibility can be of great help for many customers to make their process more digital and transparent.

2.6 Level

(Kloefer, P.)

The measurand level is one of the “Big Four” in process measurement technology, along with pressure, temperature and flow. It is obtained by applying various physical principles. A distinction (Figure 2.45) must be made between point level switches, which only detect the presence of the measured medium at one point, and continuously measuring sensors.



Figure 2.45: Level principles, a) point level; b) contact continuous; c) non-contact continuous (Source: Endress+Hauser SE+Co. KG)

A good overview of the various principles and technologies can be found in the sensor technology handbook [Tränkler et al., 2014]. Continuous level measurement is usually based on a distance measurement; the volume is then calculated using the container geometry. The media to be measured are both liquids and bulk solids. The use of level sensors in a wide variety of processes requires high standards in terms of pressure, temperature, robustness and chemical resistance, as well as numerous approvals for explosion proofness, safety, hygiene, materials, etc.

Level Measurement Trends

The sensor trends for level measurement are currently being driven by two major megatrends users are facing [Frost&Sullivan, 2024]. Firstly, demographic change, which means that process plants will have to be operated with fewer and less well-trained staff in the future. Secondly, global cost pressure with the aim of ever more efficient and resource-saving production processes.

These challenges can be tackled by the two technology trends digitization, which opens up numerous possible solutions, and function inte-

gration (e.g., ASIC), which allows far greater functionality of the device.

Regarding the issue of less well-trained staff, the resulting major sensor trend is simplicity for the user, from a significantly reduced product variety for the selection of suitable sensors, through simplified commissioning to simple and clear communication and visualization of sensor information during operation. This simplicity for the user represents a new challenge for the manufacturer and usually requires a higher functionality and complexity of the measurement device.

To support users in reducing costs by operating their plants and processes more efficiently, the sensors must provide significantly more information than just the measured level. Examples of this include self-diagnostics of the level devices, verification of the measurement capability compared to the delivery status, prediction of necessary maintenance or condition monitoring of the device, process or system. A clear transition to smart sensor (see also Chapter 4) can be observed [Frost&Sullivan, 2022].

Point Level Switches

Purely mechanical point level switches based on the float principle have been around since the 18th century and are still in use in large numbers, especially in North America. The first electronic systems that came onto the market in the 1950s used the capacitive measuring principle. Later, the robust and universal vibronic sensors were added. Both principles, together with conductive systems, are the dominant technologies in electronic point level switches.

As these systems have been on the market for a long time and have also been continuously developed further, they are largely at a mature stage of development in terms of pure measurement performance. However, the new requirements mentioned above expect more than the mere detection of the presence of a medium and lead to new development goals with new solution approaches. This can be seen in the following example (Figure 2.46), in which the previously analog sensor drive of a tuning fork is completely digitalized. The sensor (fork and piezo) and sensor drive form an electromechanical

oscillating circuit whose behavior is determined by the interaction of both components.

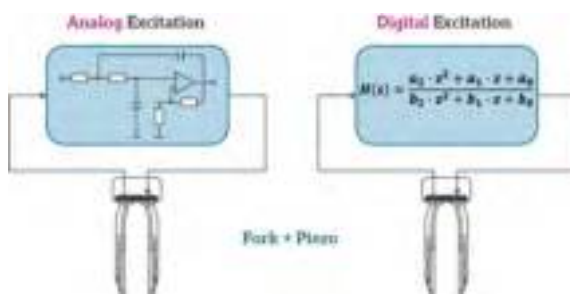


Figure 2.46: Digitalization of the tuning fork drive (Source: Endress+Hauser SE+Co. KG)

This sensor drive has been completely digitalized and its functionality is simulated using complex algorithms running on a low power consuming signal processor specially designed for this purpose. This means that the entire system can be adjusted as required via software and therefore offers several possibilities. For example, setting the sensitivity with regard to foam is a simple parametrization by the user and does not require any electronics replacement. A great deal of information can also be obtained from such a digital drive with which any operating status of the sensor system can be simulated via software for self-diagnostic purposes as well as for condition monitoring of the sensor or of the process. One example of resulting predictive maintenance is tracking the resonance frequency (Figure 2.47) of the vibrating fork. The increase indicates corrosion of the fork and it can be replaced in good time during the next maintenance. As the frequency correlates directly with the properties of the measured medium, the user can also obtain information about the medium and therefore of the process.



Figure 2.47: Detection of corrosion by tracking the oscillation frequency (Source: Endress+Hauser SE+Co. KG)

This trend towards providing a lot of information, even with previously simple limit switches, and then transmitting it, requires digi-

tal communication. This means that classic cabling, where the sensor output directly switches a pump or valve, will probably be replaced by digital wiring. Currently, this trend can already be observed with IO-Link, especially in food and beverage, and in future perhaps more so with SPE (Single Pair Ethernet) [SPE 2022] such as APL-Ethernet (Advanced Physical Layer) or PoDL (Power over Data Line).

Finally, a small glimmer of hope at point level for all those who are chasing the age-old dream of level detection from completely outside the container, which would be the easiest method for users.

Quantum sensor technology with its highly sensitive magnetometers (see also Chapter 2.9), as e.g., NV Center [Singha, A. et al., 2024], offers an approach to a solution to this problem, as magnetic fields penetrate the stainless steel most commonly used in the process industry. Figure 2.48 shows the principle: a static magnetic field penetrates through the container wall into the interior of the container, is slightly distorted by the susceptibility of the medium, and this minimal change is detected by the highly sensitive magnetometer in the sensor.



Figure 2.48: Quantum Sensing for detection medium through the steel wall (Source: Endress+Hauser SE+Co. KG)

Continuous Level Measurement

Here too, the first electronic systems were contact capacitive sensors in the 1950s. From the 1970s onwards, the emerging ultrasonic technology was the first to fulfil the user's desire for non-contact measurement. From the 1990s onwards, radar technology has been added, which is extremely robust in terms of environmental conditions, but was initially associated with

some limitations in terms of price, power consumption, size and, above all, measurement performance and reliability in the application.

The majority of these limitations were due to the measurement frequency used, which was initially 6 GHz or 10 GHz. For this reason, the focus in the further development of radar systems has been on constantly increasing the measurement frequency used. Via the intermediate step of 26 GHz, 80 GHz has become established in modern systems today. Figure 2.49 shows the advantages of the higher frequency. The higher the frequency, the better the directivity and the measurement performance (robustness against false echoes) while maintaining the same size, and the better the possibility of small process connections with good measurement performance. The sensors also become smaller with higher frequency and therefore more cost-effective.



Figure 2.49: Advantages of the higher frequency
(Source: Endress+Hauser SE+Co. KG)

The pulse method also initially dominated for level measurement, as the FMCW (frequency modulated continuous wave) principle widely used in classic radar technology was too expensive and too power consuming for two-wire devices.

Solutions have been found for all problems, mostly by utilizing parts or components from the automotive industry to benefit from the rapid development in this area. As a result, the 80 GHz used there as well as the FMCW method for modern level sensors are now state of the art. With the FMCW method, the accuracy largely depends on the stability of the frequency ramp, which meanwhile is generated completely digitally, so that even an accuracy of ± 1 mm is not a problem for today's systems, and the signal dynamic also allows ranges of up to 100 m.

A further cost reduction has been achieved in recent years by transferring large parts of the previously discrete radar module into a chip. There are now two approaches that are being pursued differently by the various suppliers of radar level sensors. As there are now derivatives of the automotive 80 GHz chip (Si-CMOS) modified for industrial applications, on which all components including a signal processor are integrated, this also offers companies with limited knowledge of RF circuit design the opportunity to develop radar level sensors. The more complex option of designing the chip (SiGe-CMOS) by oneself does not achieve the same level of integration, but the design can be completely customized to the requirements of level measurement and full flexibility is retained, especially with regard to the desired measurement frequency.

One result of this approach is the first radar sensor with a measurement frequency of 180 GHz shown in Figure 2.50 which can be used in smallest $\frac{1}{2}$ " process connections with good performance.

In addition to self-diagnostics, the sensor also offers a certified verification method, in which an index correlating with the accuracy is stored in production. A comparison with the current value during operation allows the detection of any change in sensor behavior related accuracy. It also provides a wealth of information regarding predictive maintenance (e.g., detection of built up) or condition monitoring (e.g., detection of foam).



Figure 2.50: 180 GHz radar sensor with process connection $\frac{1}{2}$ "
(Source: Endress+Hauser SE+Co. KG)

In comparison with the other technologies for continuous level measurement, radar technol-

ogy has now eliminated almost all disadvantages and limitations that initially existed and has thus developed from a problem solver for special cases to a level measuring device that can be used almost universally. As a result, these other measuring methods are already being clearly displaced and this is likely to continue in the future, probably only with the exception of applications with heavy foaming, where capacitance and guided radar will continue to have clear advantages in the future.

Due to the use of low-cost radar components from the automotive sector, radar level sensors have experienced a significant price reduction in recent years. The limit will not be determined by the actual radar technology but by the high requirements of process plants (high pressure and temperature, chemical resistance, certificates, etc.) for the complete device. For simple applications, however, very cost-effective devices will therefore be possible.

Bulk Solids with Non-flat Contour

For bulk solids applications where the surface is not flat, there is still no satisfactory solution. Only with 3D measurement of this surface contour could the volume be determined with good accuracy. LiDAR (optic based technology) systems can do this, but only in relatively clean ambient conditions and therefore mostly in storage applications [Petit, 2023]. Available robust radar sensors that also work under harsh environmental conditions are either systems in which the information from three to five individual sensors are linked, or systems in which the radar beam is mechanically rotated, neither of which are good solutions. A real imaging radar would be desirable in which radar is used to measure a narrow network of points on the surface. This is possible in principle, but from today's point of view, it involves a great deal of effort.

Sustainability

Of course, manufacturers of level sensors are also beginning to think intensively about the role of their devices in terms of sustainability and carbon footprint. Considered over the entire life cycle, energy consumption in measurement operation typically accounts for one-third of the

carbon footprint, while the production of the devices and, in particular, the use of materials (e.g., steel flange und aluminum housing) is responsible for the larger share. In the overall balance, however, this proportion in the kilogram range only plays a very minor role compared to the huge quantities of steel used for pipes, vessels, pumps, etc., for the complete process plant. In these applications, however, the carbon footprint is usually dominated by the energy and resources for the processes, which are constantly being optimized by process measurement technology such as level sensors. Their own carbon footprint is therefore negligible compared to the huge contribution to reducing the carbon footprint in process plants. Nevertheless, the topics of carbon footprint and circular economy will also have a strong influence on the design of level sensors in the future.

Trend for Level Sensing

The two "Mega-trends" that users are faced with, demographic change and high cost pressure, result in the two technological sensor trends: simplicity for the user and smart sensors. The combination of both trends poses a major challenge, but the technological trends digitization and function integration offer numerous possible solutions. Regarding the various technological principles, radar level sensors have undergone rapid development and can be expected to occupy a dominant position in level measurement.

2.7 Flow

(Drahm, W.)

Modern flowmeters provide high measuring performance with a low pressure loss and without moving parts. This is also a requirement for sustainability, where pressure loss in the measuring device should be reduced. Power consumption for pumps at the required flow rate can dominate the total energy requirement, especially in larger pipelines.

Installation of flowmeters becomes easier due to flow-profile independent measuring technologies. Flowmeters provide a wide range of diagnostic functions and self-validation.

Flow-Profile Independent Flow Measurement

For certain flow measuring technologies, there are requirements for inlet runs and installation of the flowmeter because the flow profile might affect the measuring accuracy.

Recently, sensor designs have been developed which allow for easy installation without the need for inlet runs; the devices can even be installed directly downstream of 90-degree bends or various flow disturbances.

Figure 2.51 shows a magnetic inductive flowmeter with three pairs of measuring electrodes. Owing to a suitable geometry of the magnetic field and these three pairs of electrodes, costly installation requirements can be reduced to a minimum. Challenging installations with limited space are possible.

Ultrasonic clamp-on flowmeters are installed onto an existing pipeline. Sound is transmitted from the pipe wall through the center of the pipe. Measurement errors can occur after bends or with disturbed flow profiles. A new technology is using two sound paths that are rotated 90° to each other (Figure 2.52). With this arrangement, it is possible to achieve good measurement results in any orientation of the sound path. This simplifies the installation of ultrasonic clamp-on flowmeters and avoids errors due to flow profile disturbances. [Papathanasiou et al., 2022].



Figure 2.51: Magnetic inductive flowmeter; three pairs of electrodes allow for installation independent of flow disturbances, like bends or valves.



Figure 2.52: Ultrasonic clamp-on flowmeter with two sound paths, providing good accuracy and easy installation, especially in difficult installations with limited space

Gas Measurement

For the measurement of gases, Coriolis mass meters, ultrasonic thermal flow meters and flow meters based on the vortex principle are used. Coriolis and ultrasonic flowmeters are used for important gases of energy transition, such as hydrogen, or gaseous carbon dioxide for carbon capture applications.

For large nominal diameters and custody transfer applications, ultrasonic flow meters are mainly used (Figure 2.53), whereas Coriolis mass meters are mainly used with high pressures and smaller diameters.



Figure 2.53: Ultrasonic flowmeter, special transducer design for robust operation even in wet gas applications

Multivariable Measurements

Modern flowmeters have very powerful computing units and can provide even more process variables and important information about the process and the fluid properties in addition to the flow rate. Coriolis mass flowmeters measure density and derive various concentrations from density such as alcohol content, sugar concentration, total solids, etc. The viscosity of the fluid can also be determined. Compared to laboratory rheometers, however, this is usually only possible for one shear rate or one oscillation frequency. A direct comparison between laboratory and inline measurements is therefore only possible to a limited extent. However, corresponding viscosity trends can be used for process control. Recently, viscosity measurement is also available for 2-tube and 4-tube meters as shown in Figure 2.54.



Figure 2.54: High capacity, high performance, low pressure drop 4-tube Coriolis mass flowmeter with 4 measuring tubes, including accurate density measurement and viscosity trending

Ultrasonic flowmeters can provide information about concentrations of liquids and various gases by determining the speed of sound. Devices for biogas applications can measure the methane content, which is a measure for the calorific value of the measured gas.

Thermal mass flowmeters will benefit from the determination of further media properties, resulting in simplified applicability of these meters. By measuring thermal conductivity, heat capacity, density and viscosity in addition, it is possible to draw conclusions about the fluid to be measured and determine the calorific value of the flowing gas. This allows for thermal mass

flow meters, which can measure independently of gas properties [Huber et al., 2024].

Vortex flowmeters are mainly used for steam measurement. It is now possible to also determine the steam quality. This indicates energy losses and allows for a better process control.

Magnetic inductive flowmeters (Figure 2.51) derive the flow signal from induced voltages measured at the electrodes. The electrode signals can also be used to measure the conductivity of the fluid. Additional signals are fed into the electrodes; the conductivity of the fluid can be derived from the measured impedance spectrum.

Diagnostics

Flowmeters are often used in safety instrumented systems. In order to monitor these safeguard systems, various diagnostic functions are implemented in modern flowmeters. In addition to test routines in the transmitter electronics with very high test coverage, process information like buildup, abrasion and corrosion can also be obtained. Coriolis mass flowmeters can detect abrasion and corrosion by exciting the measuring tubes with more frequencies in addition to the resonance frequency used for flow measurement. These additional measuring frequencies allow to analyze the properties of the measuring tubes during operation (Figure 2.55). For aerated fluids, information about gas content and inhomogeneities can be obtained [Zhu et al., 2016; Zhu et al., 2023]; measurement accuracy with aerated products can be improved by this “Multi Frequency Technology”.



Figure 2.55: Inside view of the 4-tube meter (see Figure 2.54); 2 different oscillation frequencies allow for additional information and diagnostics, as well as compensation of errors due to aeration of the measured product

The formation of build-up in the measuring tube of magnetic inductive flowmeters can be estimated by introducing additional signals into the measuring electrodes (Figure 2.56). Until now, it was not possible to detect buildup in a pipe. Cleaning cycles were often designed very conservatively with time consuming flushing periods. With an online diagnosis of buildup formation, these maintenance and cleaning cycles can be extended; cleaning can be initiated only if necessary.

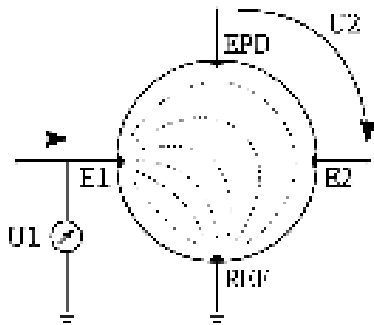


Figure 2.56: Detection of build-up in magnetic inductive flowmeter, derived from measured voltages U2 and U1; E1, E2: measuring electrodes; EPD electrode for empty pipe detection; REF: ground electrode. (Source: Stefan Heidenblut und Wolfgang Drahm)

Validation, reduction of calibration intervals

Safeguard systems usually need to be inspected once a year. This periodic inspection is often associated with removal and verification of the flowmeter in a calibration rig. The effort required for this is very large. With a correct design and configuration of the flowmeter, there is normally no shift in calibration factor found after recalibration. Therefore, it is beneficial to be able to extend the maintenance and inspection intervals by means of the various diagnostic functions. This allows to predict the need for recalibration during operation in the process. These validation routines can be triggered, and validation protocols can be generated automatically.

Disposable Flowmeter

In life sciences and pharmaceutical industries, single-use systems are increasingly found instead of multi-use systems made of glass and steel. This allows for shorter production times,

greater flexibility with faster product change-overs and greater safety. In order to achieve high measurement accuracy and mass measurement even in single-use systems, Coriolis flowmeters with a disposable flow tube are required. Figure 2.57 shows a single-use measuring system with a permanently installed base unit and a disposable Coriolis flow tube. The disposable part is made of steel and can easily be sterilized. It is inserted into the base unit with just a few simple steps. The calibration data is transferred optically from the measuring tube into the base unit by a bar code reader. After the measuring tube has been inserted into the shaft of the base unit and locked, the entire system is ready for measurement with the correct calibration factor. Measurement accuracies of 0.5 % of reading are possible.



Figure 2.57: Coriolis mass flowmeter with base unit and disposable part

High Temperature Clamp-On Flowmeters



Figure 2.58: Ultrasonic transducers for high temperature applications like thermal power plants

Temperature ranges of clamp-on ultrasonic flow meters have been extended to over 500 °C. The main application is in solar thermal

power plants, where heat transport is done via molten salts. This requires dedicated transducers (Figure 2.58).

2.8 Optical Quantities

(Ebermann, M.; Kurth, S.)

Optical measurement quantities primarily include intensity and spectral composition of electromagnetic waves in the wavelength range from ultraviolet to visible light and near-infrared to short, medium, and long-wave infrared. In many cases, image capture is required for information retrieval, so besides individual detectors, mainly detector arrays and cameras found a broad field of trending applications (information source for AI-based data mining and many kinds of digitization, autonomous driving). However, it should also be noted that photodetectors and detector arrays are very commonly used to measure completely different measurement quantities. Optical detectors are predominantly an integral part of photonic systems, each significantly influencing performance. Photodetectors are used as individual components (e.g., photodiodes, CMOS imagers) and, prospectively, as subcomponents in the form of chiplets or directly integrated detectors in photonic integrated circuits (PICs). Photodetectors are applied in the key application areas defined by the European Electronic Components and Systems Strategic Research and Innovation Agenda 2023 (ECS-SRIA) by using photonics such as distance and velocity (LiDAR), chemical composition (spectroscopy and spectral imaging), absorption (X-ray), optically encoded data (fiber and quantum communication, quantum computing), temperature (pyrometry), medical monitoring (pulse oximetry), or mechanical quantities (fiber grid-based detector, optical gyro). The application fields are extremely diverse in the areas of “consumer”, “automotive”, “medical”, and “industrial”. However, this will not be further discussed here.

Photonics significantly contributes to the European industry and economy in several ways: photonics is a key driver of innovation and productivity in various sectors, including healthcare, manufacturing, and consumer electronics. It enables the development of advanced products and solutions, leading to economic

growth and job creation. European photonics companies are at the forefront of technological advancements, giving them a competitive edge in global markets. They produce high-quality photonics components, devices, and systems that are in demand worldwide. On a global scale, European photonics companies are recognized for their expertise and contribute to the growth of various industries worldwide. Their products and technologies are sought after by global players, further strengthening Europe's position in the global photonics market.

CMOS Imager Based on Photo Diode Arrays

The basic function of a CMOS (Complementary Metal-Oxide-Semiconductor) silicon camera is to capture and convert light into digital images or video. Each pixel in the sensor contains a photodetector that converts the light into an electrical charge. The electrical charge generated by each pixel's photodetector is then converted into a voltage signal by an analog-to-digital converter (ADC). The converted voltage signals from all the pixels in the image sensor are read out row by row or in parallel. The digital signals are processed within the camera's image processing pipeline, which may involve operations such as noise reduction, color correction, and compression. The processed image data is then sent to the camera's output interface, such as USB, HDMI, or Ethernet, for display, storage, or transmission to other devices. CMOS cameras offer advantages such as low power consumption, high integration capability, and cost-effectiveness, which have led to them being widely used in various applications, including digital photography, video recording, surveillance systems, mobile devices, and scientific imaging. The state of the art for CMOS cameras advanced considerably over the last years; it includes now: more than 100 MPixel [Andanta 2016; Sony 2023b], rolling shutter and global shutter types, to reduce motion artefacts, and integrated Bayer color filter arrays.”

The continuous development has been directed towards new technologies to enhance the pixel density and fill factor, to widen the sensitive spectral range and the sensitivity for more than 15 years. The majority of CMOS camera chips are constructed for the back-side illumination principle (Figure 2.59) [Watanabe et al. 2009].

The metal wiring of the chip is placed underneath the sensitive parts of the pixels. The bulk substrate needs to be removed by grinding and etching to achieve optical access to the photo diodes (PD). Further improvement comes with wafer stacking technology. The photo diodes are arranged in a first wafer that is thinned down for back-side illumination and bonded with electric interconnects to a second wafer which includes the read-out electronics. Bump technologies are used to combine both wafers.

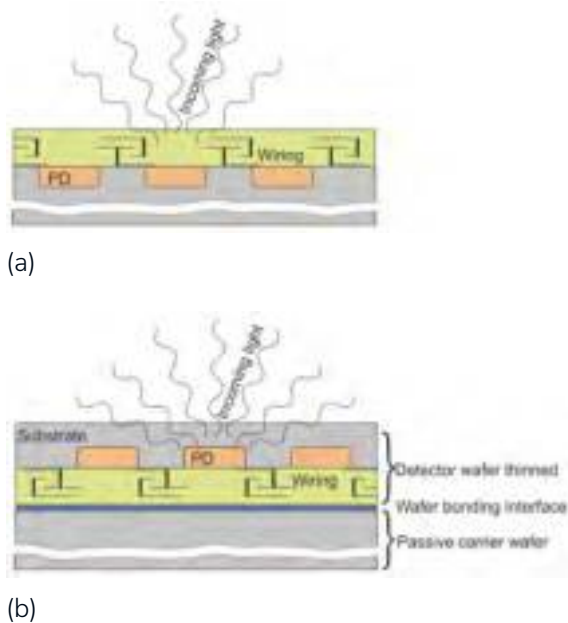


Figure 2.59: Cross sectional view of an image sensor a) with front side illumination and b) with back side illumination (Source: Steffen Kurth)

InGaAs PD Arrays

The wafer stacking technology offers the opportunity to use different semiconductor materials to generate the photo diodes, primarily InGaAs. High sensitivity and relatively high pixel numbers (e.g., 5.32 Mpixel [Sony 2023b]) with the benefits of a complex readout and image processing circuit are achieved (Figure 2.60). Bump interconnects made of indium [Zang 2024] as well as wafer direct bonding with Cu-Cu interconnects [Sony 2023b] are applied.

Image sensors of the very different types find their application in fields such as mobile and consumer area (smart phones, DSLR cameras, augmented reality and virtual reality, tablets and laptops), in the automotive and the security sectors, in industrial machine vision, in medical equipment, and in the defense area.

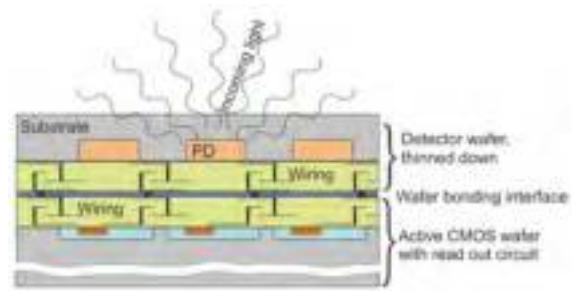


Figure 2.60: Cross sectional view of a hybrid type of image sensor. The detector wafer may consist of InP or of InGaAs to cover broader wavelength ranges with high photo sensitivity. (Source: Steffen Kurth)

Pyroelectric Detectors

The basic function of a pyroelectric photodetector is to convert changes in infrared radiation into an electrical signal. Pyroelectric materials, such as certain crystals or ceramics, exhibit a property called the pyroelectric effect. This effect means that these materials generate a temporary voltage when their temperature changes. When infrared radiation strikes the pyroelectric material, it causes a temperature change, which in turn generates a voltage signal across the material. This voltage signal is then amplified and processed to detect and measure the infrared radiation.

Pyroelectric photodetectors are commonly used in applications such as motion detection, thermal imaging, gas analysis, and non-contact temperature measurement. They are particularly sensitive to changes in infrared radiation, making them suitable for detecting heat sources and thermal variations in the environment.

In a pyroelectric photodetector, a pyroelectric material is typically coupled with an optical filter that allows only specific wavelengths of infrared light to pass through. The combination of tunable Micro-Electro-Mechanical Systems (MEMS) optical filters with detectors enables spectral analysis [Ebermann et al. 2016] and hyperspectral imaging [Kokka et al. 2023]. A MEMS optical filter is a miniaturized device that selectively transmits or blocks specific wavelengths of light. It utilizes microfabrication techniques to create tiny mechanical structures that can control the passage of light based on their physical movement and is driven by electrostatic forces in the most cases. Different types

of MEMS optical filters, such as Fabry-Perot (FP) filters or micro-mirror-based filters, may employ slightly different mechanisms while still leveraging the principles of microstructure movement to achieve wavelength control. FP filters with apertures between 0.5 mm and 23 mm [Kokka et al. 2023] for different spectral ranges, from visible light up to long wave infrared, are developed or are under development and fit to single spot sensors and to image sensors as well. They can be integrated together in a common housing (Figure 2.61).



Figure 2.61: Pyroelectric detector module with tunable FP filter mounted on top of the detector
(Source: InfraTec, www.infratec.de)

Single Photon Avalanche Diodes (SPADs)

SPADs have been substituting photo multipliers for a couple of years. The basic function of a Single-Photon Avalanche Diode (SPAD) is to detect single photons of light. It operates in a reverse-biased mode, where a small bias voltage is applied to the diode. When a photon enters the active area of the SPAD (Figure 2.62), it can generate an electron-hole pair. The applied bias voltage accelerates the electrons, which can trigger an avalanche effect due to impact ionization. This avalanche effect results in a rapid, high-gain amplification of the initial photon signal, producing a detectable electrical pulse. Detecting these individual photons, SPADs are used in various applications such as time-of-flight measurements, quantum optics, low-light imaging, and photon counting.

SPADs are used for time-resolved fluorescence measurement solutions such as fluorescence lifetime imaging microscopy (FLIM) and single-molecule detection, LiDAR, quantum communication [Ruskowski et al. 2020], photon counting,

time-correlated single-photon counting (TCSPC).

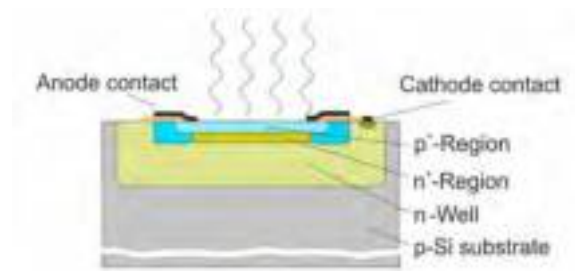


Figure 2.62: Cross-sectional view of a SPAD
(Source: Steffen Kurth)

Recent Results from R&D and Novel Products

Novel Pyroelectric Materials

HfO₂-based pyroelectric sensor elements with 3D-structured and planar layers on silicon substrate were recently tested in research labs. The fabrication process is fully CMOS compatible. Silicon substrates were structured with trenches and filled with thin doped hafnium oxide layers by atomic layer deposition to multiply the pyroelectric current sensitivity (Figure 2.63). Moreover, nanostructured plasmonic absorbers at the top layer increase the spectral selectivity. The 3D-structured HfO₂ layer magnifies the effective sensor surface and the sensitivity by a factor of up to 15 [Lehmkau et al. 2022].

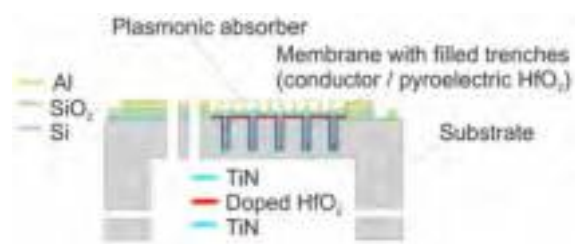


Figure 2.63: Cross-sectional view of the first samples of pyroelectric detectors with HfO₂ pyroelectric material and plasmonic absorbing structures
(Source: Steffen Kurth)

Metasurfaces as Light-Concentrating Structures

Subwavelength structures are the key elements of metasurfaces that can be designed to build lenses (Figure 2.64), for example. The structures are very thin in contrast to refractive micro lenses and have a layer thickness of less than 1 µm. They are made of a highly refractive ma-

terial (e.g., Si_3N_4 for visible light) and can be applied to concentrate the incoming radiation onto the sensitive area of the detector.

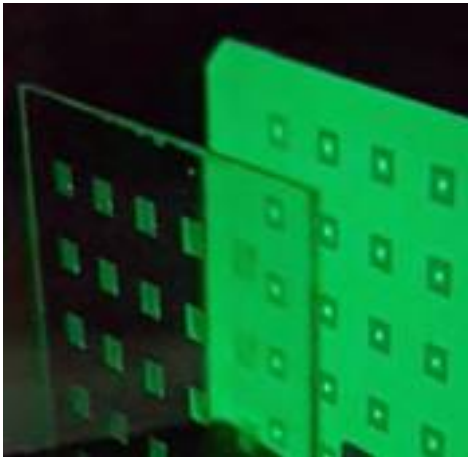


Figure 2.64: Photographic image of the test of an array of metalenses on glass substrate with parallelized green light (Source: Steffen Kurth)

2.9 Radar

(Nuss, B.)

Since the first patent application for a radar system by Christian Hülsmeyer in 1904, not only the technology has developed significantly, but also the range of applications has increased considerably. Initially intended for the detection of ships in the patent application, radar systems were primarily used in the military sector for air and sea surveillance at the beginning and middle of the 20th century, followed by corresponding applications in the civil sector. Due to the vastness of the area to be monitored, frequencies below 10 GHz and high transmission powers are mainly used here, so that ranges of up to 100 km can be covered. In this frequency range, however, the available bandwidth is severely limited, which is why only range resolutions around ten meters are possible. However, as objects in the air or at sea are normally at a certain distance from each other, this does not limit the required functionality.

Automotive Radar

However, by far the largest number of radar sensors are now used in the automotive sector, where several million radar units are sold every year. The reason for this development is that the components of the radars have been increasingly integrated into semiconductor chips

as a result of advancing technological developments, and the price has fallen drastically as a result [Waldschmidt et al. 2021]. In addition, driver assistance systems have been mandatory for new vehicle registrations in the European Union since July 2024. These assistance systems also include radar sensors, of which not just one but several sensors are often installed, especially in higher-class vehicles. On the road to autonomous driving, a further increase in the number of radar sensors is to be expected, as they are an elementary part of environment perception for the autonomous driving function alongside cameras and LiDAR sensors. The areas of application for automotive radars range from emergency brake assistants and the detection of fast-approaching vehicles during overtaking maneuvers to pedestrian, cyclist and animal detection, for example in poor visibility conditions such as fog and heavy rain.

The major advantages of radar over LiDAR sensors are that they function significantly more independently of the weather, can reliably detect the radial speed of an object with a single measurement and are also cheaper in mass production. The decisive disadvantage compared to LiDAR sensors is the poorer angular resolution. With today's automotive radar sensors, the azimuth and elevation angle of the detected objects are estimated using multiple-input multiple-output (MIMO) methods in addition to the range and velocity estimation. Here, several transmit antennas distributed spatially on the sensor aperture send uncorrelated signals, which are processed simultaneously by several receive antennas after being reflected by the objects. The fact that the transmitted signals are uncorrelated means that the receivers can deduce which signal was emitted by which transmit antenna. This allows to create from the $N_{\text{Tx}} + N_{\text{Rx}}$ physical antenna elements a virtual antenna array with $N_{\text{Tx}} \cdot N_{\text{Rx}}$ virtual channels, which can be used for angle estimation. In this way, the angular resolution can be significantly improved despite a limited number of physical channels. In this regard, the first sensor manufacturers are offering imaging radars with up to 48 transmit antennas and 48 receive antennas and therefore up to 2304 virtual channels. However, the high number of channels also requires an increase in computing power, which is why dedicated system-on-a-chip (SoC) solu-

tions combined with innovative signal processing concepts are used. Figure 2.65 shows the radar image of a 4D imaging radar that uses 12 transmit and 16 receive channels resulting in 192 virtual channels. Another trend in automotive radars, which is also related to the increasing channel count, is the change from classic patch to waveguide antennas, which can be manufactured using metallized injection molded parts [Garcia-Tejero et al. 2024].

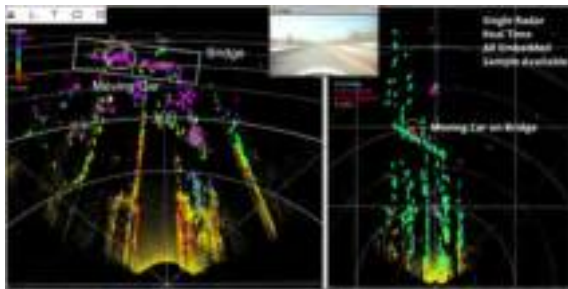


Figure 2.65: High-resolution radar image with point clouds from a 4D imaging radar from Altos Radar (Source: Altos Radar)

Applications that require an extremely high angular resolution include, for example, the detection of flat objects on the road and the associated decision as to if they can be driven over or if emergency braking must be initiated, as well as the detection of people standing next to a highly reflective target such as a truck. Along with the increasing number of channels, the size of radar sensors has also increased in recent years. However, there are limits to this, mainly for design reasons. Thus, intensive work is being carried out on networking the sensors distributed around a vehicle, which makes it possible to create a significantly larger virtual aperture, which can then be used to improve the angular resolution [Gottinger et al. 2021]. Only pre-processing then takes place in the individual sensors, while the radar data is fused in a central unit, sometimes together with camera and LiDAR data.

In addition to the number of channels, the carrier frequency, bandwidth and measurement duration are decisive parameters for the resolution capability of the radars. Current automotive radars essentially operate in the frequency range between 76 GHz and 81 GHz with a maximum bandwidth of 4 GHz, while the initial radar systems at 24 GHz with a significantly lower maximum bandwidth slowly fade out.

The main type of modulation used is chip sequence, in which several steep frequency ramps are transmitted and received in succession. The transmitted and received signals are then mixed, resulting in an intermediate frequency that is proportional to the transit time of the signal to the object and back. If the object moves in addition, phase shifts occur between the ramps due to the Doppler shift, from which the velocity can be deduced. This allows the object distance and speed to be estimated largely independently of each other, which is a clear advantage over FMCW radars which use a single slow frequency ramp.

The range resolution of a radar, i.e., the distance at which two targets of equal strength can still be distinguished, is inversely proportional to the bandwidth. In contrast, the velocity resolution is inversely proportional to the measurement duration and the carrier frequency. Efforts are currently being made to open up further frequency ranges above 100 GHz for automotive radars. In this case, however, the maximum range is reduced due to higher free-space attenuation [Köhler et al. 2013]. Beyond that, additional frequency ranges are also gaining importance as the increasing number of radar sensors leads to an increase in interference. In contrast to mobile communications, automotive radars are currently only limited by the permissible transmit power and/or the equivalent isotropic radiated power (EIRP), but there is no standardization that specifies the signal form or frequency and time raster.

As radar sensors contribute to driving safety, they have to prove their functionality in numerous scenarios during development, testing and approval. In order to avoid driving thousands of kilometers on the road for this purpose, it is planned to carry out parts of the validation in future with radar target simulators (RTS). Here, the wave emitted by the radar-under-test is received, delayed, attenuated and, if necessary, shifted in frequency. This allows a target to be emulated at a specific distance, with a specified radar cross section and a defined speed [Diewald et al. 2021]. In addition, antenna arrays can be used, as shown in Figure 2.66, which make the target appear at a specific angle. By emulating multiple point targets, extended targets with multiple scattering centers

and more complex scenarios can be generated. It is also possible to feed interference signals into many RTS.



Figure 2.66: Radar echo generator (left) with corresponding antenna array (right) to emulate objects at different azimuth angles (Source: Rohde & Schwarz)

Industrial Radar

In addition to level measurement, which is described in the section “Continuous Level Measurement”, radar sensors are used for numerous other industrial applications. These include high-accuracy distance measurements in general, measuring the thickness of materials and their material properties, as well as the non-destructive inspection of packaged goods. The advantage over camera or laser-based systems is that the frequencies used are still low enough compared to light to be able to penetrate non-conductive materials such as plastic, paper, glass, or cardboard. This allows, for example, the contents of packaging or the quality of injection-molded plastic parts to be inspected non-destructively [Jebramcik et al. 2020].

In order to achieve the best possible resolution, extremely high bandwidths are required. In the meantime, there are already systems that have a bandwidth of up to 56 GHz, allowing distance resolutions of up to 2,5 mm to be achieved [Kueppers et al. 2022]. In order to realize these high bandwidths, a correspondingly high carrier frequency must be selected. The broadband system shown in Figure 2.66, for example, operates in the D-band between 126 GHz and 182 GHz and uses FMCW as modulation type.

This allows an ADC sampling rate in the low megahertz range to be used despite the high signal bandwidth. To realize the high bandwidth, very broadband antennas with often high antenna gains are required to achieve the nar-

rowest possible measuring point to which the distance is determined. Dielectric lenses, as also shown in Figure 2.67, are one way of meeting these two requirements. A comparable system is also used in Figure 2.68. Here, a large number of high-accuracy radar sensors are arranged in a circle to measure the wall thickness of plastic pipes moving through the inner circle.



Figure 2.67: D-band Industrial radar sensor with 56 GHz bandwidth and a dielectric lens (Source: 2pi-Labs)



Figure 2.68: High-accuracy radar sensors arranged in a circle for measuring the wall thickness of pipes (Source: INOEX GmbH)

This makes use of the fact that reflections occur at the respective transitions between air and plastic. Due to the high bandwidth and therefore extremely good range resolution, the two reflections can be separated in the signal processing and the wall thickness can be determined by calculating the difference. Due to the special requirements, which often differ from the ones for automotive radar chips available on the mass market, special monolithic microwave integrated circuits (MMIC) are sometimes developed and manufactured, such as the 80 GHz chip for level measurements shown in Figure 2.69.

Recently, first radar systems have appeared on the market which, in addition to purely deter-

mining range, allow three-dimensional imaging using MIMO techniques, similar to angle estimation in automotive radars. With them, for example, image stacks of packaging and cartons can be recorded non-destructively while the objects move on a conveyor belt under the radar sensor.

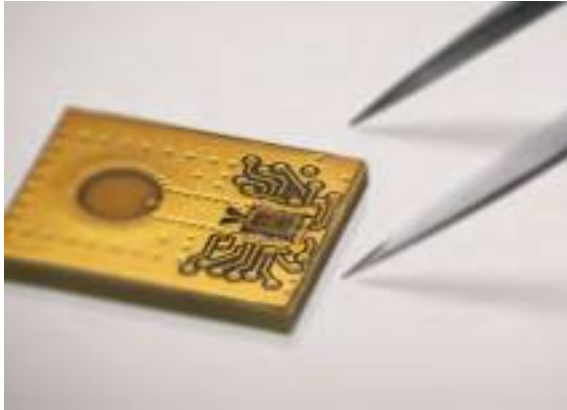


Figure 2.69: 80 GHz radar MMIC for level measurement from VEGA (Source: Vega Grieshaber KG)

Joint Communication and Sensing

Initial investigations and feasibility studies are currently being carried out for the future sixth generation (6G) mobile communications standard. In addition to simply increasing data rates and reducing latency times, new functionalities that could be included in the standard are being discussed intensively. These include, in particular, joint communication and sensing (JCAS), which could be used to add radar functionality to base stations [Giroto de Oliveira et al. 2022]. Currently, it is already possible to localize active mobile devices, for example, to direct highly directional antenna beams specifically at the users to improve the signal-to-noise ratio. The new sensing functionality additionally enables the detection of passive objects. This can be used, for example, in campus networks in warehouses to prevent accidents between autonomous vehicles and people, or in critical infrastructure to detect unauthorized access.

The biggest challenges in implementation are currently the small bandwidths available in mobile communications compared to other radar systems and the fact that most current systems operate in either frequency-division or time-division multiplexing mode. For sensing, however, the transmitted wave must be received in the same frequency band and more or less at the same time. Possible solutions here are either

full-duplex systems, in which the coupling between transmitter and receiver is suppressed as much as possible, or bistatic operation, in which the transmitter and receiver are housed separately, for example in different base stations [Shatov et al. 2024]. The problem of low bandwidths is exacerbated by the fact that higher signal bandwidths are required as data rates increase. Channels with up to 400 MHz bandwidth are currently being considered for 6G. The frequency range currently in focus for sensing is between 26 GHz and 28 GHz in the FR2 band. Efforts are also currently underway to open up additional frequency ranges in the FR3 band between 7 GHz and 24 GHz. These have the advantage for mobile communications that larger distances can be covered due to the lower frequency, but simultaneously, sufficiently high bandwidths can still be realized in comparison to even lower carrier frequencies.

2.10 Quantum Sensing

(Bongs, K.; Drese, K.; Wurz, M.; Kassner, A.)

The recent years saw intense international research and development activities in the area of quantum technologies. These promise novel possibilities for the realization of computers, communication schemes and sensors. This chapter discusses some of the sensor characteristics, while resulting fabrication needs are presented in Chapter 5.

The development of quantum mechanics at the beginning of the 20th century has led to the understanding of energy levels in various materials. This has enabled the development of technologies like the transistor and the laser. These building blocks of information technology are a firm part of everyday life and of immense economic importance. This might be termed the first quantum technology revolution.

By today, the possibility to manipulate matter has increased so much that deeper quantum effects, such as superposition and entanglement, can be harnessed to drive the next quantum technology revolution. Superposition describes the possibility for individual quantum particles to be in two states or two places at once. Entanglement is linked to the possibility of several particles to be in a mutual quantum superposition.

Perhaps the oldest of these novel class of quantum technologies are atomic clocks. These devices have been defining international time since 1967 and support the economy by the synchronization of communication and energy networks as well as by enabling satellite navigation. The development of other types of quantum sensors is rapidly progressing and, among others, allows unprecedented levels of precision in the detection of magnetic, electric, electromagnetic and gravitational fields, as well as inertial forces.

There are already several types of quantum sensors commercially available, allowing the development of novel applications based on previously inaccessible measurement data.

Quantum Clocks

In simple terms, a quantum clock replaces the macroscopic reference oscillator, such as the pendulum in a grandfather's clock, or the quartz oscillator in a watch, with the oscillation of an electron around an atomic nucleus. Mathematically, this oscillation occurs due to the superposition of the quantum mechanical wave functions corresponding to two electronic energy levels of the atom. As these energy levels are given by the laws of nature, this results in an extremely precise and reproducible oscillator. This quantum oscillator surpasses classical oscillators by many orders of magnitude and has made frequency the most precisely measurable quantity of all.

Current commercially available atomic clocks use atomic oscillations at microwave frequencies, i.e., at several GHz. For a first approximation, the available precision grows with size and cost as illustrated in Figure 2.70.

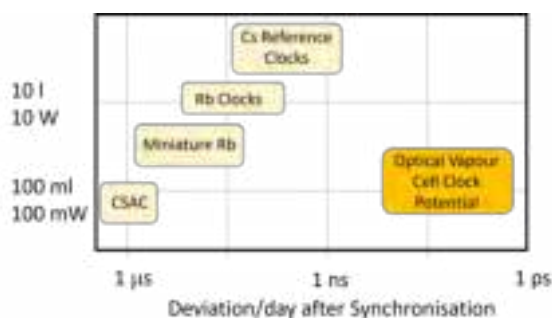


Figure 2.70: Approximate scaling of clock size and power as a function of holdover precision

One of the main application areas of these atomic clocks lies in the synchronization of energy and communication networks. Often, time distributed via satellite networks is used to provide a link to universal coordinated time (UTC), with a specified maximal deviation of 30 nanoseconds. Local clocks of various precision classes at different network levels then guarantee that network synchronization is maintained, even when satellite time is temporarily unavailable.

It is noteworthy that low latency 5G mobile phone functions are specified down to 30 nanoseconds, reaching satellite time specifications.

New challenges in network synchronization are expected in areas such as the development of the internet of things and Industry 4.0. A particular challenge lies in the wireless synchronization of mobile network participants, e.g., with autonomous cars, measurement drones and robots. In this area, new clock technologies might turn out to be key technologies enabling future developments and functions.

The current quantum technology developments are pushing a trend to so called “optical clocks”, i.e., atomic clocks using an oscillation frequency corresponding to the frequency of light. As this frequency is 100,000 times higher than the oscillator frequency in microwave atomic clocks, optical clocks promise to reach 100,000 times higher precision and much quicker synchronization. This could potentially enable synchronization within a fraction of a second to picosecond level, which then could be maintained for a day.

Within the next 10 to 15 years, the new optical clock technology might allow the development of a new generation of ultraprecise, compact and cost-effective chip scale atomic clocks. Such clocks could open economically feasible possibilities to maintain local times on ships, trains or autonomous vehicles synchronized with external networks over days without interaction.

Optical clocks are just at the verge of becoming commercially available. First commercial prototypes (e.g. Vector Atomics) are being announced and development is pushed by national funding programs.

Quantum Sensors for Magnetic Fields

Quantum magnetometers offer a new level of sensitivity compared to classical magnetometers' overall length scales (Figure 2.71).

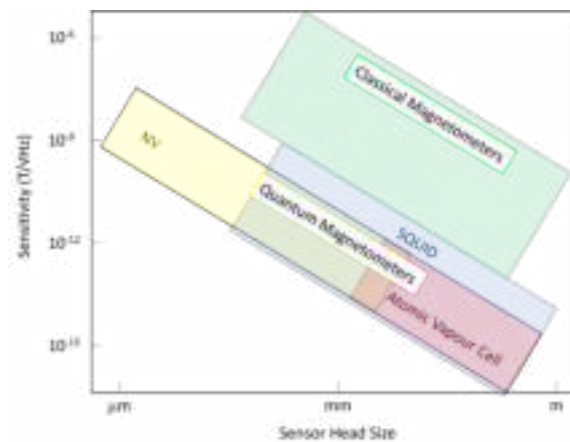


Figure 2.71: Schematic overview of sensitivity of different types of quantum sensors as compared to classical sensors

There are three main development strands for quantum magnetometers with varying levels of commercialization. SQUID (Superconducting Quantum Interference Device) magnetometers have reached a high level of maturity with commercial availability for decades. They are based on the interference of superconducting currents in a ring-shaped conductor. These magnetometers are employed where highest sensitivities are required. They have been used in applications such as geosurveys, security screening, materials testing and medical applications, such as magnetoencephalography and magnetocardiography [Clarke et al. 2004]. The main barrier to wide commercial uptake is the need for cryogenic cooling. Developments towards wider practicality are linked to the development of cryotechnology, which has recently received a boost due to the large quantum technology investments such as into superconducting quantum computers and cryogenic single photon detectors.

Another variant of quantum magnetometer is based on optically pumped atoms. They have been commercially available for a few years, but are still in a phase of rapid product innovation. Their simplest form is based on the measurement of how much the polarization of a laser beam rotates when passing through a glass cell filled with an atomic vapor. However, various

configurations are being developed which combine several lasers, or lasers with microwaves, in order to adapt to the needs of applications.

Optically pumped magnetometers have been commercially employed in geosurvey and archaeological applications for several years. More recently, ultrasensitive variants have been demonstrated in medical applications, leading to new types of magnetoencephalography systems (e.g., CERCA Magnetics, Fieldline), which offer more flexibility and thus novel diagnostic approaches as compared to SQUID-based systems. Further applications are being investigated in materials testing [Koss et al. 2022], battery diagnostics [Hu et al. 2020; Bason et al. 2022] and flow measurements [Schmieder et al. 2022]. The third quantum class of quantum magnetometers is based on impurities on pure solid-state systems, most prominently nitrogen vacancy centers in diamond (NV diamond). These are based on the measurement of magnetic field-dependent fluorescence of these impurities when excited with light and microwaves. This type of magnetometer is relatively new, and commercialization is in its infancy. They promise potential for integration and allow the smallest possible probe volume, making them particularly attractive for microscopic applications, including in the biomedical domain [Aslam et al. 2023].

Table 2.1 provides a simplified overview over typical commercial variants of these magnetometer types.

Laboratory experiments demonstrate that there is significant potential for further increases in precision as well as for miniaturization and cost reduction for both the optically pumped and the diamond NV magnetometers. For both, the integration towards chip scale systems for mass applications seems feasible in principle.

Magnetoresistive Quantum Sensors

Quantum magnetometers can be used to build magnetoresistive sensors. In simple terms, this can be done by replacing the detection coil in a metal detector with a quantum magnetometer. Such systems have been used in laboratory experiments to perform magnetic induction tomography, where an oscillating magnetic field causes eddy currents in a conducting sample,

Table 2.1: Types of commercially available quantum magnetometers

SQUID magnetometer		Optically pumped atomic magnetometer		Diamant-NV magnetometer	
+	up to 0.1 fT/Hz ^{1/2}	+	up to 10 fT/Hz ^{1/2} (potential: 0.1 fT/Hz ^{1/2})	-	100 pT/Hz ^{1/2} (potential: 0.1 pT/Hz ^{1/2})
+	probe mm-cm	+	probe ~cm	+	sub-mm probe
-	system: >100 l, >100 kg, kW	+	system: 0.5 l, 0.1 kg, 5 W	+	system: ~0.5 l, 0.1 kg, 5 W
		-	limited measurement range < 50 nT for 10 fT/Hz ^{1/2} ~0.1 mT for ~pT/Hz ^{1/2}	+	highest sensitivity at nm scale
				+	large measurement range (pT to T)

causing sample-dependent magnetic fields which are picked up by the quantum magnetometer.

The advantage of using a highly sensitive quantum magnetometer over a pickup coil is that the quantum magnetometer maintains its sensitivity for low frequencies. This allows to reduce the frequency of the excitation field to a level where the skin depth becomes sufficiently large to, e.g., the inside of pipelines under insulation or metallic objects submerged in salt water.

Quantum Sensors for Electric Fields

While several types of quantum sensors are being explored for the measurement of electric fields, the only commercial one is based on so called Rydberg atoms (commercialized, e.g., by Rydberg Technologies). Rydberg atoms are atoms in which one electron is put into a high and very weakly bound energy level. The size of the electronic wavefunction of these atoms can reach the micrometer level, 10,000 times larger than the diameter of a typical atom. At such an extent, the electron wavefunction becomes extremely sensitive to electric fields. This effect is further enhanced for electric fields, which oscillate at a frequency close to the difference between energy levels. By choosing the energy level and manipulating the atoms with external fields, the Rydberg atoms can be tuned to become sensitive to electromagnetic fields from DC up to THz frequencies.

Rydberg receivers for electromagnetic waves offer a fundamentally different detection mech-

anism to a classical antenna. The probe area can in principle be created without any use of metal. One only needs a glass cell holding an atomic vapor which is manipulated and interrogated by laser light. Such probes can be realized in a fiber-coupled way, so that a measurement of electromagnetic fields with minimal distortion of the field itself becomes possible. While commercial applications are still being explored, some of the following properties of Rydberg receivers might hold the key to overcome limitations of classical antenna systems:

- probe can be entirely dielectric,
- sensitivity can be tuned from DC to THz without changing the mechanical setup,
- probe area is defined by the vapor cell, often just mm scale, independent of the wavelength of the electromagnetic radiation to be measured,
- resistant to electromagnetic pulses,
- highly immune to interference, etc.

Inertial Quantum Sensors – Gravimeters, Accelerometers and Rotation Sensors

Inertial quantum sensors rely on the possibility to place quantum objects into a superposition of different positions. A gravity sensor or accelerometer can be realized by placing atoms into a superposition of trajectories traveling at different height in the gravitational field, or at different positions along an acceleration axis respec-

tively. This is typically done by subjecting atoms to a sequence of three laser pulses, the first placing them in a superposition of momentum states, making one part of the superposition move away from the other. The second laser pulse reverses the momenta of these two parts, making the trajectories reapproach each other. The third pulse mixes the momentum states at the point when the trajectories overlap again, causing an interference pattern. This pattern depends on the relative phase the atoms along the different trajectories. If the trajectories are separated by height in a gravitational field, the phase will depend on gravity, or if they are at different positions along an acceleration axis, it will depend on the acceleration.

If one arranges the trajectories such in a way that they enclose an area, the interference phase will also depend on the rotation of this area, just like in an optical Sagnac interferometer.

In all cases, using atoms as quantum probe particles allows a highly sensitive measurement of the respective inertial effect. The most important aspect is that quantum inertial sensors promise very low bias, low drift and a highly linear scale factor. This could overcome the key limitation of current high-performance inertial navigation systems. It will likely be several years before these types of sensors will become commercially available for use in navigation systems.

Another direction in quantum inertial sensors are mid-sensitivity compact sensors, competing with high-end MEMS-type systems. In this area, co-rotation atomic magnetometer gyroscopes have been developed towards commercial prototypes in several multinational companies. Future developments in this area could include nuclear spin comagnetometers in solid-state materials.

Photonic Quantum Sensors

Photonic quantum sensors can be loosely classed in two categories: sensors based on timed single photon detection and sensors based on correlations.

Timed single photon detection is widely used in LiDAR systems which have applications in

smartphones and autonomous vehicles. The quantum technology research in this area is driving sensitivity and timing resolution down to the low picosecond level, such that high resolution 3D images and detection of objects around corners becomes possible. One commercial application that has emerged from this is standoff imaging gas detection, e.g., methane cameras from QLM Ltd and research work towards hydrogen gas detection to support the transition to the hydrogen economy.

Sensors based on correlation are more stringently in the “Quantum 2.0” domain, using higher level quantum effects, but often these have classical “quantum inspired” counterparts, which use the basic principle behind the quantum sensing idea but realize it in a classical operational regime in order to achieve commercially interesting throughput. One example is the area of sensing with undetected photons, which uses nonlinear crystals to create correlations between photons in the visible spectrum (for easy and efficient detection, e.g., on a CCD camera) and photons in other domains of the electromagnetic spectrum, where imaging detectors are not readily available. Here, one lets the latter photons interact with the object of interest while taking an image with a standard camera. In the quantum regime with single correlated photon pairs, the image accumulation time can take minutes to hours, while operating in the classical regime allows high fluxes with images in seconds or faster.

Other approaches to use quantum effects to reduce detection noise are still in the research domain, as often an increase of signal to noise by increased light power is easier and more effective to achieve.

Challenges and Trends

In most cases, quantum sensors enter the market in the high performance/low volume segment. Often, they rely on laser systems with extreme requirements for absolute frequency and narrow linewidth, which causes high cost and low robustness in terms of environmental noise. A key challenge is thus the development of hybrid photonic-electronic integration technologies, which are scalable to mass production in a cost-effective way.

Another challenge is the low user awareness of the capabilities of quantum sensors, which is needed to drive system innovation and ultimately create market pull.

A current trend is the development of medical applications where funding structures are suited to introduce novel diagnostic methods. In addition, defense innovation programs are picking up on quantum sensors. Some funding programs, such as the QuantumBW in Baden-Württemberg, have a particular focus on quantum sensors and are starting to drive applications.

Integration of Quantum Sensors

When integrating and operating quantum sensors, there are some important features to consider. Depending on the type of sensor and the detection method, these are not available as a commercially available complete system but as individual components that must be individually adapted to the intended use and integrated into a system. Usually, boundary conditions for the environment (e.g. temperature, pressure) must be taken into account and additional peripheral components may need to be used.

As a first step, a distinction can be made between vacuum-based and non-vacuum-based sensors. For example, sensor systems based on cold atoms (e.g. atom chips in magneto-optical traps) are used in gravimeters and gyroscopes under UHV conditions. Magnetometers in the form of vapor cells can be used both under vacuum and normal pressure, while NV centers and SQUIDS are non-vacuum-based sensors. In the

case of vacuum-based systems, the outgassing rates of the materials used in the system and the hermeticity of the package are of particular importance.

A further differentiation criterion lies in the manufacturing method of the sensor. While SQUIDS, atom chips and NV centers are implemented using microtechnology methods and can therefore be integrated or combined with PIC or CMOS, the vapor cells for magnetometers are often manufactured using conventional glass blowing. They can therefore be integrated as a dedicated component. However, innovative approaches are also striving for microtechnological production here.

Another point to consider is the temperature during production, integration and operation. The design of the quantum system can be a limiting factor with regard to the maximum joining temperature and thus restrict the choice of joining method. Certain quantum systems also need to be cooled during operation. For example, SQUIDS are based on the principle of superconductivity, which requires cooling with liquid helium or, in the case of high-temperature superconductors such as YBCO, the use of liquid nitrogen.

Magnetic interference fields are a disruptive factor when measuring with SQUIDS, but also with inertial quantum sensors. This applies both to the selection of the materials used with regard to their magnetic properties and to active and passive shielding of external fields such as the earth's magnetic field.

References Chapter 2

Bonfig, K.W.: Das Handbuch für Ingenieure; Sensoren, Messaufnehmer. Ehningen: Expert Verlag 1988

Hoffmann, K.: Eine Einführung in die Messung mit Dehnungsmessstreifen, Hottinger Baldwin Messtechnik GmbH, Darmstadt, 1987

Schäfer, A.: Improved calibration and measurement capabilities – Basis of mechanical engineering, Congrès International de Métrologie (CIM 2023), Lyon, France 2023

Schäfer, A.: New strain gauge-based torque reference chain offering smallest measurement uncertainties, Proceedings of the 19th International Congress of Metrology (CIM2019), Paris France 2019

Schäfer, A.; Stock, A.: Torque as a key parameter for a better efficiency determination of electric motors and generators, Proceedings of XXIV IMEKO World Congress "Think Metrology", August 2024, Hamburg, Germany

Accreditation Advisory Board: Flexibilisation of the accreditation area of testing laboratories, calibration laboratories and medical laboratories [German: Design der 5 MN m Drehmoment-Normalmesseinrichtung], 71 SD 0 002. Revision: 2.2, issued 15.07.2015 by National Accreditation Body of Germany (DAkKS)

Gautschi, G.: Piezoelectric sensors. Springer Berlin Heidelberg. (2002)

Barjatia, M.: Lambert RH. EP3236439B1 - Acoustic presence detector, Published 19. April 2016.

Chen, YS.; Yeager, D.; Emelianov, SY.: Photoacoustic imaging for cancer diagnosis and therapy guidance. In: Elsevier eBooks ; 2014:139-158. doi:10.1016/b978-0-12-407722-5.00009-8

Zhang, N.; Zheng, T.; Wu, J.: Lead-Free (K,NA)NBO3-Based Materials: preparation techniques and piezoelectricity. ACS Omega. 2020;5(7):3099-3107. doi:10.1021/acsomega.9b03658

Pop, F. et al.: Zero-Power Acoustic Wake-Up Receiver based on DMUT transmitter, PMUTS arrays receivers and MEMS switches for intra-body links. IEEE Conference Publication | IEEE Xplore. Published online June 1, 2019. <https://ieeexplore.ieee.org/document/8808176> (accessed on: March 5th 2025)

Hashwan SSB, Khir MHMd, Nawi IM, et al. A review of piezoelectric MEMS sensors and actuators for gas detection application. Discover Nano. 2023;18(1). doi:10.1186/s11671-023-03779-8

Stoeckel, C. et al.: Thin film piezoelectric aluminum nitride for piezoelectric micromachined ultrasonic transducers. IEEE Conference Publication | IEEE Xplore. Published October 1, 2018. <https://ieeexplore.ieee.org/document/8589845> (accessed on: March 5th 2025)

Wang, J.; Zheng, Z.; Chan, J.; Yeow, JTW.: Capacitive micromachined ultrasound transducers for intravascular ultrasound imaging. Microsystems & Nanoengineering. 2020;6(1). doi:10.1038/s41378-020-0181-z

Dangi, A. et al.: A photoacoustic imaging device using piezoelectric micromachined Ultrasound transducers (PMUTs). IEEE Journals & Magazine | IEEE Xplore. Published April 1, 2020. <https://ieeexplore.ieee.org/document/8915732> (accessed on: March 5th 2025)

Jiang, X.; Lu, Y.; Tang, HY. et al.: Monolithic ultrasound fingerprint sensor. Microsystems & Nanoengineering. 2017;3(1). doi:10.1038/micronano.2017.59

Drung, D.; Krause, C.; Becker, U.; Scherer, H.; Ahlers, F. J.: Ultrastable low-noise current amplifier: a novel device for measuring small electric currents with high accuracy, Rev. Sci. Instrum., 86, 24703, <https://doi.org/10.1063/1.4907358>, 2015.

Krause, C.; Drung, D.; Götz, M.; Scherer, H.: Noise-optimized ultrastable low-noise current amplifier, The Review of scientific instruments, 90, 14706, <https://doi.org/10.1063/1.5078572>, 2019.

- Wendt, C.; Bohnhorst, A.; Zimmermann, S.; Kirk, A.T.: Ultra-low noise current meter for measuring quickly changing currents from attoampere to nanoampere, *tm – Technisches Messen*, 0, <https://doi.org/10.1515/teme-2022-0049>, 2022.
- Blaser, C.: In-line calibration of electrical quantities using the example of a 4 MW nacelle test bench, Presented in August, 2023 in the Final Workshop of the project EMPIR “19ENG08 WinEFCY Traceable mechanical and electrical power measurement for efficiency determination of wind turbines”
- Blagojevic, M.; Dieudonne, A.; Kamecki, L.; Kiziroglou, M. E.; Krastev, K.; Marty, D.; Pigué, D.; Spasic, S.; Wright, S.W.; Yeatman, E.M.: Autonomous Electrical Current Monitoring System for Aircraft, *IEEE Trans. Aerosp. Electron. Syst.*, 59, 3345–3358, <https://doi.org/10.1109/TAES.2022.3225253>, 2023.
- Popovic, R. S.; Flanagan, J. A.; Besse, P. A.: „The future of magnetic sensors,” *Sensors and Actuators A: Physical*, Bd. 56, Nr. 1–2, pp. 39–55, 1996.
- Lenz, J.; Edelstein, A. S.: „Magnetic Sensors and Their Applications” *IEEE Sensors Journal*, Bd. 6, Nr. 3, pp. 631–649, 2006.
- Žurauskiene, N.: „Engineering of Advanced Materials for High Magnetic Field Sensing: A Review” *Sensors – MDPI*, Bd. 23, Nr. 2939, 2023.
- Popovic, R.S.: “Hall Effect Devices”, 2nd Edition, CRC Press, 2003.
- Popovic; Radivoje; Dimitrijevic: Sasa Patent EP14176835.8 Vertical Hall Device, 2014.
- Popovic Renella, D. et al. “Novel 3D Hall sensor and its application in inspection robots”, *IMEKO TC4 Conference*, 2023
- Stuck, A., Mijalkovic, M., Vidojevic, M., Popovic Renella, D.: “Practical limitations of accurate magnetic measurements in industrial applications”, *IMEKO TC4 Conference*, 2023
- SENIS AG, “3D Hall sensor SENM3Dx”, <https://www.senis.swiss/sensors/3dhall-3-axis-hall-magnetic-sensor-senm3dx/> (accessed on: March 5th, 2025) 2024a)
- SENIS AG, “3D Magnetic Field Camera SEN-3D-CAM”, <https://www.senis.swiss/mappers/sen-3d-cam-magnetic-field-camera/> (accessed on: March 5th, 2025) 2024b)
- AMA Innovation Award 2024, www.ama-sensorik.de/en/science/ama-innovation-award/ama-innovationspreis-2024/ accessed on: March 5th, 2025)
- Zheng, C.; Zhu, K.; Cardoso de Freitas, S.; Chang, J.-Y.; Davies, J.E.; Eames, P.; Freitas, P.P.; Kazakova, O.; Kim, C.; Leung, C.-W.; Liou, S.-H.; Ognev, A.; Piramanayagam, S.N.; Ripka, P.; Samardak, A.; Shin, K.-H.; Tong, S.-Y.; Tung, M.-J.; Wang, S.X. Fellow, IEEE, Xue, S.; Yin, X.; Pong, P.W.T.: „Magnetoresistive Sensor Development Roadmap (Non-Recording Applications),” *IEEE Transactions on Magnetics*, Bd. 55, Nr. 4, 2019.
- Elzwawy, A.; Piskin, H.; Akdogan, N.M.; Volmer, G. Reiss; Marnitz, L.; Moskaltsova, A.; Gurel, O.; Schmalhorst, J. M.: „Current trends in planar Hall effect sensors: evolution, optimization, and applications,” *Journal of Physics D: Applied Physics*, Bd. 54, Nr. 353002, 2021.
- Oogane, M.: „Development of tunnel magnetoresistive sensors” *IEICE Transactions on Electronics*, 2023.
- Chen, J.; Zhang, Z.: „A flexible anisotropic magnetoresistance sensor for magnetic field detection,” *Journal of Materials Science: Materials in Electronics*, Bd. 34, Nr. 73, 2023.
- Wurz, M.C.; Prediger, M.: „Physical Sensors: Magnetic Sensors,” *Encyclopedia of Sensors and Biosensors*, Bd. 1, pp. 97–110, 2023.
- Li, T.; Zhang, L.; Hong, X.: „Anisotropic magnetoresistance and planar Hall effect in correlated and topological materials,” *Journal of Vacuum Science and Technology A*, Bd. 40, Nr. 010807, 2022.
- Reig, C.; Cubells-Beltran, M.D.: „GMR Based Sensors for IC Current Monitoring,” *Smart Sensors, Measurement and Instrumentation SSMI*, Bd. 6, pp. 103–131, 2013.

- Knudde, S.; Leitao, D.C.; Cardoso, S.; Freitas, P.: „Annealing free magnetic tunnel junction sensors,” *Journal of Physics D: Applied Physics*, Bd. 50, Nr. 16, 2017.
- Djayaprawira, D.D.; Tsunekawa, K.; Nagai, M.; Maehara, H.; Yamagata, S.; Watanabe, N.; Yuasa, S.; Suzuki Y.; Ando, K.: „230 % room-temperature magnetoresistance in CoFeB/MgO/CoFeB magnetic tunnel junctions,” *Applied Physics Letters*, Bd. 86, Nr. 092502, 2005.
- Zhou, Z.; Zhang, K.; Leng, Q.: „Tunneling Magnetoresistance (TMR) Materials and Devices for Magnetic Sensors,” in *Spintronics: Materials, Devices and Applications*, K. Wang, M. Yang und J. Luo, Hrsg., John Wiley & Sons Ltd, 2022, pp. 51–92.
- Bernhard, F. (Ed.): *Handbuch der Technischen Temperaturmessung*, 2. Auflage, Springer-Verlag, <https://doi.org/10.1007/978-3-642-24506-0>, 2014.
- James, S.W.; Kissinger, T.; Weber, S.; Mullaney, K.; Chehura, E.; Pekmezci, H.H.; ... & Tatam, R. P. (2022): Fibre-optic measurement of strain and shape on a helicopter rotor blade during a ground run: 1. Measurement of strain. *Smart Materials and Structures*, 31(7), 075014.
- Kissinger, T.; James, S.W.; Weber, S.; Mullaney, K.; Chehura, E.; Pekmezci, H.H.; ... & Tatam, R. P. (2022): Fibre-optic measurement of strain and shape on a helicopter rotor blade during a ground run: 2. Measurement of shape. *Smart Materials and Structures*, 31(7), 075015.
- Augustin, S., Schalles, M.: New publication of the VDI/VDE guideline 3520 “Surface temperature measurement with contact thermometers” – contents and background of the development *J. Sens. Sens. Syst.*, 12, 197–204, <https://doi.org/10.5194/jsss-12-197-2023>, 2023
- Gebhardt, J., Sosale, G., Dasgupta, S.: “Non-invasive temperature measurement of turbulent flows of aqueous solutions and gases in pipes” *tm – Technisches Messen*, vol. 87, no. 9, 2020, pp. 553–563. <https://doi.org/10.1515/teme-2020-0028>
- Cortial, Sebastien; et al.: Status of 8.5 μm pitch bolometer development at Lynred. *Infrared Technology and Application XLIX. Proc. Of SPIE Vol. 12534 125341A*; V10.1117/12.2663455, 2023.
- Guillaumont, Marc, et al.: Recent Thermoresistive Material Evolutions at LYNRED for improving uncooled Microbolometer Products Thermal Sensitivity. *Infrared Technology and Application XLVIII. Proc. Of SPIE Vol. 1210716 0277-786X*; <https://doi.org/10.1117/12.2618494>, 2021
- Yu, Le; Guo, Yaozu; Zhu, Haoyu; Luo, Mingcheng; Han, Ping; Ji, Xiaoli: Review: Low-cost microbolometer Type Infrared Detectors. *Micromachines* 11,800; <https://doi.org/10.3390/mi11090800>, 2020.
- Budzier, Helmut; Gerlach, Gerald: The size-of-source effect in thermography. *J. Sens.Sens.Syst.*, 10; 179-184; <https://doi.org/10.5194/jsss-10-179-2021>, 2021.
- Melexis Technologies NV: News Release, Galaxy watch5, 21th Febr. 2023, <https://www.melexis.com/en/news/2023/21feb-2023-galaxy-watch5-series-uses-melexis-temperature-sensor-for-menstrual-cycle-tracking> (accessed on: March 5th, 2025)
- Schieferdecker, J.; Schnorr, M.; Forg, B.; Herrmann, F.; Schmidt, C.; Leneke, W.; Simon, M.; Prangemeier, T.: New higher resolution thermopile arrays for IR imaging and surveillance, *Proceedings Volume 12534, Infrared Technology and Applications XLIX; 125341F* (2023), SPIE Defense + Commercial Sensing, 2023, Orlando, Florida, United States, <https://doi.org/10.1117/12.2668428>
- Morrison, R.: “An Alternative to Traditional Temperature Measurement Solutions”, Emerson Automation Experts Blog, www.emersonautomationexperts.com, Sep 21, 2023, (accessed on: March 5th, 2025)
- Gebhardt, J.; Sosale, G.; Ackermann, P.: Verification of industrial temperature measurements using a non-invasive approach, *IMEKO TC6 International Conference on Metrology and Digital Transformation*, September 19 – September 21, 2022, <https://www.imeko.org/publications/tc6->

2022/IMEKO-TC6-2022-041.pdf (accessed on: March 5th, 2025)

ABB Ltd.: My Measurement Assistant v6.0 - NINVA Performance Predictor, <https://my-measurement-assistant.abb.com/services/non-invasive>, 2023 (accessed on: March 5th, 2024)

Labom Mess- und Regeltechnik GmbH: "Measuring insert for In-process calibration, Type Series GA310", Datasheet DB_T4-025-45_en_12.02 2023-05, 2023, https://www.labom.com/downloads/db/DB_T4-025-45_en%20%28GA310x%29%20In-process.pdf (accessed on: March 5th, 2025)

Endress+Hauser: "iTHERM TrustSens TM371", Technical Information no. TI01292T/09/EN/08.22-00 71592470 2022-10-31, 2022, https://bdih-download.endress.com/files/DLA/005056A500261EDDB298A0A979300ABF/TI01292TEN_0822-00.pdf (accessed on: March 5th, 2025)

Tränkler, H.; Reindl L.: Sensortechnik, Handbuch für Praxis und Wissenschaft, Springer-Verlag, 2. Auflage 2014

Frost&Sullivan: Top 15 Growth Opportunities in Industrial Automation, 2024, Study K9F9-10, 2024

Frost&Sullivan: Global Pressure, Flow, Level and Temperature Sensors and Transmitters Tracker, 2022, Study K6662-10, 2022

SPE (Single Pair Ethernet System Alliance): SPE für die Feldkommunikation, Whitepaper, https://singlepairethernet.com/wp-content/uploads/2022/09/SPESA_Whitepaper_Fieldcommunication_DE.pdf (accessed on: March 5th 2025)

Singha, A.: NV-Magnetometry, Max Planck Institute for Solid State Research Web Page, 2024 <https://www.fkf.mpg.de/7721404/NV-Magnetometry> (accessed on: March 5th, 2025)

Petit, F.: Schüttgut-Erfassung mit 3D-Lidar-Sensoren, Schüttgut Magazin, 11/2023, <https://www.schuettgut.vogel.de/schuettguterfassung-mit-3d-lidar-sensoren-a-e07863e0b96d023c4317a587558bb00a/?cmp>

=nl64&uuid=f4f075e574cbe831fc1413fb7bcd1ec (accessed on: March 5th 2025)

Papathanasiou, P.; Kissling, B.; Berberig, O.; Kumar, V.; Rohner, A.; Bezdek, M.: Flow disturbance compensation calculated with flow simulations for ultrasonic clamp-on flowmeters with optimized path arrangement, Flow Measurement and Instrumentation, <https://doi:10.1016/j.flow-measinst.2022.102167>, March 2022,

Huber, C.; Schwab, S.; Lütolf, F.; Dienemann, D.; Bernhardsgrütter, R.; Hepp, C.: Fluid-independent thermal gas flow sensor, Proceedings of the 5th International Conference on MicroFluidic Handling Systems, pp 57–60, 2024

Zhu, H.; Rieder, A.; Lin, Y.: An innovative technology for Coriolis metering under entrained gas condition, Flomeko 2016, 2016.

Hao Zhu, Rieder, Alfred; Ceglia, Paul; Hai-Thuy Ngo.: Laboratory and field validation of a new Coriolis metering concept for better measurement uncertainty, reliability and process insight, Measurement 218, 2023

Andanta GmbH Detektortechnologie 2023, "Hires-CMOS 1205 60 Megapixels CMOS Image Sensor", https://andanta.de/wp-content/uploads/2023/11/ANDANTA_CMOS_Overview.pdf (accessed on: March 5th, 2025)

Sony Semiconductor Solutions Corporation 2023a, "IMX461BQR, Diagonal 55 mm (Type 3.4) CMOS Image Sensor with Square Pixel for Color Cameras (Product information)", https://www.sony-semicon.com/files/62/pdf/IMX461BQR_Flyer_ver10.pdf (accessed on: March 5th 2025)

Sony Semiconductor Solutions Corporation 2023b, "SWIR Image Sensor IMX990, IMX991, IMX992, IMX993", https://www.sony-semicon.com/files/62/flyer_industry/IMX990_991_992_993_Flyer_en.pdf

Watanabe, N.; Tsunoda, I.; Takao, T.; Tanaka, K., Asano, T.: Back-Side Illuminated CMOS Image Sensor Fabricated Using Compliant Bump, The 2009 International Conference on Solid State Devices and Materials, Sendai, 90–91, 2009.

- Zhang, J.; Wang, W.; Ye, H.; Huang, R.; Liu, C.; Zhao, W.; Shi, Y.: Ultra-Broadband Ultraviolet-Visible Light-Short Wavelength Infrared In-GaAs Focal Plane Arrays via n-InP Contact Layer Removal, *Sensors* 2024, 24, 1521. <https://doi.org/10.3390/s24051521>, 2024.
- Ebermann, M.; Neumann, N.; Hiller, K.; Seifert, M.; Meinig, M.; Kurth, S.: Tunable MEMS Fabry-Pérot filters for infrared microspectrometers: A review, *Proceedings Volume 9760, MOEMS and Miniaturized Systems XV*, San Francisco, California, United States, March 2016, 97600H, <https://doi.org/10.1117/12.2209288>, 2016.
- Kokka, A.; Holmlund, C.; Salonen, L.; Ihalainen, O.; Astola, H.; Möttö, M.; Mannila, R.; Ihatsu, T.; Stuns, U.: Passive real-time hyperspectral imager based on Fabry-Pérot interferometer filter technology, *Proc. SPIE 12737, Electro-Optical and Infrared Systems: Technology and Applications XX*, Amsterdam, The Netherlands, 127370W (23 October 2023); <https://doi.org/10.1117/12.2680355>. 2023
- Ruskowski, J.; Thattil, C.; Drewes, J.H.; Brockherde, W.: 64x48 pixel backside illuminated SPAD detector array for LiDAR applications, *Proc. SPIE 11288, Quantum Sensing and Nano Electronics and Photonics XVII*, 1128805, <https://doi.org/10.1117/12.2550634>, 2020.
- Lehmkau, R.; Mutschall, D.; Kaiser, A.; Ebermann, M.; Neumann, N.; Czernohorsky, M.; Neuber, M.; Hiller, K.; Seiler, J.; Großmann, T.D.; Shaporin, A.V.; Lienig, J.: Design and characterization of a pyroelectric detector based on three-dimensional structured hafnium oxide thin films, *Opt. Eng.* 61(12) 127102, <https://doi.org/10.1117/1.OE.61.12.127102>, 2022.
- Clarke, J., Braginski, A. (eds.), *The SQUID Handbook, Vol. 2: Applications of SQUIDs and SQUID Systems* (Wiley, New York, 2004)
- Koss, P.A.; Durmaz, A.R.; Blug, A.; Laskin, G.; Pawar, O.S.; Thiemann, K.; Bertz, A.; Straub, T.; Elsässer, C.: Optically Pumped Magnetometer Measuring Fatigue-Induced Damage in Steel. *Applied Sciences*. 2022; 12(3):1329. <https://doi.org/10.3390/app12031329>
- Hu, Y.; Iwata, G.Z.; Bougas, L.; Blanchard, J.W.; Wickenbrock, A.; Jakob, G.; Schwarz, S.; Schwarzing, C.; Jerschow, A.; Budker, D.: Rapid Online Solid-State Battery Diagnostics with Optically Pumped Magnetometers. *Applied Sciences*. 2020; 10(21):7864. <https://doi.org/10.3390/app10217864>
- Bason, M.; Coussens, T.; Withers, M.; Abel, C.; Kendall, G.; Kruger, P., (2022): Non-invasive current density imaging of lithium-ion batteries. *Journal of Power Sources*. 533. 231312. 10.1016/j.jpowsour.2022.231312.
- Schmieder, L.; Koss, P.A.; Lambrecht, A.; Kühnemann, F.: Noninvasive Magnetic-Marking-Based Flow Metering with Optically Pumped Magnetometers. *Applied Sciences*. 2022; 12(3):1275. <https://doi.org/10.3390/app12031275>
- Aslam, N.; Zhou, H.; Urbach, E.K.; et al.: Quantum sensors for biomedical applications. *Nat Rev Phys* 5, 157–169 (2023). <https://doi.org/10.1038/s42254-023-00558-3>
- Waldschmidt, C.; Hasch, J.; Menzel, W.: “Automotive Radar — From First Efforts to Future Systems”, *IEEE Journal of Microwaves*, vol. 1, no. 1, 135–148, doi: 10.1109/JMW.2020.3033616, 2021.
- Garcia-Tejero, A.; Burgos-Garcia, M.; Merli, F.: Broadband Metallized Plastic Waveguide Antenna With Robust Isolation Interface at 77 GHz, *IEEE Antennas and Wireless Propagation Letters*, vol. 23, no. 10, pp. 2875–2879, doi: 10.1109/LAWP.2024.3412424, 2024.
- Gottinger, M.; Hoffmann, M.; Christmann, M.; Schütz, M.; Kirsch, F.; Gulden, P.; Vossiek, M.: Coherent Automotive Radar Networks: The Next Generation of Radar-Based Imaging and Mapping, *IEEE Journal of Microwaves*, vol. 1, no. 1, 149–163, doi: 10.1109/JMW.2020.3034475, 2021.
- Köhler, M.; Hasch, J.; Blöcher, H.-L.; Schmidt, L.-P.: Feasibility of automotive radar at frequencies beyond 100 GHz, *International Journal of Microwave and Wireless Technologies*, vol. 5, no. 1, 49–54. doi: 10.1017/S175907871200075X, 2013.

Diewald, A.; Kurz, C.; Kannan, P. V.; Gießler, M.; Pauli, M.; Göttel, B.; Kayser, T.; Gauterin, F.; Zwick, T.: Radar Target Simulation for Vehicle-in-the-Loop Testing, *Vehicles*, vol. 3, no. 2, 257–271. doi: 10.3390/vehicles3020016, 2021.

Jebramcik, J.; Rolfes, I.; Pohl, N.; Barowski, J.: Millimeterwave Radar Systems for In-Line Thickness Monitoring in Pipe Extrusion Production Lines, *IEEE Sensors Letters*, vol. 4, no. 5, 1–4, doi: 10.1109/LENS.2020.2991778, 2020.

Kueppers, S.; Jaeschke, T.; Pohl, N.; Barowski, J.: Versatile 126–182 GHz UWB D-Band FMCW Radar for Industrial and Scientific Applications, *IEEE Sensors Letters*, vol. 6, no. 1, 1–4, doi: 10.1109/LENS.2021.3130709, 2022.

Giroto de Oliveira, L.; Nuss, B.; Alabd, M. B.; Diewald, A.; Pauli, M.; Zwick, T.: Joint Radar-Communication Systems: Modulation Schemes and System Design, *IEEE Transactions on Microwave Theory and Techniques*, vol. 70, no. 3, 1521–1551, doi: 10.1109/TMTT.2021.3126887, 2022.

Shatov, V.; Nuss, B.; Schieler, S.; Bishoyi, P. K.; Wimmer, L.; Lübke, M.; Keshtiarast, N.; Fischer, C.; Lindenschmitt, D.; Geiger, B.; Thomä, R.; Felan, A.; Schmalen, L.; Petrova, M.; Schotten, H.D.; Franchi, N.: Joint Radar and Communications: Architectures, Use Cases, Aspects of Radio Access, Signal Processing, and Hardware, *IEEE Access*, vol. 12, 47888–47914, doi: 10.1109/ACCESS.2024.3383771, 2024.

3 Chemical and Biochemical Measurands

(Sauerwald, T.; Kaiser, U.)

The measurement of chemical parameters has its particular challenges:

- the extremely large number of potential measurands, ranging from small to complex biochemical molecules at very different concentration level, leading to very different operating principles in gas sensing devices
- the complex interactions between various measurands and with the fluid matrix requiring an extensive knowledge of the application itself to meet requirements to achieve a specific reading for each measurand
- In addition, the principle requires very direct access to the measuring environment, which is why encapsulation of the systems is particularly important for stability.

Even though methods and numerous ways of tackling applications are correspondingly diverse, we would like to provide an overview of the most important trends, both technology- and application-driven, in highlights and as comprehensive as possible. The trends include new sensor technology such as miniaturization and increased integration in gas sensor systems like metal oxide semiconductor sensors or integrated photoacoustic sensors, which are driven by new applications in the fields of comfort, health and prevention of air pollutants. Moreover, it can be seen that the gap between chemical analytics and chemosensor systems is closing as more and more miniaturized analytical systems are developed which are suitable for stand-alone systems or even process monitoring. In many cases, the focus is on concepts with which expensive or problematic components can be avoided, such as high performing ion mobility spectrometers that challenge more complex systems than mass spectrometers without high vacuum, or the elimination of radioactive sources for ionization, e.g., in electron capture detectors. In other areas, such as laser spectroscopy, the focus is on increasing the versatility of miniaturized components like quantum cascade lasers, allowing for easier application optimization as well as new high-resolution

concepts (frequency combs). In the field of liquid sensing, trends in the fields of functionalization of existing measurement principles such as special electrode coating of ISFETs are driven towards applications in medical measurement technology and the measurement of biochemicals in general. In medical applications, the interaction with other sensor modalities is also particularly important in order to be able to view this complex condition multimodally. The measurement of particles in fluids and gases continues to be of great importance. Even if this is often not so much a chemical measurand in the narrow sense, the monitoring of particles plays a central role in the quality of the matrix fluid, most of all in air quality. In addition to the use of new or miniaturized sensor concepts, developments in process measurement technology are characterized by special requirements for reliability and durability. Sensor process interfaces therefore play just as important a role as self-X concepts.

3.1 Gas Sensing

(Schütze, A.; Meyer, C.)

In the previous decade, there has been a great deal of research into sensor technology for gas measurement. Particular attention has been paid to technological innovations such as miniaturization, digitization, power reduction and price reduction. However, some technological gas sensor trends, such as a universal “electronic nose” to detect unknown gas species and concentrations in any environment, have not become a reality yet, despite extensive research in the field. This chapter will focus on sensor technologies and current trends, with analytical methods being mentioned only briefly. However, some convergence is evident, from one side, by making analytical methods portable and more robust to allow their use also outside of laboratories or, from on the other side, improving the performance of sensor systems to achieve detection limits and selectivity comparable to analytical methods, at least for some specific applications.

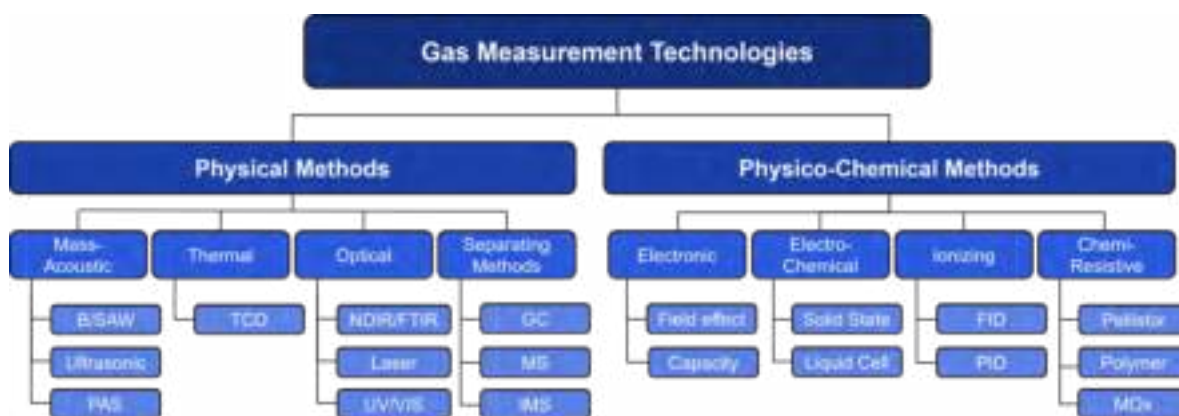


Figure 3.1 Overview of Gas Measurement Technologies (not exhaustive)

Due to the heterogeneity of the chemical measurands and the high number of use cases and applications, there is a great variety of sensors and instrumentation (see Figure 3.1).

- thermal conductivity detectors (TCD) for H₂ and (recently announced) for CO₂ detection
- non-dispersive infrared (NDIR) for CO₂ and gas leakage detection
- electrochemical cells (EC) using a solid electrolyte (e.g. Lambda-Probe for detection of Hydrocarbons) or liquid electrolyte (e.g. smoke detectors for CO)
- metal oxide semiconductor sensors (MOx) for TVOC (Total Volatile Organic Compounds)
- photoionization detectors (PID) for TVOC
- pellistors for explosive gas detection

Depending on their size and complexity, the instruments presented can also be classified as portable or stationary. The demand for inexpensive, miniaturized, portable, and highly sensitive sensors is driving current industrial sensor development.

Digitalization and miniaturization often go hand in hand, as advances in microelectronics mean that MEMS-based sensors with application-specific integrated circuits (ASICs) are smaller than ever before and can be manufactured in large quantities (see Chapters 4 and 5). These sensors contain all the necessary electronic components for signal processing, control, and communication (e.g. I2C, UART, SPI), and the

complete sensor algorithm is often also integrated as firmware, so that a processed signal, e.g., a gas concentration, is made available to the user. Microelectronic production means that the structural sizes of the components are very small, resulting in low power requirements down to the microwatt range. In addition, the very high volume of semiconductor production has led to a dramatic drop in the price of gas sensors in recent years.

These trends from the last years have enabled new devices for a wide range of gas sensor applications, from portable devices for personal use to embedded sensor systems in industrial plants. Some technologies, such as pellistors and EC cells, have been well established for a long time on the market, which is why many devices show limited technological innovation. But there are newcomers in the gas sensor field such as MEMS-based photoacoustic sensors (PAS) and also thermal conductance detectors (TCD) for detection of CO₂ or fully solid-state electrochemical gas sensors manufactured with MEMS technologies [MECS 2024]. Whereas in the early days of gas sensing, there was always research into new technologies, today, the focus is much more on optimization of existing technologies with the use of modern materials.

Current Trends in Gas Sensor Materials

New materials are steadily being proposed and qualified for gas measurement to improve the primary interface between gas phase and transducers. This interface is of course the main contributor to achieving the overarching “3S” – sensitivity, selectivity, and stability. Carbon nanotubes (CNT) and other forms of nanowires have

been studied for more than 20 years due to their promise of a high surface-to-volume ratio and, thus, expected high sensitivity [Han et al. 2019]. This was expanded to graphene and other 2D materials, basically with the same argument that the large surface should offer a high gas sensitivity [Nag et al. 2018]. Not all of these expectations really stand the test of commercial applications, which often place a higher premium on the third “S”, i.e., stability. Another novel material class are metal organic frameworks (MOF), which is a 3D material and can be tailored to optimize the absorption of gas molecules, allowing mass-sensitive devices, improved gas sampling, and integrated sensor-pre-concentrator systems [Leidinger et al. 2016]. In many cases, authors propose these materials for room temperature (RT) sensing, primarily to reduce the power consumption for IoT devices compared to metal oxide sensors. Again, while this has been extensively studied in academia, practical applications of RT sensing are scarce, because the low-power benefit also incurs several drawbacks such as susceptibility to condensation, slow response and recovery times or even irreversible operation, as gas molecules with high absorption energies will never desorb at room temperature. Trying to combine selectivity with RT operation tends to make matters worse as selectivity requires high adsorption energy for the target molecules compared to interferents, thus leading to very slow recovery or irreversible reaction, similar to biosensors with their very specific binding which are typically only used as disposables.

Key Applications as Technological Drivers

While traditionally, the focus of air quality monitoring was on regulated outside air, this has recently shifted towards indoor air quality (IAQ) for two reasons. Ventilation is the main driver for power consumption in buildings, but reducing ventilation rates also reduces IAQ, with the twin aspect of comfort and health. An optimal compromise can be reached via demand-controlled ventilation which requires sensors for continuous monitoring of IAQ. The COVID-19 pandemic in 2020 has further increased the focus on IAQ for monitoring not only pollutants, but also aerosols to estimate the virus load in the air, as PM sensors today are not sensitive enough and, again, CO₂ is used as proxy. These

days, many schools are equipped with CO₂ sensor systems to indicate the need for ventilation such as opening windows. In the long term, health will be the main driver for IAQ monitoring: more than 300,000 premature deaths were caused by air pollution in the 27 EU Member States in 2020 [European Environment Agency 2022] and studies suggest that about half of the total burden of disease is caused by indoor air. While outdoor air quality is strictly regulated and actually continuously improving for most pollutants, the importance of IAQ is rising due to unregulated indoor pollution sources (from building materials and furniture, but also human activities like cleaning and cooking) and the increasing amount of time spent indoors combined with improved insulation and reduced ventilation rates to save energy. Different environmental parameters are associated with IAQ. Today, high concentrations of carbon dioxide (CO₂) are often considered as primary indicator for IAQ, but the sum of all volatile organic compounds “TVOC” (note, however, that different definitions exist in different communities [Salthammer 2022]), oxidizing gases such as ozone (O₃) and nitrogen dioxide (NO₂) mainly from outside sources, as well as particulate matter (PM_{2.5}), are also relevant for comprehensive IAQ monitoring. Especially VOC have a negative impact on human productivity, causing effects such as dizziness, weakness, shortness of breath and, in the long term, cardiovascular diseases and cancer. Depending on the country and its legislation, there are variations in the maximum level of each gas that can be present in what is considered “good air”. IAQ monitoring is expected to be the next huge market for gas sensors integrated in IoT devices like smart speakers, smart thermostats, routers, office equipment, or even in smartphones and wearables [Sauerwald and Schütze 2020; Product links 2024] and thus currently the main driver for technological development.

Outdoor air quality monitoring is also expected to grow in the context of smart, green cities with dense low-cost sensor networks allowing new solutions like online traffic management to optimize the air quality or pedestrian and bicycle navigation to minimize pollution exposure. Another long-term target for air quality monitoring are portable devices for personal exposure monitoring that provide feedback for the users

and also allow a more in-depth understanding of causes and effects of air pollution, both outdoors and indoors.

Further new drivers are also connected to sustainable development: the Leak Detection and Repair (LDAR) regulations [EU Methane Regulations 2024] proposed by the EU commission target methane emissions in the energy sector to limit the uncontrolled emission of the highly potent greenhouse gas. Similarly, novel hydrogen (H₂) sensors to detect small leaks would be required to improve the efficiency of hydrogen as energy source. Compared to existing safety sensors which monitor the lower explosion limit (approx. 4 %), much lower detection limits in the low ppm range and excellent selectivity are required to limit losses in a hydrogen energy system.

Another push for gas sensors is expected in the field of life sciences, both for health monitoring in breath (e.g., acetone, hydrogen or nitric oxide for metabolic activity or asthma monitoring) and reducing food waste by indicating food freshness. The ultimate goal for health applications would be detection of cancer from breath or urine/feces, i.e., regular screening of the population to allow early treatment, which is today still elusive – not least because target substance patterns for trace gases have not been identified.

A final driver for new gas sensors are Instrumental Odour Monitoring Systems (IOMS), i.e., sensor systems mimicking the elusive human sense of smell. While so-called “electronic noses” were often simple chemical sensor systems, this new approach focuses on human sensing as the reference for odor. Potential applications for IOMS are food monitoring for quality/freshness and edibility, air quality monitoring, especially around industrial plants, wastewater treatment and others to provide an objective assessment of the nuisance for residents, and finally quality control of recycled materials. While first solutions are available for assessment of recycled polymers for car interiors, more research is required to enable the use of recycled materials in food packaging and similar applications.

Considering the complexity of many gas sensor applications – not only defined by low concen-

trations and complex mixtures of target molecules, but even more by the challenging matrix where interferent molecules often occur at much higher concentrations than the target compounds –, single sensors, however perfect, will suffice only in few specific cases. Thus, multi-sensor systems making use of complementary technologies (“multimodal sensing”) combined with advanced data analysis (“sensor fusion”) are required [Marco et al. 2012]. Currently, research efforts are often directed at improving the performance of artificial intelligence (AI) and machine learning models under well-controlled lab conditions, but to achieve an impact for practical applications in the future, these approaches need to be transferred from the lab to real-world scenarios. This poses two challenges: (i) more robust and transparent models (“explainable AI”) and (ii) a greatly improved calibration which takes complex interferences into account, eventually using event detection and context awareness to help interpret the measured gas composition. Novel approaches such as randomized calibration [Baur et al., 2020] have proven to achieve gas sensor systems with a performance comparable to analytical measurements, but still with full real-time capabilities [Baur et al., 2021]. Finally, calibration methods have to be adapted for mass production to still offer low-cost solutions, i.e., by using transfer learning requiring only a few training points for each individual sensor [Robin et al., 2023].

Trends in Qualification and Standardization

Qualification is relevant to ensure a long lifetime, with up to 15 years expected for some gas sensors. There are several tests, and each sensor manufacturer handles qualification differently for their sensor products. For example, the electrical performance of the sensor can be qualified using JEDEC, AEC-Q and other standards by stressing the sensor to temperature, humidity, mechanical stress, and electrical voltage. Another way to simulate lifetime is to ensure robustness against poisoning gases. For example, sulphur and silicon-containing siloxanes are known to have the potential to passivate gas-sensitive layers. In this case, accelerated lifetime testing means stressing the sensor with an arti-

ficially high gas concentration to simulate long-term exposure in a short time frame.

Due to the toxic nature of some gases, strict regulations are in place. For example, nitrogen dioxide concentrations have been drastically reduced in recent years to ensure a low risk of exposure. Guidelines and limits for individual gases are set by national or international authorities; well-known international organizations including the World Health Organization (WHO), the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), or the California Energy Code (Title-24). However, when it comes to classifying “good indoor air” by combining multiple parameters and gases, there is no universal standard for IAQ available yet. Until a decade ago, governmental agencies (e.g., the German Federal Environmental Agency) led this effort, but in recent years, many industry-driven organizations (RESET, WELL, HVI, SEMI, etc.) have taken on this responsibility and are promoting human well-being according to their own defined IAQ standard. In addition, the question of how to evaluate air quality sensors remains open, and there is no universal standard for comparing different technologies and sensor manufacturers. In early 2024, a draft of a first VOC detector test instruction was published by the VDI, which gathers best practice information from industry, sensor companies and academia, and aims to become an ISO standard within the next few years [VDI Germany, 2024].

In summary, gas sensors and even more gas measurement systems are a highly interdisciplinary field with diverse challenges:

- basic understanding of target gases and interferences
- chemical and physical effects for sensing
- materials science for chemical interaction
- MEMS technologies for integration of sensor components
- semiconductor industry for scaling to serve low-cost, high-volume applications

- data analysis including physical and data-based modelling as well as algorithm development
- calibration and testing

The complexity of various target applications necessitates application-specific solutions, so that often very different sensor technologies are required for the same target, depending on the concentration range and the gas matrix as well as the expected lifetime and cost of the solutions. Some applications have the added complexity that the target is not actually unequivocal: in fire detection, the gases indicating a fire are highly variable depending on the type of fire. Similarly, human breath analysis shows great variation depending not only on the person, but also their nutrition and general behavior. Novel applications therefore also need to be adaptive to their environment, which might include the data analysis; i.e., an IAQ sensor first learns typical ambient patterns before being able to classify situations and quantify pollutants reliably. The potential for gas sensors is huge, and sometimes it seems that too much is promised knowing that end users are hardly ever able to validate results of chemical sensors. However, to seriously address potential applications, both researchers and developers should take care or consider not to oversell their results and solutions.

3.2 Ion mobility spectrometry

(Zimmermann, S.; Kirk, A.)

Ion mobility spectrometers (IMS) should always be considered as a promising alternative to classical sensors, sensor arrays and other techniques when the application requires low instrumental effort but very fast and selective detection of compounds present in gases and liquids even at lowest concentrations down to ppt levels.

At a glance, IMS separate ions based on their specific motion through a neutral gas under the influence of an electric field. Thus, separation depends on the collision properties between ions and neutral gas molecules. Since IMS usually operate at ambient pressure, IMS can be easily coupled to atmospheric pressure chemical ionization sources with extremely high ioni-

zation rates, allowing for limits of detection in the low ppt range within one second of measuring time. Furthermore, since separation is based on the physical structure of ions, IMS offer separation in another dimension orthogonal to gas chromatography and mass spectrometry on a millisecond timescale.

The above-mentioned features have led to the widespread use of IMS for detecting chemical warfare agents, explosives, drugs and toxic industrial compounds [Eiceman et al. 2004; Borsdorf et al. 2006; Mäkinen et al. 2011; Buryakov 2011; Puton et al. 2016]. A detailed description of ion mobility spectrometry and different embodiments, such as drift time IMS (DTIMS), trapped IMS (TIMS), traveling wave IMS (TWIMS), field asymmetric IMS (FAIMS), differential mobility spectrometers (DMS) and structures of lossless ion manipulation (SLIM) can be found in the literature [Eiceman et al., 2013; Webb et al. 2014; Michelmann et al. 2015; Ridgeway et al. 2018]. Often coupled with gas chromatography, IMS are suitable for the analysis of highly complex samples, for example in the quality control of food and beverages [Karpas 2013; Hernández Mesa et al. 2017], and pharmaceuticals [O'Donnell et al. 2008; Campuzano et al. 2018], as well as in medical applications [Allers et al. 2016; Drees et al. 2019]. IMS can be also found in more analytical tasks, especially bioanalytical applications [Bohrer et al. 2008; Uetrecht et al. 2010; Zhong et al. 2012; Konijnenberg et al. 2013]. European manufacturers of stand-alone IMS and GC-IMS include Airsense, Bruker, Environics, G.A.S., ION-GAS, MaSaTECH, Olfactomics, Owlstone, Smiths Detection and STEP.

Today's research in IMS instrumentation mainly concentrates on the development of cost-effective manufacturing methods and further reduction of instrumental size [Ahrens et al. 2022; Bohnhorst et al. 2021; Ahrens et al. 2020; Ahrens et al. 2019], dual IMS for simultaneous detection of both ion polarities [Hitzemann et al. 2022; Lippmann et al. 2020], improving sensitivity [Kirk et al. 2022; Kirk et al., 2020] and highest resolving power even with compact instruments (Kirk et al., 2019; Kirk et al., 2017; Kirk et al., 2015). This includes new ideas for improved compound identification by field-induced fragmentation at ambient pressure and

use of the differential ion mobility, which relates to the ion specific field dependence of ion mobility [Bohnhorst et al. 2023; Bohnhorst et al. 2019; Bohnhorst et al., 2018].

The issue of competing ionization processes and cluster reactions is tackled by a new IMS concept that operates at pressures from 10 to 40 mbar instead of ambient pressure to reach high electrical fields in the reaction region and drift region while still being compact in size [Schaefer et al. 2023; Allers et al. 2022; Langejuergen et al., 2014]. This allows for kinetically controlled ionization and targeted manipulation of reactant ions, significantly increasing the spectrum of detectable compounds and minimizing chemical cross sensitivities during ionization including the effect of sample humidity on sensitivity. Furthermore, the differential ion mobility can be directly measured and used as a second dimension of separation for reliable compound identification.

Finally, non-radioactive ionization sources are increasingly removing radioactive sources that are still used in ion mobility spectrometry. Such non-radioactive ionization sources are often based on corona discharge, dielectric barrier discharge, cold plasma, high energetic photons, and UV radiation. With electrospray ionization, liquids can be analyzed [Thoben et al. 2021]. Recently, advances have been made in coupling droplet microfluidics and chip-based electro chromatography as well as high performance liquid chromatography with IMS [Hartner et al. 2021; Hartner et al. 2020; Piendl et al. 2019]. In addition, IMS provide a second dimension of separation in gas chromatography (GC) and mass spectrometry. GC-IMS are of particular interest when thinking of compact [Langejuergen et al., 2015] and even hand-held devices [Ahrens et al. 2021] for analyzing more complex samples.

Figure 3.2 shows a low-cost, high-performance DTIMS made from printed circuit boards with high resolving power of $R = 60$ and detection limits in the low ppt range within one second of measuring time but short drift length of just 40 mm [Bohnhorst et al., 2021].



Figure 3.2 Low-cost, high-performance DTIMS made from printed circuit boards with high resolving power of $R = 60$ and detection limits in the low ppt range within one second of measuring time but short drift length of just 40 mm. (Source: Alexander Bohnhorst)

3.3 Non-radioactive Electron Capture Detector

(Zimmermann, S.; Küddelsmann, M.)

The use of electron capture detectors (ECD) in gas chromatography (GC) is still the best choice for extremely sensitive, linear and fast analysis of many environmental pollutants, halogenated compounds and other electron-affine substances [Pellizzari 1974]. Therefore, ECDs have become one of the standard detectors in food and environmental analysis since the 1960s. As a prominent example, GC-ECDs have been an important key technology in studying man-made halocarbon emissions [Lovelock 1971; Lovelock et al. 1973] and were fundamental to the research on ozone depletion that earned F.S. Rowland, M. Molina and P. Crutzen the Nobel Prize in Chemistry in 1995.

Today, due to the high sensitivity to fluorinated compounds, ECDs can also contribute to the challenging analysis of PFAS in the context of the recently tightened EU regulations [Belisle and Hagen 1980; Koch et al. 2020; Namazkar et al. 2024]. However, ECDs have not only made us aware of the increasing global extent of pollution, they also play a valuable role in medicine [Kaiser and Martin 1978; Hamann and McAllister 1983], pharma [Ho et al. 2014; Kavrentzos et al. 2024], food flavor analysis [Zgherea et al. 2011] and detecting explosives [Collin et al. 2006].

The principle of an ECD is based on measuring free electrons in the gas phase, generated by ionizing nitrogen or argon. Through electron capture reactions with an electron-affine substance, the number of free electrons decreases as a function of the substance concentration. The remaining electrons are separated from negatively charged ions and guided towards a detector by short voltage pulses. An essential enhancement for the outstanding sensitivity and linearity of current ECDs is the so-called constant current mode [Maggs et al. 1971]. This mode maintains a constant electron current by varying the pulse frequency. This mitigates non-linear saturation effects due to electron depletion, resulting in a linear relationship between pulse frequency and analyte concentration. By using this operation principle, commercial ECDs can achieve detection limits in the low fg/ml or ppt range with a linear range of up to four orders of magnitude [E13 Committee 2011]. Additionally, most ECDs offer short response times due to their small detector volumes (e.g., Agilent μ ECD) and high temperature capability of up to 400 °C.

However, besides all the advantages, ECDs suffer from one major disadvantage: classical ECDs require a radioactive ionization source. Currently, the largest suppliers of analytical instruments, such as Agilent, Thermo Fisher Scientific, PerkinElmer, and Shimadzu, equip their GCs with radioactive ECDs, as cost efficient and performant alternatives do not exist yet. However, the radioactivity implies considering legal restrictions and safety-related requirements when purchasing, using, storing, shipping and disposing of radioactive ECDs. Additionally, depending on the activity and emitter classification, a trained radiation protection officer (RPO) and even regular wipe tests may be necessary. Furthermore, if radioactive ECDs become contaminated, the analytical performance decreases and the device must be cleaned by a specialist or even disposed of.

Several investigations have been conducted on non-radioactive electron sources, such as photoelectron sources [Simmonds 1987], photoionization sources [Wentworth et al. 1975] or high-energy electron sources [Bunert et al. 2019], which can provide free electrons for ECDs. However, only the helium plasma-based ECD

has gained further commercial attention as a non-radioactive alternative [Cai et al. 1996]. The Pulsed Discharge Detector from Vici Valco Instruments is based on a helium plasma, which generates ultra-violet light for the photoionization of an additional dopant in the carrier gas. Although the limits of detection and linearity of the Pulsed Discharge Detector are comparable to radioactive ECDs, it has not yet replaced radioactive ECDs to a significant extent. This is likely due to the dopant and the requirement for highly pure helium.

Current research is focused on the use of high energy photon sources for direct ionization of the carrier gas, similar to radioactive ECDs [Kueddelsmann et al. 2022; Bunert et al. 2023]. Such high-energy photon sources with a maximum acceleration voltage below 5 kV typically do not require approval, have a small form factor, are temperature stable up to 400 °C and can maintain constant ionization intensity for several years. If contaminated, easy cleaning is possible. Recent publications demonstrate outstanding results of an “X-ECD” equipped with a high energy photon source in terms of sensitivity, linearity, and response time [Kueddelsmann et al., 2022; Kueddelsmann et al., 2023].



Figure 3.3 Non-radioactive X-ECD based on a high energy photon source not bound to any regulatory restrictions and manufactured at low cost from printed circuit boards with detection limits in the lower ppt range and a linear range of up to four orders of magnitude. (Source: Maximilian Küddelsmann)

Current developments are focused on much higher operation temperatures, which is an es-

sential step towards becoming a potential competitor to radioactive ECDs. A promising concept could be the use of high-temperature stable printed circuit boards (PCBs) based on ceramic material for low cost, easy manufacture and compact design. A first demonstrator based on standard FR-4 PCBs is shown in Figure 3.3.

3.4 Laser Spectroscopy

(Wöllenstein, J.)

Detecting and determining the composition of gases plays a very important role in industry, safety engineering and environmental analysis. On the one hand, gaseous hazardous substances must be monitored in highly complex and often very extensive chemical plants. Toxic or explosive gases must be detected reliably and quickly at trace levels. On the other hand, in process analysis and environmental analysis, the composition of gas mixtures must be monitored with high accuracy in real time, either online or inline.

Online and inline sensors are required to provide information on the composition of chemical process and product qualities and reaction processes. Optical spectroscopic measuring systems that work without media contact offer major advantages here.

They often do not require time-consuming sampling and also offer advantages in terms of calibration and maintenance.

The most used and advanced technology is near-infrared (NIR) spectroscopy. Mid-infrared (MIR) and Raman spectroscopy are considered to have a particularly high potential for the future due to significant progress in component development. Optical developments, particularly in laser technology, are a technological boost for laser spectroscopy.

The increasing availability of cost-effective, narrow-band and powerful laser light sources for Raman spectroscopy is a key element. Another is the development of narrow-band notch and edge filters with very high suppression of the excitation radiation. Together with the development of cost-effective and powerful spectrometers (also for the infrared range up to a wavelength of around 2.2 µm), this will lead to a

rapid increase in the use of Raman spectroscopy for process applications.

The technological push was particularly strong for MIR laser sources: before the first development of quantum cascade lasers (QCL) in 1994 [Faist, J. et al. 1994], there were no compact semiconductor laser sources for operation at room temperature.

Since 2003, the first single-mode distributed feedback (DFB) QCL lasers with continuous wave operation at room temperature have been available [Aellen et al. 2003]. These lasers are now available from various manufacturers for the wavelength range of 4.3 μm to 10.6 μm . The development of interband cascade lasers (ICL), which now cover the wavelength range from 3 to 6 μm and are commercially available, has been equally rapid [Nanoplus 2005]. Due to the small tuning range of the DFB lasers of only a few wavenumbers, they were originally only of interest for the analysis of gases with narrow absorption lines.

The development of widely tunable QCLs with an external resonator (EC-QCL) has made it possible to sweep up to 1000 cm^{-1} . These powerful light sources can now be used for numerous applications of classical spectrometers.

Particularly with samples that absorb strongly in the MIR, such as liquids containing water, the high spectral power of the laser source enables measurements that are hardly possible with the thermal emitters generally used in spectrometers [Luedeke et. al. 2011].

With increasing laser power, non-linear optical methods are also gaining importance. Widely tuneable laser light sources for many wavelength ranges based on optical parametric oscillators are now commercially available.

Three applications from the field of gas analysis are shown below, which illustrate the application potential of new optical components and approaches. These are the threat-based remote detection of gas leaks, the use of quantum cascade laser-based spectrometers for agricultural applications, and double-frequency comb spectroscopy.

Airborne Remote Detection of Combustible Gases

Remote airborne gas detection is needed to detect gas leaks. When inspecting natural gas infrastructures, professional providers are moving towards using laser-based gas detection devices on drones to inspect gas pipe networks, as this allows more kilometers of pipe to be inspected in less time than the current practice of walking the pipes. Outside Germany, for example, these devices are regularly used to fly over natural gas pipelines laid underground for gas leak detection [Luedeke et. al. 2011].

Remote gas detection is essential for the field of application outlined above. In practice, remote gas detection can be implemented using tunable laser spectroscopy (TLS for short) [Wenke 2023].

There are passive gas cameras and sensitive hand-held measuring devices for optical methane detection [Kwaśny et. al 2023], particularly for natural gas leak detection applications. Gas cameras [FTIR] are actively cooled thermal imaging cameras with a gas-specific spectral filter that make gas absorption visible against a warm background radiation. Due to the high cost of a gas camera, there is a high threshold for the purchase and thus also for the spread of this measurement technology. Hand-held laser measuring devices are easy to use: the device is pointed at a target that can be aimed at using a visible pilot laser and the gas concentration is measured in $\text{ppm} \cdot \text{m}$. This measuring technique has a range of up to 100 m. Unfortunately, however, the greater the distance to the target, the greater the measurement uncertainty, and the position at which the laser beam passes through a gas cloud remains unknown.

The solution to this problem is remote detection by a drone (UAV) that flies over the pipeline and measures the gas concentration from above (see Figure 3.4). The laser beam is aimed vertically at the ground, and the position of the drone can then be used to localize the gas concentration on the ground. Laser-based measuring devices that can work on a drone are already available on the market for leak detection on natural gas infrastructure [Barchyn et al. 2017]. Measuring systems for the remote de-

tection of propane, on the other hand, are not available on the market. The laser wavelength for methane detection of commercial devices is usually in the near-infrared (NIR) harmonic spectral range at 1.65 μm . This wavelength range is unfavorable for propane gas detection because the absorption of propane in the NIR is very weak. The mid-infrared spectral range (MIR) offers strong absorption lines for both methane and propane and is therefore selected as the spectral working range. The advantages of the new spectral working range are “two gases with one measuring device” and a high sensitivity due to up to one hundred times greater absorption of the two gases in the MIR compared to the NIR.

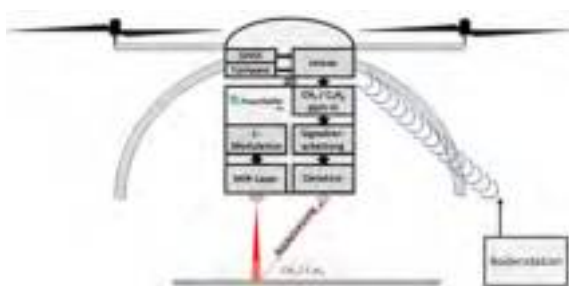


Figure 3.4: Concept of the gas measurement system on the UAV

The concept for an example of a drone-compatible gas detection system is shown in Figure 3.4. The opto-mechanics are designed as a cage system, which is light and stable. The walls and rods are made of carbon, the planes for the laser, detector, lens, and cover are made of aluminum. The cage system enables a high degree of parallelism of these planes and at the same time flexibility in the distance in order to position the detector precisely in the lens focus, for example. The challenge of the opto-mechanics lies in the requirement for parallelism of the two optical axes of the laser and receiver optics. The laser optics collimate the laser with a small divergence so that the beam diameter after 10 m is just a few centimeters. The alignment of the laser beam must be highly accurate so that the detection area of the receiving optics is hit. After 10 m, this is an area of 13 cm $\times$ 13 cm, which means that the angular error in the parallelism of the optical axes must be less than 0.38°.

The optical power of the collimated ICL at the operating point for 2,968 cm^{-1} is approximately 5 mW (ICL from nanoplus). The laser tempera-

ture is set to either 23 °C or 27 °C for spectral matching between the methane and propane application. The beam is aligned using a compact kinematic holder, which is adjusted to the detection area. An uncooled (mercury-cadmium-telluride (MCT)-based IR quantum detector with a 1 mm $\times$ 1 mm area (PVI-3.4 from Vigo-Systems) is used to detect the backscattered laser radiation. The high detectivity of 4 $\times$ 1,010 $\text{cm}^2/\text{Hz} \cdot \text{W}$ makes it possible to detect low optical power even without active cooling of the detector element. This is an important aspect, as the electrical power consumption can be kept low without thermo-electrical cooling.

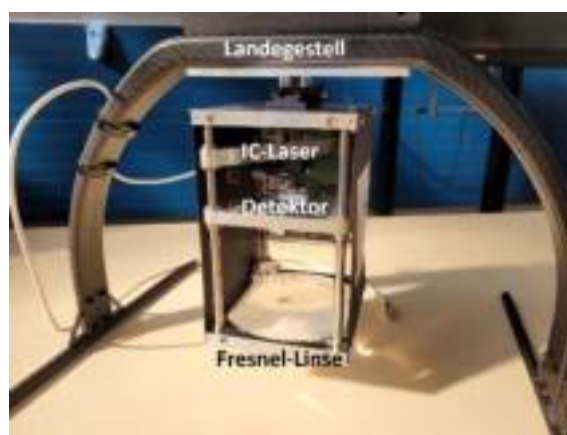


Figure 3.5: Photo of the measuring system on the UAV's landing gear. The measuring system has three levels. The receiving optics through a Fresnel lens, the detector level with an infrared detector, and the interband cascade laser with an emission wavelength of 3369 nm

The entire electronics for laser control, data acquisition and communication have been designed so that the measuring system can be operated with less than 2 W via the 5 V USB power supply (Figure 3.5). The dimensions of the circuit board are 5 cm $\times$ 8 cm. The sawtooth modulation of the laser emission wavelength of 120 Hz and a sampling rate of 1,000 points per period result in a sampling rate of 120 kB/s with an ADC resolution of 16 bit. This data volume is processed with the firmware of the evaluation algorithm on a small microcontroller (PSoC 63 Dual Core). The concentration value frequency of approximately 4 Hz is achieved through the number of curve averages (e.g. 32 $\times$).

These values are sent during the flight via the drone together with the GPS position to a ground station. The gas concentration in the

flight path is then displayed there using a color scale.

A portable laser spectroscopic system for measuring nitrous oxide emissions on fertilized cropland (Figure 3.6)

Nitrous oxide is a greenhouse gas that is released in large quantities in agriculture through fertilization. With a global warming potential about 273 times higher than that of CO₂ [EPA, US 2025]), nitrous oxide emissions make agriculture a sector with a major impact on climate change. When too much fertilizer is applied, it leads to excessive nitrate levels in the soil. The nitrate not needed by the plants is converted into nitrous oxide and released from the soil surface. In addition, the unconverted nitrate remains in the soil and leads to pollution of the soil and groundwater. The aim of conscious use of fertilizers is to apply only as much fertilizer as the plants need. This protects the environment and saves resources and money, while the benefit of fertilization, a high yield, is maintained.



Figure 3.6: The portable system on a corn field

Since 1990, there has been no discernible trend towards a reduction in N₂O emissions from agricultural soils in Europe. To achieve this goal, it is very important to have a clear understanding of the nitrogen cycles in the soil to know the relationships between fertilization, nutrient use by plants and N₂O emissions. To investigate these relationships, detailed studies on the local distribution of N₂O emission fluxes [Alberti et. al. 2013] on different agricultural areas depending on mapped data such as vegetation, soil composition and moisture must first be carried out.

This requires precise N₂O measurement systems. Once the nitrogen cycles are well under-

stood and precise measurement systems for N₂O emissions are available, needs-based fertilization can be significantly improved. However, the determination of N₂O emission fluxes is a difficult task, as only a small increase in N₂O concentration compared to a natural background of 333 ppb needs to be measured. Therefore, stable calibration and high instrument precision are required. This section presents the development and validation of a compact, mobile and fast laser spectroscopic system for measuring N₂O emission fluxes on-site on the ground and for easy handling in agricultural environments.

Systems that can measure N₂O in the concentration range relevant in agriculture are already available. One option for measuring N₂O is using a cavity ring-down spectrometer. The Picarro G5310 is able to measure N₂O with high precision [Picarro.com 2023]. However, this system is very expensive and, with a power consumption of 200 W, it is only designed for use in static installations and not for mobile platforms.

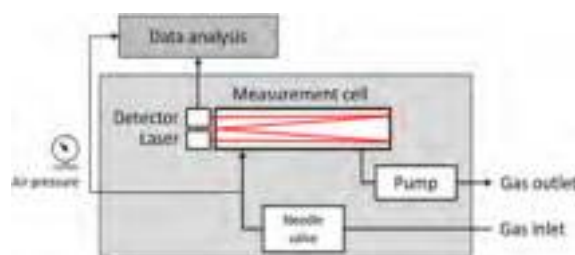


Figure 3.7: Schematic view of the portable measurement setup

Therefore, there is still a need for portable and economically viable N₂O measurement systems for agricultural research. This motivated us to develop the system described below, which measures N₂O using laser absorption spectroscopy in the MIR. The optical system is set up as shown schematically in Figure 3.7. It consists of a distributed feedback (DFB) laser with an emission wavelength of 4.5 μm, a multi-reflection long-path cell with an optical path length of 720 cm and a volume of 300 ml, and a three-stage thermoelectrically cooled MCT photodetector (Vigo System, S.A., Ożarów Mazowiecki, Poland). The peripheral devices include thermoelectrically cooled control electronics (Meerstetter Engineering GmbH, Rubigen, Switzerland) and an in-house development of the LDD con-

trol electronics. It was designed to control the absolute pressure in the long-travel cell to about 290 mbar. The pressure is measured with a built-in pressure sensor (MPL3115A2, NXT Semiconductors N.V., Eindhoven, Netherlands). The given pressure value is an empirical value that results from a compromise between maximizing the absorption signal of N_2O and minimizing line broadening effects, as indicated by simulations using the HITRAN database [Rothmann et al. 2013].

The first measurements in the field were carried out in a corn field near Schallstadt, south of Freiburg in Germany. The first step of the sampling procedure was to place the bell-shaped container with the top valve open to avoid overpressure that could impede N_2O diffusion from the soil below. After placement, the top valve was closed. This initial sampling step lasted five minutes. For data evaluation, the ambient air concentration is set to 333 ppb N_2O as a reference before each measurement. This reference value can be assumed to be approximately constant [Umweltbundesamt 2023].

A typical measurement curve is shown in Figure 3.8. The sample bags are measured alternately with laboratory air, which serves as a reference for the N_2O ambient concentration (333 ppb). Figure 3.8 shows the measured N_2O concentrations for three different measurement locations in the field. The increased N_2O concentration of the sample bags can be clearly seen. The first measurement point was recorded two days after fertilizer application, with no significant increase in the measured N_2O concentration. After six more days, a strong increase in concentration can be observed. Thereafter, the concentration decreases in the following measurements and approaches the reference concentration.

Frequency Combs

A variety of sensors based on different measuring principles are available to determine the concentration or to detect individual components of a gas mixture. Sensor systems that make use of the property of many gases to absorb light play a special role, as they have advantages in terms of response time, reduced drift behavior, and cross-sensitivity [Hodgkinson

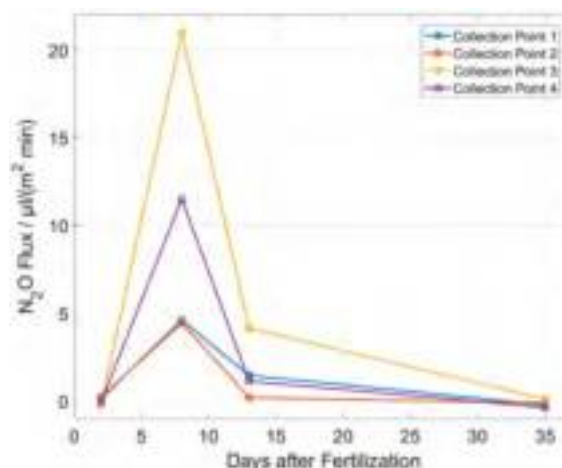


Figure 3.8: Measured nitrous oxide concentration for four different positions in a field as a function of the days since the last fertilization

et al. 2012]. The use of tunable lasers as a light source enables fast response times, high sensitivity and selectivity in the determination of individual gas components, while broadband light sources such as thermal emitters in combination with a Fourier transform spectrometer enable the parallel detection of many gas components. These two approaches to optical gas detection can be regarded as extremes in the parameter space with the dimension's spectral coverage – relevant for the detection of multiple components – and sensitivity – important for the detection of small traces of individual components. However, lasers are limited in their tuning range and spectrometers are limited in their spectral resolution and sensitivity, so that a gap opens in the middle of the parameter space of optical gas detectors.

Optical frequency combs represent a new approach to close this gap. Frequency combs span a broad spectral range of interest with many laser modes with a fixed and precisely known frequency spacing. They are therefore also known as optical rulers, and for their discovery and development, the Nobel Prize in Physics was awarded in 2005 to T. W. Hänsch and J. L. Hall [Hänsch 2005]. They are increasingly used for applications in the field of distance measurement, hyper-spectral imaging and spectroscopy [Udem et al. 1999].

The combination of two frequency combs [Schiller 2002] is of particular interest for spectroscopy. Frequency combs with slightly different mode spacing are superimposed so that

beats are generated from two assigned mode pairs of the lasers. The beats of different mode pairs have different frequencies, typically in the radio frequency range, and an interferogram is formed in analogy to Fourier transform spectroscopy. These interferograms can be measured using a single photodetector and the radio frequency spectrum can be calculated using a Fourier transform. Since the frequencies of the laser modes involved and thus also the beat frequencies are known, the optical spectrum can be derived from the radio frequency spectrum. The use of a classic spectrometer and the associated limitations in resolution can thus be avoided.

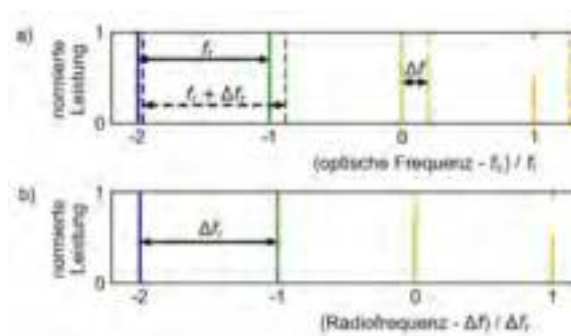


Figure 3.9: Exemplary representation of the spectrum of two frequency combs with five frequency comb modes

In Figure 3.9, the carrier frequency f_c of one frequency comb (solid lines) is offset by the amount Δf from the carrier frequency of the second frequency comb (dashed lines). The other modes of the frequency combs are symmetrical about the corresponding carrier frequencies and have different mode spacings f_r by Δf_r . Part b) shows the spectrum of the beats between the combs resulting from superposition. The beat frequencies between the closest optical frequencies from a) between two assigned frequency comb modes are shown. The beat frequencies are centred around a radio frequency carrier wave with frequency Δf and sort themselves symmetrically around it with a frequency spacing of Δf_r . Mode 1 shows an attenuated optical power, which results from absorption by a sample. This information is transferred to the radio frequency image using the second frequency comb [Nitzsche 2023].

An example is shown in [Nitzsche et al. 2021] in which this approach is used to generate electro-optical combs in the near infrared. In a second

step, the superimposed frequency combs are converted to the mid-infrared for tuning. In this way, a spectrometer is realized that enables flexible resolutions, spectral coverage and measuring ranges. The mid-infrared range from 3 μm to 5 μm is selected as the measurement range of interest, as all greenhouse gases and many other relevant gases exhibit strong and characteristic absorptions in this range. These methods were evaluated using measurements of a gas mixture containing nitrous oxide and carbon dioxide in the ppm range, and the performance of the spectrometer was quantified in terms of the linearity of the response behavior and the accuracy as a function of the integration time.

For this purpose, an additional laser tunable from 1,000 nm to 1,300 nm was set up as a pump for the conversion and resonantly boosted. This means that the double frequency combs can be provided in the spectral range from 3,000 nm to 4,700 nm without losing their flexibility. This is used for the detection of atmospheric concentrations (ppm to ppb) of the gases methane, nitrous oxide and carbon dioxide. The capability of the spectrometer for the simultaneous detection of two trace gases is demonstrated using an exemplary series of measurements of gas mixtures with diluted carbon monoxide and nitrous oxide components (ppm). The system shows a linear response behavior. With a 10-Hz update rate, the concentrations can be tracked with an accuracy of 6 % in the ppm range

In summary, laser-based techniques have now found their way into industrial measurement technology. With the help of lasers, solutions can often be found inline or online in the process for tasks that previously required time-consuming sampling or preparation and/or laboratory analysis.

Three examples from the field of gas analysis showed that this trend will continue in the future. The rapid development of laser light sources and passive optical components is enabling new measurement methods that will find their way into online and in-situ analysis.

3.5 Liquid Sensing

(Hild, O.R.)

The biochemical and chemical analysis of liquids continues to play a prominent role in sensor technology. Some examples of fields of application and challenges are described below.

Environmental Water Analysis

In the field of environmental analysis, agriculture and water management, the focus is on water analysis. The most important parameter here is and remains the pH value. It reveals how acidic or alkaline the water or soil is. Typical pH values are in the range of 5.5 to 8. However, depending on the soil conditions and plants, very acidic pH values in the range of 4 to 5.5 are also typical for moors.

Although ion-sensitive field effect transistors (ISFETs) have numerous advantages over glass electrodes, the latter continue to dominate pH analysis. The reasons for this are the preconceptions that ISFETs drift strongly, have a high sensitivity to light and are not CIP (Cleaning in Place, Cleaning in Process) stable. In fact, there are still challenges in this area. The minimization of drift is achieved by controlling the underlying transistor. Light sensitivity is solved by the ISFET chip structure and CIP stability by the sensor layer. Nevertheless, the technology is not easy to master, which is why there are only a few commercial ISFET manufacturers worldwide. The manufacturing effort is worthwhile, as ISFETs have the advantage that they are insensitive to breakage and have no problems with suspended particles. Optical methods are only suitable to a limited extent, as inherent coloration or turbidity of the sample can distort the result. ISFETs are outstanding for on-site measurements or continuous measurements as they are robust and, unlike glass electrodes, can also be stored dry. In Figure 3.10 A, a 5 mm × 5 mm ISFET, wire bonded to a ceramic support, is shown. To protect the edges of the chip as well as the contacts and bond wires, the chip is encapsulated with a chemically stable resist. This is shown in Figure 3.10 B. A large contact surface is required so that the chip can be well wetted by the analyte. The sensitive area and the chip can be made many times smaller for laboratory ap-

plications.

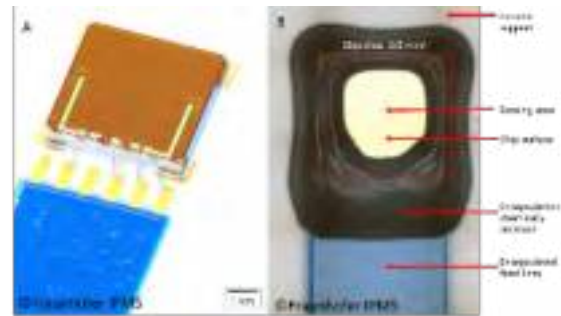


Figure 3.10: A: ISFET Chip die and wire bonded on a ceramic support. B: ISFET after encapsulation (Source: Lukas Lorenz, Fraunhofer IPMS)

Both ISFETs and glass electrodes require a reference electrode. A silver wire coated with silver chloride is also used as a reference electrode, which is connected to the measuring medium via a diaphragm in usually a 3 M KCl solution. Figure 3.11 shows the simplified combination of a conventional Ag/AgCl reference electrode with an ISFET.

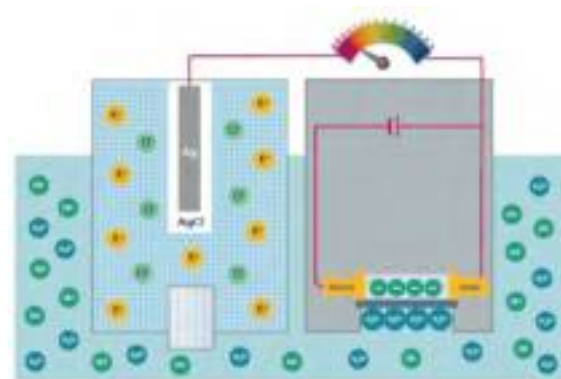


Figure 3.11: Simplified pH-Measurement set up with an ISFET and an Ag/AgCl reference electrode as two half-cells (Source: Laura Bayer, Fraunhofer IPMS)

Replacing these reference electrodes, also known as second-type electrodes, remains a major challenge. There are already numerous approaches to producing a solid-state reference electrode which, if of sufficient quality, would revolutionize pH measurement technology, because second-type electrodes are not free of material conversion, therefore have to be calibrated frequently and can hardly be miniaturized. Stable solid-state reference electrodes are the key to reproducible, long-term and miniaturizable measurements for many biological and chemical sensor applications. Current developments in this area include the use of conductive

polymers, in particular PEDOT:PSS and graphene oxide (GO) [Vu et al. 2022]. The challenges for future developments lie in controlling sensor and electrode drift, which should be less than 100 $\mu\text{V/h}$, and avoiding cross-sensitivities.

One driver for new developments is the increasing demand for continuous on-site measurements, which rely on energy-efficient, durable, robust and low-maintenance sensors. Rapidly changing environmental conditions lead to a great need for such sensors which can also be networked over long distances and whose measurement data can be easily linked with data from other sources. For example, the linking of pH value data from water monitoring can be combined with weather data in order to predict critical living conditions for fish.

In addition to pH value determination, quantitative ion detection is another key application in inorganic analysis and is therefore rightly the subject of intensive research. The measurement of ion concentrations is important, for example for assessing drinking water quality (e.g., nitrate, heavy metals), nutrient content in soil and water (e.g., nitrate, phosphate) or in biological sensors for measuring sodium or potassium concentrations in body fluids. There are numerous solutions for the quantitative determination of the relevant ions, some of which have already been commercialized. Ion-selective electrodes (ISE), which consist of an electrode with an electrolyte or a field-effect transistor combined with an ion-selective membrane, are well known. The membrane often consists of PVC with a plasticizer and the actual ion-selective component, an ionophore. Ionophores are usually complexing agents that selectively and reversibly bind certain ions, thereby making them measurable. The measurement can then be carried out, for example, as a change in the capacitance of an FET or as an ion concentration-dependent voltage measurement between an ISE and a reference electrode. New developments in this field include the development of 2D materials that enable improved selectivity and service life of the membranes.

Body Fluids as Analyte

In the field of biosensor technology, the analysis of body fluids continues to be highly relevant.

After the countless developments in COVID-19 detection provided a major boost to innovation, there are now high hopes of transferring the findings to other areas, such as cancer diagnostics. Promising technologies here include the connection of biomarkers to sensor surfaces. 2D materials such as graphene are seen as promising and will enable compact and selective biosensors and sensor arrays in the future. In particular, sensors worn on the body, either as life science or health products, are becoming increasingly important. There is still a need for research into component stability and reproducibility. One promising approach is the use of actively controllable sensors and sensor arrays as field-effect transistors.

One trend in chemical and biochemical analysis is therefore the use of 2D materials, in particular graphene and its derivatives. The fundamental problems of production and processing appear to have been solved thanks to research funding, for example through the EU Graphene Flagship [Xue et al. 2022; www.graphene-flagship.eu] Initiative, and the research results enable their use in sensor applications, among other things. Numerous applications and possible uses in liquid analysis for 2D materials could thus be investigated. The detection methods are based on the interaction of a functionalized 2D layer with the analyte. This can take place via antibodies, enzymes or nucleic acid sequences. The actual measurement is then carried out using a transducer, which usually works electrochemically or optically. This is followed by further signal processing, e.g., using amplifiers or subsequent calculations. These methods have been used to develop sensors that can selectively detect cancer biomarkers, for example for lung cancer [Kwon et al. 2022] or colorectal cancer, with a high hit probability.

Increasing antibiotic resistance is a constantly growing problem for mankind. Quantitative detection methods for on-site use are therefore becoming increasingly important. Flauzino et al. [Flauzino et al. 2023] have developed an antibiotic detection method based on a graphene derivative. In addition to graphene, another outstanding development, honored with the Nobel Prize for Carolyn Bertozzi, Barry Sharpless and Morten Meldal in 2022, is used: "Click chemistry". As a basic method, it enables a wide range

of applications for the development and production of selective sensors. Flauzino et al. used fluorophene chemistry to produce a graphene derivative equipped with alkyne groups and immobilized an aptamer on it, using click chemistry. This enables the selective determination of ampicillin in real samples. The electrochemical aptasensor showed a detection limit of 1.36 nM and also a high selectivity towards other antibiotics.

2D Sensor Materials and Application Examples

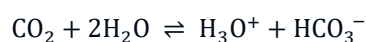
In addition to graphene, 2D materials based on MXenes are becoming increasingly important. By definition, MXenes have an $M_{n+1}X_nT_x$ structure, where M is a transition metal = Sc, Y, Ti, Zr, Hf, V, Nb, Ta, Cr, Mo, W, X is a carbon and/or nitrogen, T_x stands for surface terminations such as O, OH, F or Cl, and $n = (1...4)$. Transition metal carbides and nitrides are metallic conductors or semiconductors, often exhibit high hardness, a large surface area and excellent chemical stability. Examples are Ti_2C and Ta_4C_3 . The variety of electrical material properties combined with modifiable surfaces make this substance class attractive for sensory applications. MXenes are usually synthesized from MAX starting phases (A= Al, Si, or Ga) using multi-stage processes.

MXenes are used in glucose measurement. By modifying the surface of MXenes, enzymes can be immobilized, and biosensors can be produced that can measure glucose electrochemically. For example, Rakhi et al. [Rakhi et al. 2016] succeeded in developing an amperometric glucose biosensor with immobilized GOx on Nafion-soluble Au/MXene nanocomposite over a glassy carbon electrode (GCE) with a sensitivity of $4.2 \mu A \text{ mM}^{-1} \text{ cm}^{-2}$ and a detection limit of $5.9 \mu M$ in the linear concentration range of 0.1 mM to 18 mM. There are now numerous other material developments in this area, for example Selvi et al., who used MXenes in porous carbon-based Cu_2O nanocomposite ($Cu_2O/M/AC$) as a sensor material for the electrochemical measurement of glucose and achieved a limit of detection (LOD) of $1.96 \mu M$ (Selvi et al. 2024).

Cell-based Biosensors

In cell-based biosensors, living biological cells are used as sensitive sensor components. The use of cells enables the direct investigation of plants, humans and animals. A wide variety of cells can be examined. The use of organ-specific human cells thus enables person-specific diagnostics and may lead to personalized treatment options in the future.

Living cells have receptors that react to certain specific analytes. Graphene is an attractive substrate for cellular biosensors due to its surface modifiability. Field-effect based transistors are also used as sensors here. The measuring principle is usually based on the metabolism of living cells. Cells produce adenosine triphosphate (ATP) to generate energy for cell functions. To do this, cells absorb glucose and oxygen and produce ATP as well as water and carbon dioxide as waste products during cellular respiration. The CO_2 is present in the aqueous medium as a weak acid according to the equilibrium relation:



Intact, living cells thus produce hydronium ions that lower the pH value, which can be measured in real time with the sensor, for example a pH-ISFET, provided that the distance between the cells and the gate is around 50 nm to 150 nm [Sakata 2019]. In contrast to healthy cells, cancer cells have a significantly higher metabolic rate, which leads to a significantly greater pH change than in healthy cells.

Alternatively, (neuronal) microelectrode arrays are also used. The main challenge is the miniaturization of the electrode dimensions to cell dimensions. This makes it possible to record neuronal activity with high spatial resolution and to capture non-linear neuronal dynamics. A corresponding high-density graphene array with ultra-small electrodes was developed and demonstrated by predicting cellular calcium activity from surface potential recordings.

3.6 Medical Microsensors and Micro Implants

(Scholles, M.)

The current megatrends illustrate the omnipresence of healthcare in our society. Urbanization is directly correlated to an increasing population density with healthcare-associated issues. The ageing demographic leads to more health issues like chronic diseases. Healthcare costs are escalating worldwide. According to a study published in *The Lancet*, the world will spend an estimated 20 trillion US dollars per year on healthcare in 2040, an increase of 150 % compared to 2014 [Dieleman 2017]. This explains why almost all countries have developed an explicit national digital health strategy in conjunction with a roadmap for the deployment of solutions. The adoption of technology through the digital transformation of healthcare is seen as a key element in ensuring the sustainability of healthcare systems worldwide.

The emergence of so-called P4 healthcare – predictive, preventive, personalized and participatory healthcare – as opposed to reactive healthcare is blurring the boundaries between the medical technology (MedTech) and pharmaceutical and electronic components and systems (ECS) industries and paving the way for innovation in healthcare. This is a great opportunity for the ECS industry as well as for German mid-sized MedTech companies, as the new healthcare ecosystem will be based on digital instruments, advanced electronic sensors and photonics, microelectromechanical systems (MEMS) and the high-volume, high-quality and low-cost manufacturing capabilities of the ECS industry.

The technologies enabled by the chip industry have the potential to significantly change the healthcare industry. They will change the way healthcare is delivered, facilitate access to healthcare and improve patient outcomes. This will improve the overall well-being and quality of life for many people.

Apart from better accessibility and cost-efficiency, the integration of artificial intelligence and advanced data analytics facilitates collaboration between healthcare professionals to

make informed decisions, which in turn leads to better outcomes for patients. In addition, the implementation of predictive analytics helps in the timely detection of diseases, promotes early intervention and prevents further complications. Patients experience healthcare in a more interactive and engaging way. Hospitals and clinics can use data analytics to predict patient inflow and manage their resources more efficiently. Big data analytics can provide valuable insights into disease patterns, treatment outcomes, and patient behavior to drive research and innovation as well as to monitor and respond to global health crises such as pandemics.

All aspects mentioned above rely on advanced sensors, sensor modules, and related systems based on different technologies. Technical challenges that must be addressed to establish the described change in the health care system are listed in the following paragraphs.

Vital Parameter Monitoring

For future trends in measuring vital parameters, one must differentiate between clinical settings and continuous monitoring outside of hospitals and the like.

The monitoring of various vital parameters during intensive care treatment and therapy is state of the art. There are numerous hardware and software-based solutions for monitoring individual or a very small number of vital signs, such as heart rate or blood pressure, which are established on the market or are close to market maturity. These focus on clinical use in the ICU. They are closed systems without standardized or open interfaces that cannot be flexibly adapted for different diseases. Both offer scope for further developments with regard to sensor systems.

The use of AI and machine learning is now making inroads but is typically limited to extracting patient status variables from the raw sensory data. Overall, it can be stated that a comprehensive system that realizes patient monitoring according to ITS standards in other environments is currently not known but would also be desirable from a medical point of view.

There is also a need for further development of individual sensor solutions. Biosignals, such as

chest movement during breathing or the chemical analysis of the breathing air itself, are not covered by the devices available on the market. The design of a modular and therefore expandable system with defined, open interfaces also offers the possibility of using available or commercial sensor solutions where no added value can be achieved through R&D work (e.g., temperature measurement).

Different sensor solutions are preferable for individual vital parameters. For long-term measurement of ECG parameters, a textile-integrated variant is preferable, which overcomes the disadvantages of the adhesive electrodes used almost without exception in medical applications. Pulse chest belts only provide calculated characteristic values (e.g., heart rate). ECG patches or smartwatches record ECG signals without adhesive electrodes but require a special measurement procedure (e.g., touching contact points) and therefore only enable signal recording for a limited period of time (spot measurement). Work is being carried out on textile-integrated solutions for mobile long-term monitoring with dry electrodes. However, only a few systems are approved as medical devices and often lead to very severe restrictions for the user groups due to the textile concept.

Until now, differentiated lung ventilation has only been possible as a snapshot using imaging procedures such as a chest CT. However, the bedside methods used for lung monitoring in intensive care units (surrogate parameters, auscultation) only provide global or regionally limited information. Sensory information such as “ventilated lung” vs. “non-ventilated/consolidated” vs. “non-ventilated/collapsed lung sections” would be desirable. The assessment of the type and nature of lung tissue changes or damage initially remains the domain of imaging procedures (X-ray, CT, MRI, sonography). However, these imaging procedures have the disadvantage that they do not allow continuous monitoring and therefore no real-time assessment during the course of the disease or a dynamic image during therapeutic interventions such as ventilation therapy. In addition, X-rays and CT scans in particular should only be used in specific cases where there is an appropriate indication in view of the health risks involved. The use of stethoscopes (1D point measurement several

times manually) is currently predominant. Stethoscope technology is over 200 years old and still well-established. Electrical impedance tomography (EIT) is more recent. Corresponding products on the market enable 2D imaging of a single sectional plane using a chest strap and 16 sensors. However, it would make sense to develop a real-time 3D acquisition system based on an array of textile-integrated acoustic sensors, which would enable continuous spatial visualization of the lungs in real time without radiation exposure, comfortable handling for the patient and diagnostic support for medical staff.

Radar sensors with FMCW (Frequency Modulated Continuous Wave) technology are ideal for the contactless monitoring of biosignals. The breathing frequency is typically around 0.1 Hz to 0.4 Hz. The movement of the chest caused by breathing can be measured with the radar system using the Doppler principle. High-frequency radar sensors, which operate in the millimeter wave range, are particularly sensitive to the smallest physiological movements and can detect them very well. Various institutions, such as FAU Erlangen or the consortium of TU Ilmenau, Friedrich Schiller University Jena and Jena University Hospital, are currently conducting research in the field of determining vital parameters. The focus here is on determining the vital parameters of a test person. FAU Erlangen, for example, has developed a millimeter wave sensor that can be used to determine the vital signs of a test person. However, this work only considers the case of measuring a person’s vital parameters. The sensor must be placed above the chest of the person to be monitored. In contrast, future systems that simultaneously measure the respiratory rate of several people would be useful. In this case, the sensor does not have to be placed in the immediate vicinity of the test subjects, but can be installed near the ceiling, for example.

Optical methods, such as a hyperspectral image sensor, aim to record the so-called photoplethysmographic curve (PPG curve) which allows the determination of parameters such as oxygen saturation or pulse rate. In clinical use, SpO₂ sensors designed as finger clips are typically used to determine blood oxygen saturation. This finger clip measurement is both simple and robust but restricts the patient’s comfort and free-

dom of movement. Particularly in the case of continuous monitoring, especially in the case of small or premature babies, this leads to low patient acceptance. There is therefore a need for low-invasive or non-invasive methods for continuous measurement of oxygen saturation.

For completely non-invasive photoplethysmography, the use of imaging techniques is recommended, which ideally allow continuous monitoring of patients under normal environmental conditions without direct mechanical contact. Camera-based “remote” PPG methods (rPPG) are described in the literature, which determine the patient’s heart and respiratory rate. Standard RGB cameras can be used. The measurement can also take place under normal ambient lighting, so that no dedicated lighting needs to be integrated into the system. The achievable data quality of the rPPG methods is comparable to that of invasive standard sensors. Both face and hands can be used as measurement zones.

Pulmonary function tests allow conclusions to be drawn about respiratory sufficiency and the presence of ventilation disorders by spirometrically measuring the patient’s mobilizable lung volume. Respiratory volumes and airflow velocities are usually determined using pneumotachographs, turbines or ultrasound. Alternatively, whole-body plethysmography is used, in which residual volume and lung capacity are determined spirometrically in an airtight chamber. This method is not suitable for a flexible or even portable solution due to the measurement setup alone.

Pulmonary function tests are usually carried out on an outpatient basis in general practitioners’ surgeries or by pulmonologists. The patient breathes into the mouthpiece of the spirometer while their nose is closed with a nose clip. In addition to measuring devices designed for stationary use, there is an increasing number of mobile spirometer solutions. Examples of commercially available systems are the Vitalograph microSpirometer from KS Medizintechnik (based on differential pressure measurement), SpiroSensePro or mySpiroSense from Pari GmbH (based on planar heating anemometers) or the EasyOnePro from ndd Medizintechnik AG (based on ultrasound technology for flow and volume measurement). Different operating prin-

ciples are used in the commercially available products: variable area flow measurement has the disadvantages of low accuracy and limited integrability in digital measuring systems. Differential pressure measurement uses two separately positioned pressure sensors which influence the accuracy of the system. The method is susceptible to attenuation or kinking of the hose configuration. Coriolis flow meters are characterized by high sensitivity but are more suitable for stationary systems due to their relatively large dimensions. Calorimetric flow meters are based on heating anemometers, which either only measure the amount of gas flow unidirectionally or require more complex systems to determine the direction. Ultrasound-based spirometry is a particularly advantageous measuring principle due to its precise, contact- and resistance-free measurement, ease of use without calibration, and simple design. As a rule, conventional piezo ultrasound sensors are used in commercial systems. They are expensive to manufacture and contain undesirable materials such as lead. The latter is not only disadvantageous in terms of RoHs conformity, but also critical with regard to the disposal of such components.

Ultrasound

Of course, medical imaging and diagnostics still make heavy use of ultrasound technology. Advanced medical applications like endoscopic in-situ ultrasound imaging becomes reality through ultrasound sensors and actuators designed and manufactured in MEMS CMUT technology. For further trends on this technology please refer to Chapter 2.2.

Photonic Biosensors

Many applications in the healthcare market benefit from photonic sensors and related components that can detect biomarkers with high sensitivity in blood plasma or other bodily fluids. The challenge is to develop reusable compact sensor architectures that can compete with conventional diagnostic methods (ELISA, PCR) and other established sensing techniques, e.g., surface plasmon resonance (SPR), while retaining the advantages of photonic integration (sensitivity, multiplexing and being label- or reagent-free). While passive waveguide sensor circuits

can be developed for highly scalable mass production, co-integration with on-chip lasers, photodetectors and microfluidics remains a challenge due to the costly serial assembly processes involved. Future work must aim to develop versatile, highly integrated, high-performing (in terms of sensitivity, specificity, LOD) and reusable multiplexed biosensors in an innovative concept. While high sensitivities can be achieved with complex structures (e.g., plasmonic metamaterials), the most easily integrated, most mode-limiting structures are based on micro ring resonators (MRR) and Mach-Zehnder interferometers (MZI). PIC sensors are often developed on Si_3N_4 -on- SiO_2 material platforms with the aim of using low-loss nitride PIC technology (Figure 3.12). Integrated photonics will lead to diagnostic tests for diseases based on on-the-fly generation of complex “finger-prints” of many analytes and accelerate the development of global digital medical diagnostics. For example, neurodegenerative diseases such as Alzheimer’s and Parkinson’s can be diagnosed at a much earlier stage than is currently possible, even though they have complex patterns of biomarkers and their detection is a major challenge for existing mass screening methods.



Figure 3.12: Silicon chip-integrated photonics as biosensors for optical detection of biomolecules
(Source; Dr. Florenta Costache, Fraunhofer IPMS)

Gas Analysis/IMS

Non-invasive diagnostics also includes sensors for gas analysis that may be applied to human breath but also to the gas bubble called head space that builds upon, for instance, urine samples. Ion mobility spectroscopy (IMS) is a common method for determining the concentration of VOCs (volatile organic compounds) directly in gases. These occur as biomarkers in the ppb range in exhaled air and increase significantly in the event of illness. In the IMS, the VOCs are ionized and then separated by means of an electric field according to their characteristic ion mobility. For more details on IMS technology please refer to Section 3.1.4.

3.7 Particle Sensing

(Burtscher, H.)

Aerosol particles contribute significantly to air pollution. Besides this negative effect, they play an increasingly important role in industrial products (e.g., nanomaterials) and also in medical applications (inhalation of pharmaceuticals). Therefore, it is important to have sensors for an adequate characterization and quantification of these particles. The size range of importance ranges from few nanometers to some tens of microns. Usual metrics for a physical characterization are particle total mass concentration, mass concentration of certain size fractions (PM₁₀, PM_{2.5}, mass of all particles smaller than 10 μm or 2.5 μm respectively), number concentration or surface concentration (e.g., the lung deposited surface area, LDSA [Ebdebali et al. 2023]). Depending on the size range of interest, different metrics are applied and different sensor techniques are needed. Particle mass is mainly used for larger particles, number concentration for nano-particles, and surface shows the best correlation to health effects. Important applications are monitoring networks for ambient air quality and, increasingly, also indoor air quality. The availability of low-cost sensors allows installing networks with many sensors to achieve a good spatial and temporal resolution.

Conventionally, mass has been determined by gravimetry, number concentration using condensation particle counters, and surface by the BTE-technique (see, for example, [Kulkarni et al.

2011]. All these methods are designed more for laboratory use, not for sensors, in particular not for low-cost sensors. Most low-cost sensors are based on light scattering; sensors for very small particles often use detection by diffusion charging. In contrast to gravimetry, these techniques are indirect. For example, a scattering intensity has to be transferred into a particle mass concentration or an electrical current into a number concentration. This conversion usually requires a certain knowledge about particle properties as index of refraction or shape of the size distribution, and the sensors have to be calibrated for envisaged application.

3.7.1 Light-Scattering Sensors

Light scattering is the most frequently used technique in low-cost sensors (a typical setup is shown in Figure 3.13). The scattering intensity for particles smaller than the wavelength of light (Rayleigh scattering) scales with d^6/λ^4 , where d is the particle diameter and λ the wavelength of the light [Kulkarni et al. 2011]. By choosing the detection angle (here 90°) the sensitivity to the particle size can be varied. When measuring mainly forward scattering diffraction becomes important, favoring large particles.



Figure 3.13: Typical setup of a light-scattering sensor.

This means that very small particles cannot be detected by this technique. For high-quality laboratory instruments, the limit is in the order of 50 nm, for low-cost sensors some 100 nm. They can operate as single-particle detectors, counting the number of scattered light pulses, and use the pulse height to evaluate the particle size or measure the integrated scattering intensity. The probably most frequently used application of the second type are smoke detectors (Figure 3.14).

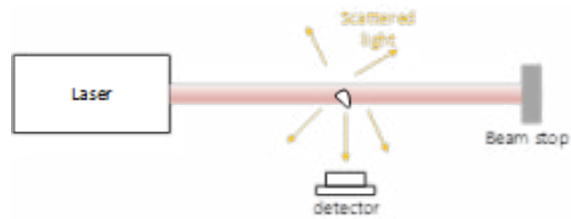


Figure 3.14. Smoke detector configuration

Sometimes, a mix of both operating modes is used: single-particle evaluation for particles large enough to detect single peaks, and evaluation of the “background” signal to obtain information on the small fraction.

Most commercial devices are calibrated to yield the mass concentration of ambient air particles (PM10, PM2.5, PM1 and even smaller). This requires assumptions on optical properties (index of refraction) and size distribution. Sensors evaluating the pulse height of the single-particle scatter pulses also give information on the size distribution. An increasing number of such optical sensors are available. Besides improvements in the sensors itself, the performance is becoming better due to more sophisticated data processing. An evaluation of some low-cost optical sensors can be found in [Rabuan et al. 2023]. So far, most sensors have a fan, sucking air through the sensor being in a closed case. Recent developments work with open sensors, using backscattering [Trumpf 2024]. Similar configurations are also in discussion for smoke detectors.

3.7.2 Electrical Measurement

Most sensors based on electrical measurement use unipolar diffusion charging (DC-Sensors, Figure 3.15). Ions are produced by applying a high voltage to a thin wire or a tip. These ions attach to the particles by diffusion and thus charge them. Free ions are removed by an ion trap. The charged particles can be captured by an isolated mounted particle filter; the current produced by these particles (in the range of some fA to some pA) is then measured by a sensitive current amplifier [Kulkarni et al. 2011].

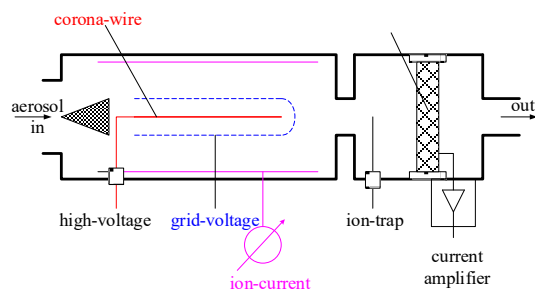


Figure 3.15: Typical setup of a sensor based on diffusion charging

The charging probability approximately scales with the particle surface, meaning that the sensor signal is related to the surface concentration. If the collecting filter is replaced by a diffusion screen, having a collection efficiency approximately inverse to the charging probability, the measured current is related to the number concentration. Another option is replacing the collection filter by a Faraday cage and pulsing the corona. In this case, the particles are not precipitated in a filter but pass the Faraday cage. The clouds of charges periodically passing the cage induce an AC current, which is measured. The information obtained is the same, but contamination of the sensor is reduced, because particles are not precipitated. In addition, amplifier drift no longer influences the measurement, as only the AC fraction contains the information needed [Fierz et al. 2014].

Instead of only one collector, several diffusion screens with different cutoffs can be used. This allows getting information on the particle size distribution (electrical diffusion battery [Fierz et al. 2002]). Similar results can be obtained by electrostatic precipitation [Schriffl et al. 2019].

Many European countries recently reintroduced a periodical technical inspection (PTI) of vehicles, including particle emission measurements. This required the development of new sensors, many of them based in diffusion charging [Melas 2023].

3.7.3 Other Techniques

Light scattering and electrical diffusion charging are dominating the market today. However, a number of promising other techniques are available, some of which will be briefly introduced.

UV Photoemission: Instead of charging the particles by attachment of ions, they can be charged by emission of electrons due to irradiation with UV light. Sensors based on photoemission were introduced a long time ago [Burtscher and Siegmann 1994]. They can be used to get information on the particle surface as attached polycyclic aromatic compounds or oxides [Ramos Contreras et al. 2019; Olszok et al. 2023]. These sensors require UV sources in the wavelength range of 200 nm to 240 nm. Due to progress in UV LED development, reliable and cheap diodes for these wavelengths might soon be available, allowing the design of very small and cheap sensors.

Photoacoustic sensors and photothermal interferometry: An important species in ambient air and in emissions from combustion processes is black carbon (BC). BC dominates light absorption and thus can be measured by light absorption. For particles smaller than λ , optical absorption is directly related to the mass of the absorbing material, i.e., the BC concentration. If light is absorbed, temperature increases, which can be measured by photoacoustic sensors [Fischer and Smith 2018] or photothermal interferometry [Betschon et al. 2023].

Total mass and total carbon measurement: Total mass can be determined by Quartz Crystal Microbalance (QCM) sensors or MEMS resonators, making use of a change in resonance frequency when particles are deposited on the sensor. A recently introduced instrument for a total carbon measurement is based on oxidizing the carbon and measuring the produced CO_2 [Keller et al. 2023].

Acoustic particle detection: Impactors have been used for decades to precipitate particles according to the aerodynamic diameter on impaction plates, where they can be weighted or chemical analysis can be performed. A recently introduced sensor places a piezo transducer on an impaction plate, measuring the impact intensity of every particle impacting on the plate. This allows to count particles and determine their mass for particles $> 1 \mu\text{m}$ [Hoffmann et al. 2022].

3.8 Sensors for Process Automation (Ulrich Kaiser)

The technical infrastructures for process engineering processes are an important field of application for sensors. According to DIN 66201, a process is “a set of interacting operations in a system by which matter, energy or information is transformed or stored”. In process engineering processes, material flows with individual chemical and physical properties are changed into new products with new properties. In the chemical industry, for example, the raw material crude oil is converted into plastic granules, in the food industry, milk is turned into cheese, and in the pharmaceutical industry, modified coliform bacteria produce insulin from sugar in a biotechnical process. These properties are recorded using sensors in the running process and at the locations where these properties occur (Figure 3.16). Sensors are used to record the quality of input, output and intermediate products in the processes. They are used to monitor process conditions such as temperature and pressure. They are indispensable for occupational health and safety. And, ultimately, processes can only be automated with the help of sensors. The market for sensors in the process engineering industry is very large. A large chemical site in Germany, where more than 500,000 process sensors are installed, may serve as an example.

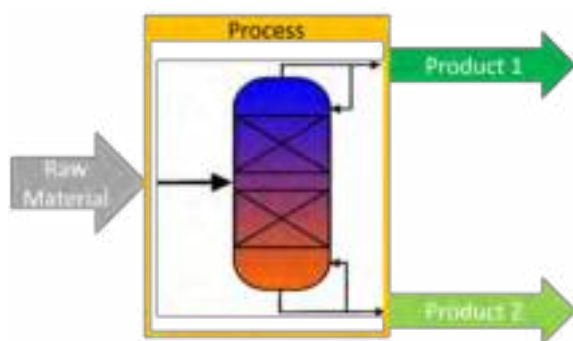


Figure 3.16: Principle of a process engineering process with sensors

Special Requirements for Process Sensors

Process sensors are based on the same principles and operating mechanisms as sensors for other applications. However, they must meet special requirements. The first of these is greater ruggedness and durability of the sensors. Process systems can last for decades, and

process sensors must be able to keep up. Robustness here means insensitivity to extreme temperatures and temperature fluctuations, vibration, and especially exposure to the process medium. In chemical applications, sensors often need to be explosion-proof. For use in safety-critical applications, a design with functional safety in accordance with DIN EN 68511 is also required. In the food and pharmaceutical industries, hygienic requirements must be considered, such as those defined by EHEDG [EHEDG Glossary 2020]. The hygienic requirements for sensors used in biotech reactors are very high. They must be sterilizable, either by steam or gamma ray sterilization. Disposable reactors [Eibl et al. 2010] also require sensors that are only used once. These are designed in a way that the wetted parts of the sensor are sterilized only once and then replaced and discarded after the production batch. Disposable reactor technology has taken off in pharmaceutical production and now dominates it. Sensor technology must follow this trend.

Because of the inaccessibility of sensors in process plants – think of sensors in a rectification column – and because of automation, sensors must of course be remotely controllable, either wired or wireless, with digital or analog data transmission. This lack of accessibility also requires that sensors not only transmit readings, but also information about their status, preferably in a predictive way, so that predictive maintenance is possible [Scheuermann 2018].

Process engineering processes often run continuously. Any interruption reduces productivity, is economically disadvantageous and should therefore be avoided. Sensors must be regularly calibrated and, if necessary, adjusted to maintain their metrological integrity. A key requirement is therefore that process sensors require little, i.e., infrequent and ideally no maintenance at all, including calibration and adjustment.

Process Sensors for Classic Parameters

Sensors for the classic measured variables of temperature, pressure, level, and flow have dominated process engineering systems to date. Chapter 2 of this study describes the technology for these measurements and their future development in detail. A very comprehensive

description is provided in the Handbook of Process Automation [Früh et al. 2018]. From the perspective of the process engineering industry, the following trends are evident. Firstly, the ability of these sensors to be used in biotechnical processes. As an example, Figure 3.17 shows the single-use version of a magnetic flow sensor. And secondly, the requirement for optimized maintenance; see the section on maintenance of process sensors.



Figure 3.17: Electromagnetic flow sensor with wetted components in single-use design (Source: KROHNE Messtechnik)

The Trend Towards Substance Analysis – Process Analysis Technology

Traditionally, process engineering processes are controlled and regulated using physical parameters such as pressure and temperature. However, there has long been a trend towards using sensors to record material parameters as well as process parameters. This trend is set to continue. A variety of device technologies are used for this process analysis technology, which in turn are based on different physical and chemical laws. What all methods have in common is that they use measurable properties of substances or groups of substances as specifically as possible for them and enable statements to be made about the quantity of these substances or groups of substances present. One technology that is already widely used is electrochemical pH measurement [Mettler Toledo 2015]. However, this only provides a sum parameter. Sensor technologies that measure substances more selectively are also required. By recording material parameters, processes can be further optimized in terms of yield, throughput time, energy requirements and product quality. And the understanding of the processes can be increased. To achieve this, the properties must be measured directly in the process – inline – with-

out influencing the process and without being influenced by the process itself.

Optical measurement methods are particularly suitable for this purpose. Optical methods are ideal for inline process analysis. The excitation light can be introduced into the process medium comparatively easily, without influencing it through contamination or hydraulically – at most through excessive energy input. The response of the medium is in turn triggered by light, which minimizes the interaction of the medium with the sensor technology itself. The optical methods are based on the principles of the interaction of electromagnetic radiation with chemical substances [Oesterle 1995]. The methods of infrared (Günzler et al. 2003), UV-VIS [Owen 1996], and Raman spectroscopy [Lewis et al. 2001] are probably the most frequently used methods and their use is constantly increasing. The first implementation of infrared spectroscopy in the chemical industry is probably the non-dispersive URAS for the trace measurement of CO in ammonia synthesis from 1938 [Kloska 2017].

There are various design principles for infrared spectrometers. The simplest is the one with a movable diffraction grating; newer spectrometers use a fixed diffraction grating with a line detector. The intensive technological development of line detectors in terms of resolution and sensitivity has attracted a great deal of attention to this principle. A standard for sophisticated NIR (Near InfraRed) spectroscopy is still the FT-NIR (Fourier-Transform NIR) spectrometer [Arnold], which operates according to the Michelson principle. This has a higher speed and sensitivity and is the benchmark, particularly in terms of wavelength stability. The disadvantages of this principle are its moving parts when used in harsh process environments and the high price. This is where spectrometers with line detectors have an advantage. A comprehensive comparison and evaluation of these principles can be found in [Schilling 2017]. The trend is towards simpler and therefore cheaper, more compact spectrometers.

Another trend in process engineering is the use of sensors based on the TDL (Tunable Diode Laser) principle (Mettler Toledo 2012). These also work according to the principle of infrared

absorption. In terms of their technical concept, they stand between non-dispersive photometers and NIR spectrometers and combine the advantages of both methods. They measure an analyte with high selectivity, are simple, allow large temperature and pressure ranges, require no sample preparation and are considered to be low-maintenance. This technology is comparatively new, but is experiencing great momentum and is already offered by many manufacturers. See Figure 3.18 for an example. TDL sensors are often used to measure O_2 , CO and CO_2 for the control of combustion processes. They are also used to measure gas humidity.



Figure 3.18: Sensor using the TDL method (Source: Mettler Toledo)

This technology is based on new high-performance laser diodes that are designed for an absorption wavelength of the analyte to be measured and that can be tuned to a certain extent (fractions of nanometers) via the externally applied electrical power. This allows the laser frequency to be driven over the absorption peak of the analyte and this absorption peak to be measured as precisely and selectively as with a spectrometer. Most of the TDL sensors on the market work with absorption waves in the near-infrared range. However, with the new cascade laser technology which continues to develop, longer wavelengths can also be detected, so that, in future, more TDL sensors will also be available for the analytically very interesting MIR wave range $3\ \mu m$ to $30\ \mu m$.

Another interesting development in infrared spectroscopy is MEMS-based spectrometers. An overview of methods and applications can be found in [Beć et al. 2021]. One realization is a wavelength filter using a Fabry-Perot interferometer where two mirrors are shifted against each other using electrostatic force. (See Figure 3.19 for an example.) The dimensions of these spectrometers are significantly smaller, which makes it possible to further reduce the

cost of the overall system. A price reduction of several orders of magnitude can be expected. This opens up many new areas of use and applications in the process engineering process that are not yet economically viable with conventional technology.



Figure 3.19: MEMS-based IR-Spectrometer (Source: Spectral Engines)

In a roadmap study [NAMUR 2021], the process engineering industry has given some thought to the requirements for current and future process sensors. One trend identified in this roadmap is the increased use of inline process analytics, which is also required. It also shows which analysis methods will be ready for use in process engineering and when. One candidate, for example, is NMR spectroscopy, which can provide further information on the above-mentioned optical methods [Meyernist et al. 2016]. In principle, all methods of instrumental chemical analysis are suitable if they can be made suitable for the process. It is then a matter of implementing the analytical methods currently realized as laboratory devices as field devices for process analysis. [Falk et al. 2018]. These field devices are then process sensors.

In the case of sensors for process engineering processes, the creation of robustness and longevity, especially if this sensor interacts with the medium – which is often unavoidable – often poses a greater challenge than solving the actual measurement task. It therefore makes sense to use proven techniques from process engineering sensors when creating new sensors for material properties. There are already good examples where new sensors for material parameters have been created for use in defined applications by combining classic methods from level and/or flow measurement technology. One example is an ultrasonic flow sensor that has been extended to measure CO_2 concentrations

by also recording the speed of sound, and this for use in biogas plants. Another example is a sensor that combines the measurement of ultrasound, temperature and vibronics to measure viscosity and concentration in liquids [Bregartner et al. 2022] (Figure 3.20). The application is the monitoring of fermentation, for example in the production of beer. This approach offers potential, and it can be assumed that there will be more sensors of this type for multiple applications in the future.



Figure 3.20: Multi-sensor for monitoring fermentation processes (Source: Endress+Hauser)

Methods for Digitizing Sensor Data Processing

Newer technologies are probably only slowly gaining acceptance due to the longevity of the process engineering systems. For example, current loop connection and signal transmission technology, which is over 50 years old, is still state of the art. This only allows the slow transmission of a small amount of data. Newer technologies – from the 1990s –, such as Profibus [Profibus Nutzerorganisation 2024] were only able to reach a small proportion of systems. Now, with the Advanced Physical Layer [Ethernet-APL 2020] transmission technology and the Namur Open Architecture [NAMUR 2020] standard, the prerequisites for complete internet-based digitization in process engineering are in place, so that, in the coming years, we will see increased use of standardized digital infrastructures such as cloud services, which enable sophisticated evaluation of sensor data, e.g., using AI methods. Sensors can then be objects of the Internet of Things. These can then communicate wired or wirelessly via internet standards. This means that Industry 4.0 will also have arrived in process engineering.

Maintenance of Process Sensors

The technical maintenance of sensors in process engineering poses a particular challenge. In order to replace, repair or calibrate a sensor, the

process may have to be interrupted. In addition, sensors are often installed in places that are difficult to access. Anything that reduces the maintenance effort and extends the maintenance intervals is therefore welcome. For this reason, sensors that have a self-diagnostic function or even enable predictive diagnostics are increasingly being used where available. Predictive diagnostics at the level of an individual sensor naturally requires internal variables that can move monotonically in the direction of a fault condition. These can then be used as indicators for future error states. However, such internal variables are not available or cannot be accessed with most sensor technologies. At most, the formation of deposits or corrosion caused by the medium, if they can be detected, can be used as indicators for predictive diagnostics. In addition, the self-diagnosis can also take into account environmental variables that can impair the function of the sensor or cause error states, for example an increased temperature. Information about the process medium can then also be generated from these environmental variables [Fröhlich et al. 2021].

Calibration is the verification of a sensor by comparing it with a reference to determine whether the correct measured value with the specified measurement uncertainty is still being maintained. The reference is in turn checked by tracing it back to reference standards. To ensure that ageing or operation has not altered the metrological capabilities of the sensor, calibration must be repeated regularly. If some components of the sensor that create the metrological capabilities can now be regularly checked by the sensor itself in an extended self-diagnosis, this consequently increases confidence in the sustainability of the meteorological capabilities and calibration needs to be performed less frequently [Fröhlich et al., 2021]. Of course, complete self-calibration would be ideal. This is currently only feasible for a few sensors. For the example of a temperature sensor, see Chapter 2. In the future, there will also be sensors that implement the entire calibration traceability chain through to the reference standards in the sensor itself. The keyword is “NIST on a chip” [Tzalenchuk et al. 2022]. External calibration will then no longer be necessary for these sensors.

Collective Uses of Sensors in Process Automation

Sensors in process automation only provide individual pieces of information about the process medium. For example, they provide information about the fill level in tanks, the flow rate in pipes, the fat content of the milk in the separator in a dairy, the concentration of a certain hydrocarbon in a rectification column. However, further information can be obtained from the measurement results of all the sensors together. One application is predictive maintenance. This is based on the assumption that faults or impending faults can be registered in some way by the sensors involved. For example, the clogging of a filter leads to increased flow resistance, which can be detected by a pressure sensor. Two basic procedures are feasible: Firstly, in a training phase, all sensor values are recorded over a longer period of time together with any error states that occur. A neural network then uses this to determine which constellation of measured values is characteristic of a fault condition or the development of a fault condition. This can then be used to predict trained error states. One example of this is the PUMon system already used in the process industry [Ross et al. 2014]. Of course, this approach assumes that all possible error states have been experienced once during the training phase. A second, but less informative approach is anomaly detection. Here, the network is only trained for the fault-free good state and then indicates deviations from the normal state during the operating phase.

Another collective sensor application that is very relevant for process automation is soft sensor technology. The aim here is to record a measurand that is difficult to measure in a defined process using several sensors for measurands that are easier to measure [Bakirov et al., 2017]. "Difficult" means that this measurand can only be measured using complex laboratory technology or that suitable measurement technology cannot be used in an application. Soft sensors can be described as a set of physical sensors with a computational model. The computational models are used to aggregate the measured values of the physical sensors into a new measured value. These computational models can be based on chemical and physical

properties of the measurement object and/or be data-driven.

The principle on which the soft sensors are based can be taken further. In a process engineering process, the quality of the end product should be able to be represented by the collective of all sensors involved in the process. This of course assumes a defined quality of the input materials. Currently, the quality of the end product is assessed by laboratory analysis or, in the food industry, by flavor testers. Their results can then be used as ground truth in an AI network. This trained network can then be used to predict the quality of the end product from the sensor data. This would reduce the need for explicit, time-consuming final inspections. There are already activities in the process industry in this area, although these have not been publicized. The result would be a major gain in productivity.

Digitization in process plants in conjunction with developments in artificial intelligence methods should promote collective use of sensors in process automation.

Trends for Sensors in Process Automation

The most important trends for process sensors are summarized below. Probably the most important trend, which is repeatedly mentioned by operators of process plants, is the increasing demand for sensors for material analysis. On the one hand, these sensors can arise from the further development of classic process measurement technology methods or – which has much greater potential – from the process-compatible design of methods of instrument-based chemical analysis. Newer high-performance components such as laser diodes and image sensors enable the cost-effective and compact design of spectrometers that can be used inline in the process. Due to their simplicity and low cost, sensors with spectrometers in MEMS technology have the potential to take up a large proportion of process sensors for material analysis in process engineering systems in the future. The increasing proportion of biotechnological processes in pharmaceutical production requires sensors for many parameters in single-use design.

Hardly any other application places such high demands on robustness and low maintenance

as applications in the process industry. This requires sensors with self-diagnostics. In addition, extended self-diagnosis of the metrological functions is required to reduce the need for external calibrations. In future, the results of the “NIST on a Chip” program will mean that many process sensors will no longer need to be calibrated externally at all.

With the Ethernet-APL and NAMUR Open Architecture standards, the conditions have finally been created to implement process sensors as the Internet of Things and to benefit from the functions of the internet. Together with advances in artificial intelligence methods, this will also promote the use of collective use of sensors.

References Chapter 3

MECS-Technology™ by Faradaic Sensors GmbH, Berlin, AMA Innovation Award Young Enterprise 2024, <https://faradaic.io/Technology.html> (accessed on: March 11th 2025)

Han, T.; Mukhopadhyay, S. C.; Nag, A.; Xu, Y.: Carbon nanotubes and its gas-sensing applications: A review, *Sensors and Actuators A: Physical* (2019) 291, 107–143, doi: 10.1016/j.sna.2019.03.053.

A. Nag, A. Mitra, S. C. Mukhopadhyay: Graphene and its sensor-based applications: A review, *Sensors and Actuators A: Physical* (2018) 270, 177–194, doi: 10.1016/j.sna.2017.12.028.

M. Leidinger, M. Rieger, T. Sauerwald, C. Alépée, A. Schütze: Integrated pre-concentrator gas sensor microsystem for ppb level benzene detection, *Sensors and Actuators B: Chemical* (2016) 236, 988–996, doi: 10.1016/j.snb.2016.04.064.

European Environment Agency: Health impacts of air pollution in Europe, 2022, web report, <https://www.eea.europa.eu/publications/air-quality-in-europe-2022/health-impacts-of-air-pollution> (accessed on: March 11th 2025)

Salthammer, T.: TVOC – Revisited, *Environment International* (2022) 167, 107440, doi: 10.1016/j.envint.2022.107440

Sauerwald, T.; Schütze A.: Indoor air quality monitoring, in: E. Llobet (ed.): *Advanced Nanomaterials for Inexpensive Gas Microsensors* (2020), 209–234, doi: 10.1016/B978-0-12-814827-3.00011-6

Product links:

- <https://www.cisco.com/c/en/us/products/collateral/collaboration-endpoints/webex-room-series/datasheet-c78-744227.html> (accessed on: March 11th 2025)
- <https://news.microsoft.com/source/features/digital-transformation/electrolux-smart-air-purifier-breathe-easy-polluted-cities> (accessed on: March 11th 2025)

- <https://www.safera.com/stoveguards/>, (accessed on: March 11th 2025)

- <https://broan-nutone.com/en-us/overture> (accessed on: March 11th 2025)

EU Methane Regulations, <https://www.iea.org/policies/18209-eu-methane-regulations> (accessed on: March 11th 2025)

S. Marco, A. Gutierrez-Galvez: Signal and Data Processing for Machine Olfaction and Chemical Sensing: A Review, *IEEE Sensors Journal* (2012) 12(11), 3189–3214, doi: 10.1109/JSEN.2012.2192920

T. Baur, M. Bastuck, C. Schultealbert, T. Sauerwald, A. Schütze: Random gas mixtures for efficient gas sensor calibration, *J. Sens. Sens. Syst.* (2020) 9, 411–424, DOI 10.5194/jsss-9-411-2020

T. Baur, J. Amann, C. Schultealbert, A. Schütze: Field Study of Metal Oxide Semiconductor Gas Sensors in Temperature Cycled Operation for Selective VOC Monitoring in Indoor Air, *Atmosphere* (2021) 12, 647, DOI 10.3390/atmos12050647

Y. Robin, J. Amann, T. Schneider, A. Schütze, C. Bur: Comparison of Transfer Learning and Established Calibration Transfer Methods for Metal Oxide Semiconductor Gas Sensors, *Atmosphere* 2023, 14(7), 1123, doi: 10.3390/atmos14071123#

VDI Germany: VDI/VDE 3518 part 4, draft: Multigas sensors, Standardized test instructions and test gases for VOC detectors for indoor air quality measurement, <https://www.vdi.de/richtlinien/details/vdivde-3518-blatt-4-multigas-sensoren-standardisierte-pruefanweisung-und-pruefgase-fuer-voc-detektoren-zur-innen-raumluftguetemessung> (accessed on: March 11th 2025)

Eiceman, G. A.; Stone, J. A.: Peer reviewed: ion mobility spectrometers in national defense, *Anal Chem*, 76(21), 390A–397A, <https://doi.org/10.1021/ac041665c>, 2004.

- Borsdorf, H., Eiceman, G. A.: Ion mobility spectrometry: principles and applications, *Appl Spectrosc Rev*, 41(4), 323–375, <https://doi.org/10.1080/05704920600663469>, 2006.
- Mäkinen, M.; Nousiainen, M.; Sillanpää, M.: Ion spectrometric detection technologies for ultra-traces of explosives: a review, *Mass Spectrom Rev*, 30(5), 940–73, <https://doi.org/10.1002/mas.20308>, 2011.
- Buryakov, I. A.: Detection of explosives by ion mobility spectrometry, *J Anal Chem*, 66, 674–694, <https://doi.org/10.1134/S1061934811080077>, 2011.
- Puton, J.; Namieśnik, J.: Ion mobility spectrometry – current status and application for chemical warfare agents detection, *TrAC Trends Anal Chem*, 85, 10–20, <https://doi.org/10.1016/j.trac.2016.06.002>, 2016.
- Eiceman, G. A., Hill, H. H.; Karpas, Z.: Ion mobility spectrometry, CRC Press, 2013.
- Webb, I. K.; Anderson, G. A.; Chen, T.-C.; Garmella, S. V. B.; Ibrahim, Y. M.; LaMarche, B.; Norheim, R. V.; Prost, S. A.; Smith, R. D.; Tolmachev, A. V.; Zhang, X.: Experimental evaluation and optimization of structures for lossless ion manipulations for ion mobility spectrometry with time-of-flight mass spectrometry, *Anal Chem*, 86(18), 9169–9176, <https://doi.org/10.1021/ac502055e>, 2014.
- Michelmann, K.; Park, M. A.; Ridgeway, M. E.; Silveira, J. A.: Fundamentals of trapped ion mobility spectrometry, *J Am Soc Mass Spectrom*, 26(1), 14–24, <https://doi.org/10.1007/s13361-014-0999-4>, 2015.
- Ridgeway, M. E.; Jordens, J.; Lubeck, M.; Mann, M.; Park, M. A.: Trapped ion mobility spectrometry – a short review, *Int J Mass Spectrom*, 425, 22–35, <https://doi.org/10.1016/j.ijms.2018.01.006>, 2018.
- Karpas, Z.: Applications of ion mobility spectrometry (IMS) in the field of foodomics, *Food Res Int*, 54(1), 1146–1151, <https://doi.org/10.1016/j.foodres.2012.11.029>, 2013.
- Hernández-Mesa, M.; Escourrou, A.; Dervilly-Pinel, G.; Le Bizec, B.; Monteau, F.: Current applications and perspectives of ion mobility spectrometry to answer chemical food safety issues, *TrAC Trends Anal Chem*, 94, 39–53, <https://doi.org/10.1016/j.trac.2017.07.006>, 2017.
- O'Donnell, R. M.; Sun, X.; Harrington, P. B.: Pharmaceutical applications of ion mobility spectrometry, *TrAC Trends Anal Chem*, 27(1), 44–53, <https://doi.org/10.1016/j.trac.2007.10.014>, 2008.
- Campuzano, I. D.; Lippens, J. L.: Ion mobility in the pharmaceutical industry, *Curr Opin Chem Biol*, 42, 147–159, <https://doi.org/10.1016/j.cbpa.2017.11.008>, 2018.
- Allers, M.; Gaida, A.; Hohlfeld, J. M.; Holz, O.; Langejuergen, J.; Schuchardt, S.; Zimmermann, S.: Measurement of exhaled volatile organic compounds from patients with chronic obstructive pulmonary disease (COPD) using closed gas loop GC-IMS and GC-APCI-MS, *J. Breath Research*, 10(2), 026004/1–10, <https://doi.org/10.1088/1752-7155/10/2/026004>, 2016.
- Drees, C.; Althoff, K.; Kunze-Szikszay, N.; Legler, T. J.; Liedtke, S.; Lippmann, M.; Perl, T.; Rosin, C.; Vautz, W.; Yildiz, D.; Zimmermann, S.: GC-IMS headspace analyses allow early recognition of bacterial growth and rapid pathogen differentiation in standard blood cultures, *Applied Microbiology and Biotechnology*, 103(21–22), 9091–9101, <https://doi.org/10.1007/s00253-019-10181-x>, 2019.
- Bohrer, B. C.; Clemmer, D. E.; Hilderbrand, A. E.; Koeniger, S. L.; Merenbloom, S. I.: Biomolecule analysis by ion mobility spectrometry, *Annu Rev Anal Chem*, 1, 293–327, <https://doi.org/10.1146/annurev.anchem.1.031207.113001>, 2008.
- Uetrecht, C.; Heck, A. J. R.; Lorenzen, K.; Rose, R. J.; van Duijn, E.: Ion mobility mass spectrometry of proteins and protein assemblies, *Chem*

- Soc Rev, 39, 1633–1655, <https://doi.org/10.1039/B914002F>, 2010.
- Zhong, Y.; Hyung, S.-J.; Ruotolo, B.T.: Ion mobility-mass spectrometry for structural proteomics, *Expert Rev Proteomics*, 9(1), 47–58, <https://doi.org/10.1586/epr.11.75>, 2012.
- Konijnenberg, A.; Butterer, A.; Sobott, F.: Native ion mobility-mass spectrometry and related methods in structural biology, *Biochim Biophys Acta*, 1834(6), 1239–1256, <https://doi.org/10.1016/j.bbapap.2012.11.013>, 2013.
- Ahrens, A.; Allers, M.; Bock, H.; Ficks, A.; Hitzemann, M.; Zimmermann, S.: Detection of chemical warfare agents with a miniaturized high-performance drift tube ion mobility spectrometer using high-energetic photons for ionization, *Analytical Chemistry*, 94(44), 15440–15447, <https://doi.org/10.1021/acs.analchem.2c03422>, 2022.
- Bohnhorst, B.; Kirk, A.T.; Zimmermann, S.: Toward compact high-performance ion mobility spectrometers: Ion gating in ion mobility spectrometry, *Analytical Chemistry*, 93(15), 6062–6070, <https://doi.org/10.1021/acs.analchem.0c04140>, 2021.
- Ahrens, A.; Hitzemann, M.; Moehle, J.; Zimmermann, S.: Novel ion drift tube for high-performance ion mobility spectrometers based on a composite material, *Int. J. for Ion Mobility Spectrometry*, 23(2), 75–81, <https://doi.org/10.1007/s12127-020-00265-0>, 2020.
- Ahrens, A.; Hitzemann, M.; Zimmermann, S.: Miniaturized high-performance drift tube ion mobility spectrometer, *Int. J. for Ion Mobility Spectrometry*, 22(2), 77–83, <https://doi.org/10.1007/s12127-019-00248-w>, 2019.
- Hitzemann, M.; Bohnhorst, A.; Kirk, A.T.; Lippmann, M.; Zimmermann, S.: Miniaturized drift tube ion mobility spectrometer with ultra-fast polarity switching, *Analytical Chemistry*, 94(2), 777–786, <https://doi.org/10.1021/acs.analchem.1c03268>, 2022.
- Lippmann, M.; Hitzemann, M.; Kirk, A.T.; Zimmermann, S.: Compact and sensitive dual drift tube ion mobility spectrometer with a new dual field switching ion shutter for simultaneous detection of both ion polarities, *Analytical Chemistry*, 92(17), 11834–11841, <https://doi.org/10.1021/acs.analchem.0c02166>, 2020.
- Kirk, A.T.; Kueddelmann, M.J.; Zimmermann, S.: Ultrasensitive ion source for drift tube ion mobility spectrometers combining optimized sample gas flow with both chemical ionization and direct ionization, *Analytical Chemistry*, 94(28), 9960–9969, <https://doi.org/10.1021/acs.analchem.2c00955>, 2022.
- Kirk, A.T.; Bohnhorst, A.; Kueddelmann, M.J.; Lippmann, M.; Zimmermann, S.: Improving ion mobility spectrometer sensitivity through the extended field switching ion shutter, *Analytical Chemistry*, 92(7), 4838–4847, <https://doi.org/10.1021/acs.analchem.9b04259>, 2020.
- Kirk, A.T.; Allers, M.; Bohnhorst, A.; Raddatz, C.-R.; Zimmermann, S.: Ultra-high resolution ion mobility spectrometry – current instrumentation, limitations and future developments, *Analytical and Bioanalytical Chemistry*, 411(24), 6229–6246, <https://doi.org/10.1007/s00216-019-01807-0>, 2019.
- Kirk, A.T.; Raddatz, C.-R.; Zimmermann, S.: Separation of isotopologues in ultra-high resolution ion mobility spectrometry, *Analytical Chemistry*, 89(3), 1509–1515, <https://doi.org/10.1021/acs.analchem.6b03300>, 2017.
- Kirk, A.T.; Zimmermann, S.: Pushing a compact 15 cm long ultra-high resolution drift tube ion mobility spectrometer with R=250 to R=425 using peak deconvolution, *Int. J. for Ion Mobility Spectrometry*, 18(1–2), 17–22, <https://doi.org/10.1007/s12127-015-0166-z>, 2015.
- Bohnhorst, A.; Kirk, A.T.; Zygmanski, A.; Yin, Y.; Zimmermann, S.: A highly efficient ion manipulator for tandem ion mobility spectrometry: Exploring a versatile technique by a study of primary alcohols, *Analytical Chemistry*, 95(18),

7158–7169, <https://doi.org/10.1021/acs.analchem.2c05483>, 2023.

Bohnhorst, A.; Kirk, A.T.; Yin, Y.; Zimmermann, S.: Ion fragmentation and filtering by alpha function in ion mobility spectrometry for improved compound differentiation, *Analytical Chemistry*, 91(14), 8941–8947, <https://doi.org/10.1021/acs.analchem.9b00810>, 2019.

Bohnhorst, A.; Berger, M.; Kirk, A.T.; Zimmermann, S.: Fast orthogonal separation by superposition of Time of Flight and Field Asymmetric Ion Mobility Spectrometry, *Analytical Chemistry*, 90(2), 1114–1121, <https://doi.org/10.1021/acs.analchem.7b03200>, 2018.

Schaefer, C.; Beijer, N.; Beukers, M.; Knotter, J.; Lippmann, M.; van de Kamp, B.; Zimmermann, S.: Detection of triacetone triperoxide by High Kinetic Energy Ion Mobility Spectrometry, *Analytical Chemistry*, 95(46), 17099–17107, <https://doi.org/10.1021/acs.analchem.3c04101>, 2023.

Allers, M.; Ahrens, A.; Hetzer, R.; Hitzemann, M.; Kobelt, T.; Schaefer, C.; Schlottmann, F.; Zimmermann, S.: Detection of volatile toxic industrial chemicals with classical ion mobility spectrometry and high kinetic energy ion mobility spectrometry, *Analytical Chemistry*, 94(2), 1211–1220, <https://doi.org/10.1021/acs.analchem.1c04397>, 2022.

Langejuergen, J.; Allers, M.; Kirk, A.T.; Oermann, J.; Zimmermann, S.: Quantitative detection of benzene in toluene- and xylene-rich atmosphere using high kinetic energy IMS, *Analytical Chemistry*, 86(23), 11841–11846, <https://doi.org/10.1021/ac5034243>, 2014.

Thoben, C.; Lippmann, M.; Raddatz, C.-R.; Salehi Moghaddam, Z.; Zimmermann, S.: Electrospray ionization ion mobility spectrometer with new tristate ion gating for improved sensitivity for compounds with lower ion mobility, *Talanta*, 233, 122579/1–9, <https://doi.org/10.1016/j.talanta.2021.122579>, 2021

Hartner, N.T.; Belder, D.; Raddatz, C.-R.; Schirmer, M.; Thoben, C.; Wink, K.; Zimmermann, S.: Coupling droplet microfluidics with ion

mobility spectrometry for monitoring chemical conversions at nanoliter scale, *Analytical Chemistry*, 93(40), 13615–13623, <https://doi.org/https://doi.org/10.1021/acs.analchem.1c02883>, 2021

Piendl, S.K.; Belder, D.; Hartner, N.T.; Raddatz, C.-R.; Thoben, C.; Zimmermann, S.: On-line coupling of chip-electrochromatography and ion mobility spectrometry, *Analytical Chemistry*, 92(22), 15129–15136, <https://doi.org/10.1021/acs.analchem.0c03446>, 2020

Belder, D.; Hartner, N.T.; Piendl, S.K.; Raddatz, C.-R.; Thoben, C.; Varias, R.; Zimmermann, S.: 2D in seconds: coupling of chip-HPLC with ion mobility spectrometry, *Analytical Chemistry*, 91(12), 7613–7620, <https://doi.org/10.1021/acs.analchem.9b00302>, 2019

Langejuergen, J.; Beutel, S.; Hopmeier, T.; Scheper, T.; Wagner, C.; Zimmermann, S.: Non-invasive monitoring of bacterial growth and auto-induced protein production in a bioreactor with a closed-loop GC-IMS, *Int. J. for Ion Mobility Spectrometry*, 18(1-2), 9–15, <https://doi.org/10.1007/s12127-014-0163-7>, 2015.

Ahrens, A.; Zimmermann, S.: Towards a handheld, fast and sensitive gas chromatograph-ion mobility spectrometer for detecting volatile compounds, *Analytical and Bioanalytical Chemistry*, 413(4), 1009–1016, <https://doi.org/10.1007/s00216-020-03059-9>, 2021.

Bohnhorst, A.; Kirk, A.T.; Zimmermann, S.: Toward compact high-performance ion mobility spectrometers: Ion gating in ion mobility spectrometry, *Analytical Chemistry*, 93(15), 6062–6070, <https://doi.org/10.1021/acs.analchem.0c04140>, 2021.

Pellizzari, E.D.: Electron capture detection in gas chromatography, *J. Chrom. A*, 98, 323–361, [https://doi.org/10.1016/S0021-9673\(00\)92077-6](https://doi.org/10.1016/S0021-9673(00)92077-6), 1974.

Lovelock, J.E.: Atmospheric Fluorine Compounds as Indicators of Air Movements, *Nature*,

230, 379, <https://doi.org/10.1038/230379a0>, 1971.

Lovelock, J.E.; Maggs, R.J.; Wade, R. J.: Halogenated Hydrocarbons in and over the Atlantic, *Nature*, 241, 194–196, <https://doi.org/10.1038/241194a0>, 1973.

Belisle, J.; Hagen, D.F.: A method for the determination of perfluorooctanoic acid in blood and other biological samples, *Analytical biochemistry*, 101, 369–376, [https://doi.org/10.1016/0003-2697\(80\)90202-X](https://doi.org/10.1016/0003-2697(80)90202-X), 1980.

Koch, A.; Aro, R.; Wang, T.; Yeung, L.W.: Towards a comprehensive analytical workflow for the chemical characterisation of organofluorine in consumer products and environmental samples, *TrAC Trends in Analytical Chemistry*, 123, 115423, <https://doi.org/10.1016/j.trac.2019.02.024>, 2020.

Namazkar, S.; Abel, S.; Abou-Elwafa Abdallah, M.; Benskin, J. P.; Branzell, F.; Harrad, S.; Josefsson, A.; Ragnarsdottir, O.: Characterization and dermal bioaccessibility of residual- and listed PFAS ingredients in cosmetic products, *Environmental science. Processes & impacts*, 26, 259–268, <https://doi.org/10.1039/D3EM00461A>, 2024.

Kaiser, D.G.; Martin, R.S.: Electron-capture GLC determination of ibuprofen in serum, *Journal of pharmaceutical sciences*, 67, 627–630, <https://doi.org/10.1002/jps.2600670514>, 1978.

Hamann, S.R.; McAllister, R.G.: Measurement of nifedipine in plasma by gas-liquid chromatography and electron-capture detection, *Clin Chem*, 29, 158–160, <https://doi.org/10.1093/clinchem/29.1.158>, 1983.

Ho, T.D.; Anderson, J.L.; Chetwyn, N.P.; Wang, J.; Yehl, P.M.; Zhong, Q.: Determination of trace level genotoxic impurities in small molecule drug substances using conventional headspace gas chromatography with contemporary ionic liquid diluents and electron capture detection, *J. Chromatogr. A*, 1361, 217–228, <https://doi.org/10.1016/j.chroma.2014.07.099>, 2014.

Kavrentzos, A.; Karavas, E.; Tzanavaras, P.D.; Vastardi, E.; Zacharis, C.K.: Analyzing Alkyl Bromide Genotoxic Impurities in Febuxostat Based on Static Headspace Sampling and GC-ECD, *Pharmaceuticals*, 17, 422, <https://doi.org/10.3390/ph17040422>, 2024

Zgherea, G.; Stoian, C.; Peretz, S.: Analytical aspects regarding the flavor compounds in beer, *Journal of Liquid Chromatography & Related Technologies*, 34, 1268–1282, <https://doi.org/10.1080/10826076.2011.588070>, 2011.

Collin, O.L.; Derhodes, K.E.; Jackson, G.P.; McCord, B.R.; Niegel, C.: Fast gas chromatography of explosive compounds using a pulsed-discharge electron capture detector, *Journal of forensic sciences*, 51, 815–818, <https://doi.org/10.1111/j.1556-4029.2006.00171.x>, 2006.

Maggs, R.J.; Davies, A. J.; Joynes, P.L.; Lovelock, J.E.: Electron capture detector. New mode of operation, *Anal. Chem.*, 43, 1966–1971, <https://doi.org/10.1021/ac60308a014>, 1971.

E13 Committee: Practice for Use of Electron-Capture Detectors in Gas Chromatography, ASTM International, West Conshohocken, PA, <https://doi.org/10.1520/E0697-96R11>, 2011.

Simmonds, P.G.: Electron-capture detector with a photoemissive electron source, *J. Chrom. A*, 399, 149–164, [https://doi.org/10.1016/S0021-9673\(00\)96118-1](https://doi.org/10.1016/S0021-9673(00)96118-1), 1987.

Wentworth, W.E.; Batten, C.F.; Tishbee, A.; Zlatkis, A.: Photo-electron capture detector, *J. Chrom. A*, 112, 229–246, [https://doi.org/10.1016/S0021-9673\(00\)99956-4](https://doi.org/10.1016/S0021-9673(00)99956-4), 1975.

Bunert, E.; Bernhold, B.; Sehlmeier, M.; Woidtke, J.N.; Zimmermann, S.: Non-radioactive electron capture detector for gas chromatography – A possible replacement for radioactive detectors, *J. Chrom. A*, 1606, 460384, <https://doi.org/10.1016/j.chroma.2019.460384>, 2019.

Cai, H.; Stearns, S.D.; Wentworth, W.E.: Characterization of the pulsed discharge electron cap-

- ture detector, *Anal. Chem.*, 68, 1233–1244, <https://doi.org/10.1021/ac951047j>, 1996.
- Bunert, E.; Kueddelsmann, M.J.; Zimmermann, S.: Electron capture detector based on X-ray ionization, *tm - Technisches Messen*, 89, 72–76, <https://doi.org/10.1515/teme-2022-0059>, 2022.
- Kueddelsmann, M.J.; Bunert, E.; Kirk, A.T.; Stadler, J.J.; Zimmermann, S.: Non-radioactive electron capture detector based on soft X-ray ionization for gas chromatography - A possible replacement for radioactive detectors, *J. Chrom. A*, 1711, 464453, <https://doi.org/10.1016/j.chroma.2023.464453>, 2023.
- Kueddelsmann, M.J.; Bunert, E.; Zimmermann, S.: Electron capture detector based on X-ray ionization, *tm - Technisches Messen*, 89, 72–76, <https://doi.org/10.1515/teme-2022-0059>, 2022.
- Bunert, E.; Kirk, A.T.; Kueddelsmann, M.J.; Stadler, J.J.; Zimmermann, S.: Non-radioactive electron capture detector based on soft X-ray ionization for gas chromatography – A possible replacement for radioactive detectors, *J. Chrom. A*, 1711, 464453, <https://doi.org/10.1016/j.chroma.2023.464453>, 2023.
- Faist, J. et al., *Science* 1994, 264 (5158), 553 – 556. doi: 10.1126/science.264.5158.553
- Aellen, T. et al., *Appl. Phys. Lett.* 2003, 83 (10), 1929–1931. doi: 10.1063/1.1609044
- Nanoplus, DFB Interband Cascade Lasers from 3000 nm to 6000 nm, 2005, <https://nanoplus.com/products/interband-cascade-laser> (accessed on: March 11th 2025)
- Luedeke, S.; Fischer, P.; Pfeifer, M.: *J. Am. Chem. Soc.* 2011, 133 (15), 5704 – 5707. DOI: 10.1021/ja200539d
- Wenke, L.: „Standoff detection of backscattered light based on tunable diode laser absorption spectroscopy,“ *Infrared Physics & Technology*, Bd. 130, p. 104, 586, 2023.
- Kwaśny, M.; Bombalska, A.: „Optical Methods of Methane Detection,“ *Sensors*, Bd. 23, Nr. 5, p. 2834, 2023.
- Barchyn, Z.E.; Bauer, J.; Hugenholtz, C.H.; Myshak, S.: „A UAV-based system for detecting natural gas leaks,“ *Journal of Unmanned Vehicle Systems*, Bd. 6, Nr. 1, p. 18, 2017.
- Alberti, G.; Augustin, J.; Ball, B.C.; Boeckx, P.; Cantarel, A.; Castaldi, S.; Chirinda, N.; Chojnicki, B.; Giebels, M.; Rees, R.M.; et al. Nitrous oxide emissions from European agriculture - an analysis of variability and drivers of emissions from field experiments. *Biogeosciences* 2013, 10, 2671–2682, doi:10.5194/bg-10-2671-2013.
- Picarro.com: Inc, P. Picarro_G5310 Analyzer Datasheet. Available online: https://www.picarro.com/environmental/g5310_analyzer_datasheet (accessed on: March 11th 2025)
- Rothman, L.S.; Gordon, I.E.: The HITRAN Molecular Database. *Aip Conf Proc* 2013, 1545, 223–231, doi:10.1063/1.4815858.
- Umweltbundesamt. Atmosphärische Treibhausgas-Konzentrationen 2023 <https://www.umweltbundesamt.de/daten/klima/atmosphaerische-treibhausgas-konzentrationen#lachgas> (accessed on: March 11th 2025)
- Hodgkinson, J.; Tatam, R.P.: Optical gas sensing: a review. In: *Measurement Science and Technology* 24 (2012), nov, Nr. 1, S. 012004
- Hänsch, T.W. *Passion for Precision*. 2005
- Udem, T.; Hänsch, T.W.; Holzwarth, R.; Reichert, J.: Absolute Optical Frequency Measurement of the Cesium D1 Line with a Mode-Locked Laser. In: *Phys. Rev. Lett.* 82 (1999), May, S. 3568–3571
- Schiller, S.: Spectrometry with frequency combs. In: *Optics letters* 27 (2002), May, Nr. 9
- Nitzsche, L.: Doppel-Frequenzkamm-Spektrometer für die Spurengasdetektion, *Gas Sensors*, 14 Shaker Verlag, Düren, 2023 ISBN: 9783844091885
- Nitzsche, L.; Goldschmidt, J.; Kiessling, S.; Kühnemann, F.; Wöllenstein, J.; Wolf, S.: “Tunable

dual-comb spectrometer for mid-infrared trace gas analysis", *Opt. Express* 29, 25449–25461 (2021)

EPA, U.S.; OA. Understanding Global Warming Potentials | US EPA.2025
<https://www.epa.gov/ghgemissions/understanding-global-warming-potentials> (accessed on: March 11th 2025)

FTIR: <https://www.flir.de/instruments/optical-gas-imaging/> (accessed on: March 11th 2025)

Goldschmidt, J.; Lambrecht A.; Nitzsche, L.; Wöl-
lenstein, J.: "Two-component gas sensing with
MIR dual comb spectroscopy", *tm - Technisches
Messen*, Vol. 89, Iss. 1, p. 50 (2022)

Vu et al.; Realization of a PEDOT:PSS/Graphene
Oxide On-Chip Pseudo-Reference Electrode for
Integrated ISFETs Sensors 2022, 22, 2999,
<https://doi.org/10.3390/s22082999>

Xue, M.; Mackin, C.; Weng, WH.; et al. Inte-
grated biosensor platform based on graphene
transistor arrays for real-time high-accuracy ion
sensing. *Nat Commun* 13, 5064 (2022).
<https://doi.org/10.1038/s41467-022-32749-4>

<https://graphene-flagship.eu/> (accessed on:
March 11th 2025)

Kwon et al., 2022. The significance of elevated
tumor markers among patients with interstitial
lung diseases. *Sci. Rep.* 12, 16702
<https://doi.org/10.1038/s41598-022-20683-w>

Flauzino, José MR, et al., "Click and Detect: Ver-
satile Ampicillin Aptasensor Enabled by Click
Chemistry on a Graphene–Alkyne Derivative";
Small (2023), DOI: 10.1002/sml.202207216

Rakhi, R.B; Alshareef, H.N.; Nayak, P.; Xia, C.;
(2016) Novel amperometric glucose biosensor
based on MXene nanocomposite. *Sci Rep*
6(1):36422. <https://doi.org/10.1038/srep36422>

Selvi Rajasekaran, S.J.: Gopal, T.; Abeykoon, C.;
Alodhayb, A.N.; Amarnath, K.; Grace A. N.; Gun-
aseelan, B.; James, J.T.; Kumar, V.G.; Malathi, A.
C. J.; Mr M; Pandiaraj, S.; Pitchaimuthu, S.;
Raghavan, V.; Ramesh, K.; MXene-Embedded
Porous Carbon-Based Cu₂O Nanocomposites
for Non-Enzymatic Glucose Sensors. *ACS*

Omega. 2024 Feb 12;9(7):8448–8456.
doi:10.1021/acsomega.3c09659. PMID:
38405472; PMCID: PMC10882672.

Sakata, T.: Biologically coupled gate field-effect
transistors meet in vitro diagnostics. *ACS*
Omega, 2019, 4(7), 11852–11862.

Dieleman J.L. et.al Future and potential spend-
ing on health 2015–40: development assistance
for health, and government, prepaid private, and
out-of-pocket health spending in 184 countries.
The Lancet, Volume 389, Issue 10083, 2017

Edebeli, J.; Anet, J.; Fierz, M.; Fluck, S.; Spirig, C.:
Spatiotemporal Heterogeneity of Lung-Depos-
ited Surface Area in Zurich Switzerland: Lung-
Deposited Surface Area as a New Routine Met-
ric for Ambient Particle Monitoring, *Int J Public
Health* 68:1605879, [https://doi:
10.3389/ijph.2023.1605879](https://doi.org/10.3389/ijph.2023.1605879), 2023.

Kulkarni, P.; Baron, A.; Willeke, K., (Eds.): Aero-
sol Measurement, Principles, Techniques, and
Applications, J. Wiley and Sons.,
ISBN:9780470387412, 2011.

Rabuan, U., et al.: Evaluations of Low-cost Air
Quality Sensors for Particulate Matter (PM_{2.5})
under Indoor and Outdoor Conditions, *Sens.
Mater.*, 35, 2881–2895,
<https://doi.org/10.18494/SAM4393>, 2023.

TRUMPF (2024) Whitepaper-ViP-VCSEL-with-
integrated-photodiode. www.trumpf.com (ac-
cessed on: March 11th 2025)

Fierz, M.; Burtscher, H.; Scherrer, L.: Real-time
measurement of aerosol size distributions with
an electrical diffusion battery, *J. Aerosol Sci.*, 33,
1049–1060, [https://doi.org/10.1016/S0021-
8502\(02\)00057-5](https://doi.org/10.1016/S0021-8502(02)00057-5), 2002.

Burtscher, H.; Fierz, M.; Meier, D.; Steigmeier, P.:
Aerosol Measurements by induced currents.
Aerosol Sci. Technol., 48, 350–357,
[https://doi.org/10.1080/02786826.2013.87598
1](https://doi.org/10.1080/02786826.2013.875981), 2014.

Schriebl, M.A.: Bergmann, A.; Fierz, M.; Design
Principles for Sensing Particle Number Concen-
tration and Mean Particle Size With Unipolar
Diffusion Charging, *IEEE Sensors*, 19, 1392–

1399, [https://doi:10.1109/JSEN.2018.2880278](https://doi.org/10.1109/JSEN.2018.2880278), 2019.

Melas, A., Vasilatou, K., Suarez Bertoa, R., and Giechaskiel, B.: Laboratory measurements with solid particle number instruments designed for periodic technical inspection (PTI) of vehicles, *Measurement*, 215, 112839, JRC132681, <https://doi.org/10.1016/j.measurement.2023.112839>, 2023

Burtscher, H.; Siegmann, H.C.: Monitoring PAH-Emissions from Combustion Processes by Photoelectric Charging, *Combust. Sci. Technol.* 101, 327–332, <https://doi.org/10.1080/00102209408951880>, 1994.

Ramos-Contreras, C.; Molina-Pérez, F.; Ramírez-Casas, G.: Real-Time Monitoring of Polycyclic Aromatic Hydrocarbons associated with particles in high traffic flow roads of the Aburrá Valley Metropolitan Area (AMVA), 9 Congreso Colombiano y Conferencia Internacional de Calidad de Aire y Salud Pública (CASP), pp. 1–6, [https://doi:10.1109/CASAP48673.2019.9364044](https://doi.org/10.1109/CASAP48673.2019.9364044), 2019.

Olszok, V.; Rembe, Ph.; Weber, A.: Aerosol Photoemission as a Versatile Tool for Nanoparticle Surface Investigations: Evaluation of Metal Oxide Formation and Surface Properties of Multi-Component Particles, *Aerosol Sci. Technol.*, 58, 54–69, [https://doi:10.1080/02786826.2023.2285307](https://doi.org/10.1080/02786826.2023.2285307), 2023.

Fischer, D.; Smith, G.: A portable, four-wavelength, singlecell photoacoustic spectrometer for ambient aerosol absorption, *Aerosol Sci. Technol.*, 52, 393–406, [https://doi:10.1080/02786826.2017.1413231](https://doi.org/10.1080/02786826.2017.1413231), 2018.

Betschon, F.; Bilal, J.; Flöry, N.; Rüggeberg, T.; Steigmeier, P.; Visser, B.; Weingartner, E.; Wipf, M.: Waveguide based passively demodulated photothermal interferometer for light absorption measurements of trace substances. *Appl. Optics* 62 (2): 374–384, <https://doi.org/10.1364/ao.476868>, 2023.

Hoffmann, J.; Karlen, N.; Rüggeberg, T.; Visser, B.; Weingartner, E.; Weiss, D.: Single Aerosol Particle Detection by Acoustic Impaction, *IEEE*

Sensors, 22, 11584–93., doi.org/10.1109/jsen.2022.3172861, 2022.

Keller, A.; Specht, P.; Steigmeier, P.; Weingartner, E.: A novel measurement system for unattended, in situ characterization of carbonaceous aerosols, *Aerosol Res.*, 1, 65–79, <https://doi.org/10.5194/ar-1-65-2023>, 2023.

Eibl, D.; Eibl, R.; Kaiser, S.; Lombriser, R.: Disposable bioreactors: the current state-of-the-art and recommended applications in biotechnology. *Appl Microbiol Biotechnol.* 2010 Mar;86(1):41-9. [doi: 10.1007/s00253-009-2422-9](https://doi.org/10.1007/s00253-009-2422-9)

Scheuermann, A: Neuer Ansatz für Predictive Maintenance in Prozessanlagen, *CHEMIETECHNIK*, 2018, <https://www.chemietechnik.de/anlagentechnik/automation/neuer-ansatz-fuer-predictive-maintenance-in-prozessanlagen.html> (accessed on: March 11th 2025)

Früh, K.F.; Schaudel, D.; Tauchnitz, T.; Urbas, L. (Hrsg): *Handbuch der Prozessautomatisierung, Prozessleittechnik für verfahrenstechnische Anlagen*, 6. Auflage, Deutscher Industrieverlag, 2018

Oesterle, G.: *Prozessanalytik: Grundlagen und Praxis*, Oldenbourg Verlag 1995

Günzler, H.; Gremlich, H.-U.: *IR-Spektroskopie: Eine Einführung*. 4. Auflage. Wiley-VCH, Weinheim 2003, ISBN 978-3-527-30801-9

Lewis, I.R., Edwards, H. (Eds): *Handbook of Raman Spectroscopy: From the Research Laboratory to the Process Line*, CRC-Press, 2001

Kloska, M.: *Analytic Journal* 2017, www.analyticjournal.de (accessed on: March 11th 2025)

Arnold, R.: FTIR-Prinzip. Alles über FTIR-Spektroskopie: www.ir-spektroskopie.de (accessed on: March 11th 2025)

Schilling, M.: *Near-infrared spectroscopy: Comparison of techniques*, 2017; <https://www.metrohm.com/content/dam/metrohm/shared/documents/white-papers/WP-020EN.pdf> (accessed on: March 11th 2025)

Mettler Toledo: Tunable Diode Laser Spectroscopy, Theory and Background, 2012

Beć, K.B.; Grabska, J.; Huck, C.W.: Principles and Applications of Miniaturized Near-Infrared (NIR) Spectrometers. Chemistry. 2021 Jan 21;27(5):1514-1532. doi: 10.1002/chem.202002838

Bakirov, R.; Fay, D.; Gabrys, B.: "Multiple adaptive mechanisms for data-driven soft sensors" Computers and Chemical Engineering, vol. 96, pp. 42–54, 2017

NAMUR – Interessengemeinschaft Automatisierungstechnik der Prozessindustrie e. V.: Technology-Roadmap: Process-Sensors 2027+, 2021

Meyer, K.; Guthausen, G.; Kern, S.; Maiwald, M.; Zientek, N.: Process control with compact NMR, TrAC Trends in Analytical Chemistry, Volume 83, Part A, 2016, Pages 39-52, ISSN 0165-9936, <https://doi.org/10.1016/j.trac.2016.03.016>

Falk, J.; Heisterkamp, M.; Kaiser, U.: Von der Laboranalyse zum Feldgerät, October 2018, atp magazin 60(10):60, doi: 10.17560/atp.v60i10.2374

Brengartner, T.; Lopatin, S.; Rosenheim, J.; Schleiferböck, J.: Multiparameter Sensorik zur Überwachung von Brauprozessen, Dresdner Sensor Symposium, 2022, doi 10.5162/16dss2022/6.2

Profibus Nutzerorganisation, 2024, <https://www.profibus.com/technologies/profibus> (accessed on: March 11th 2025)

Ethernet-APL: Ethernet to the field, 2020, <https://www.profibus.com/download/apl-white-paper/> (accessed on: 6th March 2025)

NAMUR: NAMUR Open Architecture NOA Concept, 2020, <https://www.namur.net/de/fokusthemen/namur-open-architecture.html> (accessed on: 6th March 2025)

Fröhlich, H.-J.; Kaiser, U.; Persson, D.: Von der Feldgerätediagnose zum Prozess- und Anlagenmonitoring, May 2021, atp magazin 63(05):78-83, doi 10.17560/atp.v63i05.2527

Tzalenchuk, A.; Bubanja, V.; Goldstein, B.; Hendricks, J.; Ilić, D.; Pan, Y.; Prior, T.; Spethmann, N.; Temporão, G.; Yu, D.: The Expanding Role of National Metrology Institutes in the Quantum Era, Nature Physics, [online], 2022, <https://doi.org/10.1038/s41567-022-01659-z>

Ross, T.; Frey, C.: Statusermittlung nicht-intelligenter Prozessabschnitte mit dem Softwarewerkzeug PUMon, 2014, Jahrbuch Maintenance S, 78–79.

EHEDG (European Hygienic Engineering & Design Group): EHEDG Glossary, 2020, <https://www.ehedg.org/guidelines-working-groups/guidelines/guidelines/detail/ehedg-glossary> (accessed on: March 11th 2025)

Mettler Toledo: Bewährte Arbeitsverfahren für pH-Sensoren, 2015

Owen, T.: Fundamentals of Modern UV-Visible Spectroscopy: A Primer, 1996, OCLC 918510068

4 Smart Sensing

(Osten, J.; Fleck, S.; Reichenstein, T.; Barth, J.)

While classical sensors measure specific physical, chemical, or biological parameters, smart sensors combine these capabilities with advanced data processing and communication technologies. The structure of this chapter follows the path of data treatment. After an introduction with the definition of smart sensors, the data processing and network are discussed. Subsequently, information about data communication and reliability is provided, and finally, examples of industrial monitoring and predictive maintenance are listed.

4.1 Background and Motivation

(Fleck, S.; Jablonski, I.; Osten, J.; Schäfer, A.; Wöckel, S.)

The last century has been marked with a significant increase of technological advancement, driven not only by curiosity of researchers but first of all because of expectations formulated by business and its customers. More and more thorough insight into the nature of complex systems and processes is conditioned by strategies of observation strictly related to measurement action, which requires the use of sensing units. The development to smart sensors, e.g., Figure 4.1, is outlined in the following. The origin of sensors comes from the observation that one (inspected and unknown) quantity can be expressed through the prism of proportional change of a known and controlled quantity measurand [Morawski 1994]. This experimental finding, together with a fundamental knowledge on mathematical functions, brings a human being to an engineering achievement – a transducer. Preliminarily, one non-electrical quantity was transformed into another feature of a non-electrical physical field, e.g., cyclic changes of sun light were converted to a section of time (or frequency), i.e., day, number of springs. This smart achievement was an enabler for the sequences of following observations, stated facts, and discoveries [Varak et al. 2018]. In the meantime, our subjective statements became more and more objective thanks to the measurement units and even some kind of systematic in that range, e.g., the SI unit system. In conclu-

sion, a sensor as a transducer is a block which realizes the function analogous to human senses and, at the same time, is the first technical component in the measurement chain that provides the user (researcher, customer, observer in general) with information about the surroundings. This information is encoded into the data samples collected during the measurement act. Thus, data are like a suit which covers/can determine the truth about the body and human being. Here, in sensing and observation of a selected object, data are “only” the noisy carrier of the facts about the system structure, properties, and undergoing processes.



Figure 4.1 Example for smart sensor functions and features (Source: HBK)

In contrast to the interdisciplinary nature of measurement science, for many decades, a development in sensing and data exploration has been led through isolated paths. A sensor as a device was more the focus of physicists and engineers, whereas signal/data processing was the natural field of interest for mathematicians and then for computer scientists (here, mainly the domain of discrete mathematics). There were some poor interconnections that allowed to improve the interpretations of data findings with understanding the contributions from sensor properties, e.g., physical-mathematical modeling of a measurement chain, including sensor properties. The next change in the sensing paradigm was to measure more than one quantity in one device, and even to produce a sensor output which would be a kind of aggregated response to multi-excitations existing permanently in the surroundings. The assump-

tion behind that was that we can obtain more information at one time step of device (sensor) operation. The next big thing was the introduction of a computational unit, especially its miniaturized version – the microprocessor. Now, engineers were able to control the process, synchronizing the data (and information) flow and even converting raw samples of data into some product expression. Again, we have moved closer to data processing with our sensors. The true breakthrough for sensor technology comes from the development of communication systems and sophisticated schemes of signal/data processing. Firstly, a growing expectation of societies in permanent movement was to operate in distributed systems, and then even to substitute human-operated terminals with surrounding-aware and connected technical peripherals (machine-to-machine communication). Secondly movement in space was accompanied with requirements to be ever faster, and even more precise in a sense of space and time. To address these needs, engineers designed faster and faster computing devices, and specialists in data processing created more and more efficient schemes of data exploration. Schemes, here, means not only the algorithms, but also the architecture of the systems which can boost data flow between multiple peripherals collaborating in a networked-like structure. In analogy to the human connectome networks [Banavar et al. 1999; Barabasi 2007], data flowing through the pipeline of communication channels not only need to be controlled, but also processed and managed adequately to the physical context. This is the motivation to apply the cutting-edge findings in data science, which now knocks on the door of extremely efficient processing of data heterogeneous in nature, fusion of information, and even of the imitation of human reasoning [Zhu et al. 2023]. This paves the way to saying that, with the smart sensor and regarding the trends to miniaturization, small invasiveness and even visualization, we can expect that sensor transducers which have been well-known for a century will migrate to the soft sensing blocks [Perera et al. 2023]. The common denominator of the so-called “classical” and the “smart” sensor is that both devices participate in the acquisition of raw data. Since computational intelligence operating on measured data is the leading paradigm for injecting intelligence into technical devices (here: sen-

sors), and the linking of sensors and computing blocks (in a cloud or edge architecture) in the measurement path expresses advances in modern sensing technology, algorithmics relevant to extracting information from raw data has become an unavoidable component of the smart sensor. In this way, professionals involved in designing smart sensors use a spectrum of signal processing tools ranging from deterministic, through statistical mathematics, to statistical learning techniques valid in artificial intelligence; here, the latter shows the most powerful potential for extracting and aggregating knowledge from noisy raw data.

There are followers of two standpoints on artificial intelligence (AI) in the scientific and engineering community [Searle 1980]. The former – so called strong artificial intelligence – argue that the strength of artificial intelligence lies in the hardware configuration where the algorithms are implemented, while the latter point to the dominant role of algorithms and software in the quality and performance of AI circuits – so called soft artificial intelligence. From the business point of view, which uses measurement methods and instrumentation, the key is to minimize the latency in observation of (dynamical) objects and processes. It means that we should operate efficiently as close as possible to the observed object, i.e., in a first technical block in the measurement pipeline – the sensor. This sensor can communicate with the other terminal devices operating in network structure, but some information can now be retrieved directly with the hardware/software configuration of the sensor circuits. In the field of techniques, this concept is referred to as working at the edge, while in the domain of sensing, it is termed edge sensors/devices. Since the potential to be smart can be encoded both in the system configuration and the algorithm design, and the same artificial intelligence can imitate the individual and/or collective emanation of smartness, currently the technique is looking for the best performance of smart sensing systems mixing the cloud and edge systematics, and constantly improving the hardware and software (data processing algorithms) layers of smart sensors. Undoubtedly, that effort in smart sensing will enable to define and realize the conception of future autonomous (zero-touch) systems, significant for businesses and stakeholders.

In past decades, with a classic measurement chain, consisting of a sensor and data acquisition, data processing usually took place in the backend.

Depending on the physical or chemical measurement quantity, the sensor is processing

- quite static quantities, e.g., temperature and pressure, or
- more dynamic data such as vibration (accelerometers, see Figure 4.2), but also other mechanical quantities like force (e.g., in a braking system or a durability testing machine), torque (e.g., jitter i.e., micro-vibrations in aerospace or electric cars), or load (e.g., filling systems) increasingly produce incredible volumes of dynamic data.



Figure 4.2 Accelerometer series 7500 (Source: HBK)

As sensors are resource-limited systems, many challenges arise, especially in the second category. At the same time, if data are processed at the sensor level while using a data bus as a way to transmit the processed data, this clears the way for machinery diagnostics.

Definition of Smart Sensor

The term “smart sensor” was first coined in the mid-1980’s by [Giachino 1986]. Since then, many descriptions for smart sensors have been introduced [Travis 1996; Dierauer 1998]. To offset some of the confusion, the IEEE and U.S. National Institute of Standards and Technology (NIST) derived the smart-sensor standard, which standardizes the networking protocol and features embedded in sensor technology [Frank 2000]. Overall, the prevailing definition of a smart sensor classifies such a device as a sensor that incorporates communication capability, self-diagnostics, and intelligence (decision making). Of course, utilizing such broad criteria for smartness ensures that the class of smart sensors encompasses a wide range of variations. For example, intelligence could represent anything from simple switching logic to a compli-

cated sequence of behaviors. Thus, in order to realistically categorize smart devices, a classification or taxonomy must be utilized to discriminate between the extremes of intelligence.

By analyzing the intelligence capabilities that advanced sensor class (consisting of smart, cognitive and intelligent sensors) devices should exhibit, five main attributes are derived. Advanced sensors must be capable of:

- *Self-knowledge*: identifying its purpose and understanding its operational functions
- *Communication*: transmitting/receiving information (versus raw data) to/from other devices
- *Perception*: the ability to recognize, interpret, and understand sensory stimuli
- *Reasoning*: making decisions based on perception of sensory stimuli
- *Cognition*: the intellectual process of knowing, which includes aspects such as awareness, perception, reasoning, and judgment

Based on these desired capabilities, a hierarchy is defined for grouping sensor devices together based on their intelligence. This process provides us with three layers of sensor devices: smart sensors, intelligent sensors, and cognitive sensors (Figure 4.3). A smart sensor exhibits attributes of self-knowledge and communication, such as defined by [Giachino 1986]. An intelligent sensor builds upon the smart sensor construct and incorporates the perception trait into its feature set. The cognitive sensor further expands its capabilities by including the qualities of reasoning and cognition into its design.

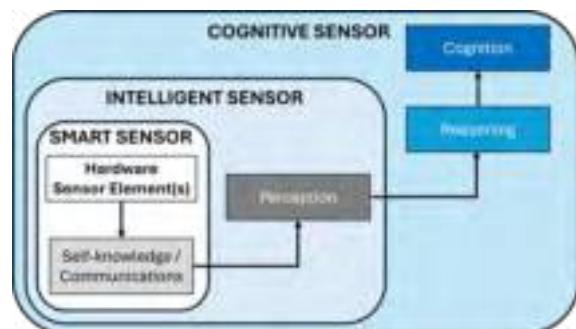


Figure 4.3: Intelligence hierarchy for advanced sensor devices (Source: Dr. Irek Jablonski, Fraunhofer IPMS)

To truly understand this hierarchy (Figure 4.3), consider the following example of a sensor capable of intelligent fault tolerance in a robotic system. In this case, a sensor capable of fault detection would be classified as a smart sensor. It possesses self-knowledge, for it can detect anomalies based on its standard operation, but it does not “understand” the cause of an anomaly and thus would not be classified as an intelligent or cognitive sensor. On the other hand, a sensor capable of fault diagnosis not only detects faults as they occur but can determine the cause of an anomaly by interpreting the data input in real time. This type of sensor would be classified as an intelligent sensor. Continuing with this logic, a cognitive sensor would be represented by a sensor capable of fault repair, in addition to detection and diagnosis. Such a sensor would not only reason about the data but would be able to decide how to overcome its deficiencies by using its embedded knowledge base. Cognitive sensors may implicitly include world modeling as a function of cognition. While this is not a requirement, they typically include some form of internal representation contrived from raw sensor inputs that can be reasoned about to achieve a concept of “knowing”.

Using explanations as above, we can clearly see that – regardless of smartness, intelligence, or cognition – the modern understanding of artificial intelligence is strictly attributed to the computation capability, which materializes as an algorithmic cycle of calculation operations (algorithm) realized on hardware resources [Zhu et al., 2023].

For our immediate purposes, we are mainly concerned with the development of the cognitive sensor, with the realization that the hardware for each sensor type may remain the same whether cognitive, intelligent, or smart. The main difference between each sensor type lies with the intelligence, and thus the focus is on the software that is embedded within the device. The physical realization of an advanced sensor is a hardware sensor device coupled with software-based intelligence embedded in an on-board microcontroller, digital signal processor (DSP), field programmable gate array (FPGA), application-specific integrated circuit (ASIC), or other computing device(s). The hardware structure defines the sensor class, while

the software characterizes the type of intelligence capabilities exhibited by the hardware.

Comparison of a Classical Sensor to a Smart Sensor

Summing up, the terms “sensor” or “sensor system” classically describe a system of two components: the physical sensor head and the measurement electronics. Typically, the sensor converts a physical into an electrical signal. In the next step, the meaning of “smart sensors” describes mostly the additional combination with processing intelligence or algorithm extracting the desired physical information and communication capabilities.

In this study, a detailed description of different physical (Chapter 2) and chemical (Chapter 3) measurement quantities is presented. There, you can find descriptions of physical principles for different classical sensors: mechanical measurands, acoustic measurands, electrical measurands, magnetic measurands and optical measurands. In dependence of the exact classical sensors, different shortcomings might occur. A classical sensor consists of the measuring unit for mainly one specific measurand and might be connected to a computer for further data analysis. A smart sensor also has a measurand unit and, in addition, more computation power and a connection to other sensors or the cloud. In the following overview, different properties of sensor types are compared. Both sensor types have in common that the initial sensor input is the same and systematic errors can occur. In the following, properties of a classical sensor are compared to the smart sensor. The classical sensor is always mentioned first, followed by the smart sensor.

Measurement Control:

- Classical sensor: slow measurement control if done by human (manual) but faster when done by preprogrammed software
- Smart sensor: faster measurement control, which can be done automatically based on the evaluated measurement data

Data Processing:

- Classical sensor: low computation capacities on the sensor side, raw data transferred to be analyzed off side
- Smart sensor: Powerful computation and communication capabilities, digital signal, which could be preprocessed or analyzed on side (edge), or the data is processed in a cloud.

Data Amount:

- Classical sensor: raw data (digital or analog)
- Smart sensor: pre-processed data (digital), reduced data amount compared to raw data, less initial data compared to classical sensors required because of easier data analysis

Analytics of the Data [Arino et al. 2019]

- Classical sensor: univariate analysis, multivariate analysis is not common
- Smart sensor: array of cross-sensitive sensors combined with multivariate data processing tools (multivariate analysis) for non-trivial data analysis

Corrected Values in Dynamic Measurement Applications [Bruns and Eichstädt 2018]

- Classical sensor: not possible
- Smart sensor: knowledge about interaction and own internal properties and state leads to corrected measurement values.

Effect of Measurement Disturbing Effects

- Classical sensor: maybe false measurement signal
- Smart sensor: synchronization of different smart sensors reduces measurement errors of the complete system

After this comparison, the definition and the components of a smart sensor are introduced.

Smart Sensor Design

The development of a cognitive sensor involves embedding hardware and software into one unified cognitive system. A general design process begins with identification and selection of sensing elements or devices based on the range of desired applications. Requirements derived from the functional description of a particular application are used to drive the refinement of sensor device specifications, embedded software design, and any necessary hardware augmentations (e.g., actuator selection for active sensing systems). Following the selection of baseline components of the cognitive sensor, interfacing and data flow issues must be addressed. The interplay of architectural interfaces defining data flow between the key components and the processor, as well as sensing and control signals among them, must be carefully considered. An appropriate trade-off between these extremes must be made based under consideration of the target application and the capabilities of selected components. At this point in the design process, the cognitive sensor is simply a programmable sensing and computing device. The design process may conclude with a typical embedded software design and development cycle focused on the target application. With a more or less static hardware architectural configuration, a range of capabilities for a given cognitive sensor may be realized by simply changing the embedded software application – a means to achieve re-usability of the same underlying hardware infrastructure for alternative sensing functionality.

A sensor is a device that detects and responds to inputs from the physical environment, such as light, heat, motion, moisture, pressure, or various other environmental phenomena. The output from a sensor is typically a signal that is converted to a human-readable display at the sensor location or transmitted for further processing or reading.

On the other hand, a sensor system encompasses not just the individual sensors but also an integrated set of components that support the sensors' functionality. This includes processing units, communication interfaces, power management, and software algorithms that are designed to interpret and act on the data col-

lected by the sensors. The added functionality within a sensor system enables more complex operations, such as the fusion of data from multiple sensors, real-time analysis, and decision-making capabilities.

To elucidate the relationships and performance metrics within various parts of a sensor system, the concept of virtual pins is useful. Virtual pins act as clearly defined interfaces between the individual components of a sensor system, facilitating the specification and measurement of Key Performance Indicators (KPIs) and performance values at these junctures. This structured approach aids in the analysis and optimization of the overall functionality and performance of the sensor system.

Incorporating standards such as the IEEE P2020 [IEEE Standards Association P2020 2020] standard for automotive imaging is critical in this context. The IEEE P2020 standard focuses on defining performance metrics and methodologies for evaluating the quality of automotive imaging systems, which are a crucial part of sensor systems in vehicles. By aligning with standards like IEEE P2020, developers and engineers can ensure that their sensor systems meet rigorous quality and performance benchmarks, particularly for applications that rely heavily on visual inputs, such as autonomous driving technologies. This reference to a recognized standard emphasizes the importance of measurable, standardized criteria for assessing

and ensuring the effectiveness of automotive sensor systems.

Smart sensors in contrast to a traditional raw sensor head are conceptually visualized in Figure 4.4.

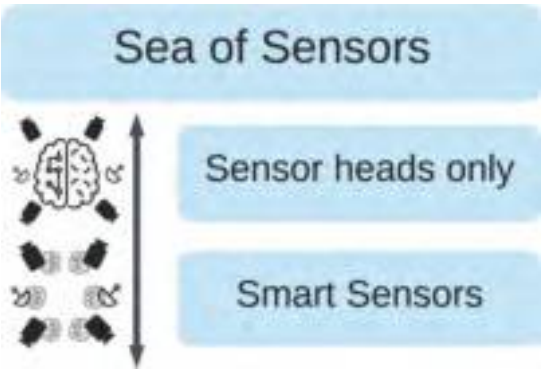


Figure 4.4 Sea of sensors

In the domain of Autonomous Driving (AD), a specific example of smart sensors vs. a centralized approach with sensor heads is illustrated in Figure 4.5.

Future and Market of Smart Sensors

The combination of IoT trends with either advanced sensors (e.g., intelligent camera) or sensor swarms, both producing a large amount of data, emerges as one of the modern examples how the concept of a smart sensor system can be realized. Beside the classic model-based processing of the data, the advances and the acceptance of AI-technologies will characterize the future application of those smart sensors.

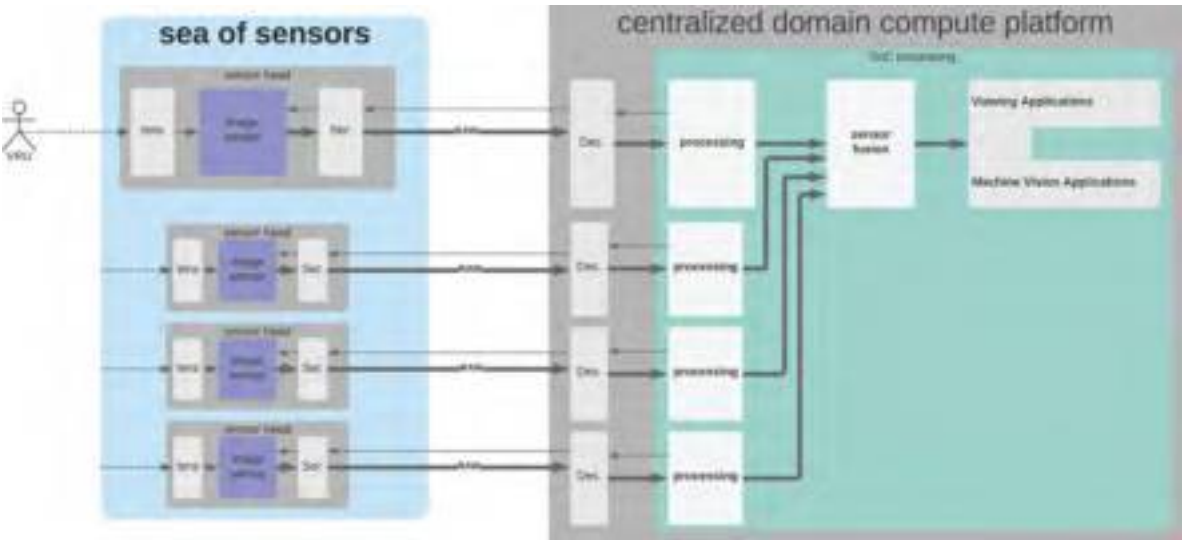


Figure 4.5 Sensor head approach

The major advances are at hand: the interplay between AI and IoT creates real added value for many IoT areas, particularly for automation and networked production. Thanks to AIoT (Artificial Intelligence of Things), machines provide data via their sensors that can be analyzed quickly and efficiently using machine learning [Dusun 2024]. AI could even also be the solution for avoiding unnecessary data transfer.

In 2023, the terms smart sensor and IoT, Artificial-IoT and Security were among the most frequently cited IoT trends. And, for the first time, industrial uses cases with AI are showing up (AIoT) [Günes 2024]. Another trend is that sensors are becoming smarter and can act as edge devices [De Luca 2023]. In 2024, awareness of the benefits of AI for IoT projects increased and the first companies combined artificial intelligence in production with the Internet of Things.

Looking to the future, in 2028, IoT and AI named AIoT will be a standard tool. Looking at the growing number of industrial field devices in combination with sensors, the major challenges when interconnecting the sensors via internet technologies will be the sustainable (energy conserving) processing and communication and the secure handling of the data. Additional international challenges will be the regulation of the wireless technologies for interconnection and secure distribution of information on physical storage over the world. Applied AI belongs to one of the major tech trends. This trend also affects information technology and electronics. For example, machine learning and prediction can be part of smart sensing [Chui et al. 2023]. AI-based machine vision for image sensors is a technology trend mainly for event-based cameras. The use of edge AI in machine vision system for different applications fields is possible [Bouhamari et al. 2024]. The addition of AI to ultrasound sensors could bring automated interpretation and measurement to support diagnosis and decisions [Delbos et al. 2023]. Other business models of smart sensors are the use of data from process sensors and the monitoring of production modules as described in [Bassler et al. 2021].

Market

It has been observed that developments tailored to specific targeted applications (market

pull) are increasingly dominating basic innovations (technology push). There is an interdependence between market push and technology pull, and there is the potential of technology-driven leading-edge research to create entirely new markets over period of time [National Research Council 1995]. This might be the case for the application of AI to sensors.

Looking at industrial devices with processing power in Germany, this concerns a number of 35 million field devices in 2020, growing to a number of 45 million devices in the year 2030 [Edge-Power 2024], not including all IoT sensors that are connected to each field device.

In addition to pure IoT sensors in the process industry, a total of up to 15 billion IoT devices will be connected to company infrastructures by 2030. This means that 75 % of all devices are expected to be IoT devices [Perri 2023].

The global smart sensor market size was valued at \$ 37.12 billion in 2019, and smart sensor market size is projected to reach \$ 91.37 billion by 2027, to register a CAGR of 14.30 % from 2020 to 2027. Smart sensors are occurring for different measurement task. Trends might be different for different sensors [Sachan and Mutreja 2021]. It is expected that the boom in the Fourth Industrial Revolution (4 IR) contributes to over two trillion euros to the EU economy by the end of 2030. Sensors do belong to one of the three core technologies of 4 IR [Grilli et al. 2022].

The European patent office analyzed SME (small and medium-sized enterprises) belonging to 4IR in Europe. These SME created technological developments in the areas of IoT and data management (up to 69 %), automation of devices (44 %) and 3D-Systems technologies (24 %). 4IR SME active in these fields have higher investment intensity compared to the average SME in the EU [Grilli et al. 2022]

Figure 4.6 shows that the US has twice as many 4IR SME compared to the EU. In both areas, the number of 4IR international patents is increasing over time; in Europe from 9 % up to 11 % in 2018.

In short, smart sensors have what it takes to multiply the number of measurement tasks,

making them one of the most tempting growth opportunities in the sensor industry.

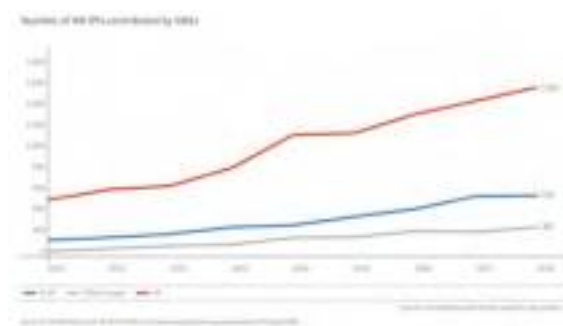


Figure 4.6 Number of 4IR International patent families in dependence of years for EU27, other Europe and US (Source: © Grilli et al. 2022)

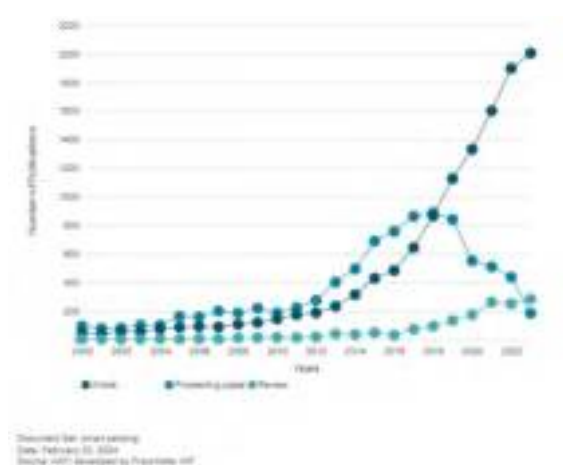


Figure 4.7 Number of publications about smart from 2000 to 2023 (Source: Dr. Julia Osten, Fraunhofer IPMS)

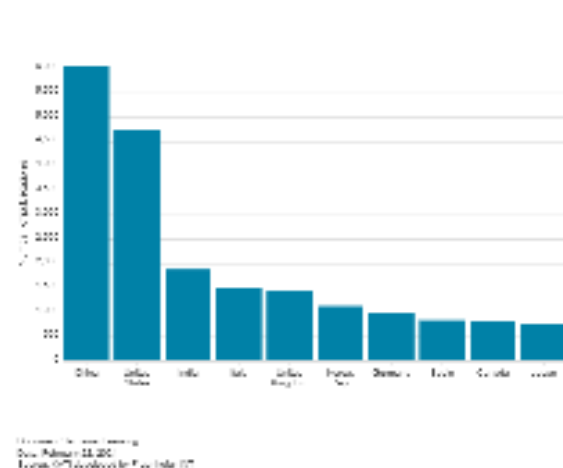


Figure 4.8 Number of smart sensing publications per country from 2000 to 2023 (Source: Dr. Julia Osten, Fraunhofer IPMS)

As shown in Figure 4.7, the number of reviewed articles in web of science which are dealing with smart sensors have been continuously increasing from 2020 onwards. There is a decrease in

proceeding papers and a slight increase in reviews about this topic. The top three categories where one can find publications on this topic are: engineering, electrical and electronics, telecommunications, and material science. The countrys' publication activity in this time period shows that Germany is globally on the seventh place. China, the United States, and India are the most active countries concerning publications with correlation to smart sensing [Fraunhofer 2024; Marcus et al. 2021].

In the strategic research and innovation agenda 2023 about electronic components and systems, various aspects of smart sensors like edge computing, embedded artificial intelligence and connectivity are mentioned in the section "cross-sectional technologies" [ECS Community 2024]. Also, cybersecurity-related issues are addressed with five major challenges. To sum up, smart sensor technologies are a hot topic when it comes to the scientific community and are also part of other strategic roadmaps.

Ethical Aspects of AI

AI is changing human interaction in almost all areas of society. Therefore, ethic aspects are an important issue when dealing with smart sensors. These aspects are addressed by the German ethics council. In its publication "Humans and Machines – Challenges of Artificial Intelligence" [Deutscher Ethikrat 2023], the German ethics council discussed selected topics like medicine, public communication, public administration, and cross-divisional topics. Cross-divisional topics with high overlap to smart sensors are data sovereignty, critical infrastructure, bias and discrimination, and transparency. In this publication, ethical advice on smart sensors can be found.

The draft of the EU Artificial Intelligence Act adopts a risk-based approach with the categories: unacceptable risk, high risk, limited and minimal risk [Future of Life Institute 2024]. All of these upcoming regulations will have an effect on further AI development. In the following subchapters, we are focusing on the technical aspects of smart sensors.

The order of the following subchapters corresponds to the data processing path. The start is with data processing and networking, followed

by data communication. In the fourth part, reliability is discussed. At the end, you will find various examples of condition monitoring.

4.2 Data Processing and Network

(Osten, J.; Fleck, S.; Trsek, H.; Lohweg, V.; Jablonski, I.)

Expectations formulated by customers require mimicking human reasoning using historical data, but also forecasting the expected evolution of the system over a given time horizon. Users want to proactively predict the future and even control it. Let us imagine the application of smart sensors in autonomous cars – here, the “virtual driver” should be able to identify the traffic scenario several steps ahead, understand the causes of this development and ways to control it, formulate alternatives to the current state, choose an appropriate maneuver and execute it, all with multi-threaded processing, non-homogeneity of data and information, and minimal latency. From the point of view of data science, all this requires embedding descriptive, predictive, and prescriptive functions in a smart sensing unit. Descriptive analytics answers the question “What happened?” Looking into the future requires answering the question “What will happen?” – requiring predictive analytics. Finally, we want to know how we can make it happen, which leads us to scenario simulation and recommendations – again requiring prescriptive analytics.

Basic Concepts on Fusion

Sensors and actuators, but also other sources such as databases, serve as data sources for the realization of condition monitoring in various applications or for the acquisition of characteristic parameters, such as production parameters. The data originate from sources which are spatially distributed over systems, shop floors and the like. Modern industrial plants are equipped with an increasing number of sensors generating a large amount of data. The task of processing these large amounts becomes increasingly complex. Computation takes longer and necessary communication may exceed the available bandwidth. Furthermore, users are unable to properly process and draw correct conclusions from the generated information [Mönks et al. 2016]. The issues caused by the increased

complexity are addressed by Sensor and Information Fusion (SEFU/IFU) mechanisms. These collect and combine data and information from different sources to reduce complexity as well as uncertainty. The resulting fused information is of higher value and precision than the information gained by the individual single sources [Talbur et al. 2019]. The idea of SEFU/IFU is to create new or more precise knowledge about the system's environment or status (such as physical quantities or occurring events) by taking into consideration different information sources [Hall and Llinas 2001; Salicone and Prioli 2018].

Hall and Llinas describe that the aim of SEFU/IFU is to optimize “the accuracy of applications” [Mönks 2017]. Which criterion is to be optimized needs to be defined before the SEFU/IFU application is designed. Only then can meaningful signal sources, which are able to obtain data containing the required information to derive a precise and accurate statement about the criterion, be chosen. As described in [Ruser and Puente León 2006], if two sensors S1 and S2 work with complementary physical principles, the combined performance should be larger than the addition of the two performances per sensor.

Sensor and Information Fusion

Sensor and information fusion systems appear in various kinds. They all have in common, that the information originating from a number of homogeneous or heterogeneous sources is combined in order to reduce amount and dimensionality of data, and to obtain information of higher quality. Comprehensive overviews over information sources, general fusion system models, and theoretical backgrounds of the fusion algorithms provides [Hall and Llinas 2001]. For modelling, the sensor information, and carrying out the fusion, one of various evidence theories (e.g., probability, possibility, belief theory) as well as concepts derived from them are applied most often [Holst and Lohweg 2022].

Sensor and information fusion as a specialized field has recently taken on new aspects in addition to information aggregation. These include dealing with aleatory (noise, random variations, material characteristics, etc.) and epistemic (incompleteness, imprecision, production toler-

ances, etc.) uncertainty [Salicone and Prioli 2018; Hüllermeier and Waegeman 2021] and the quality of fusion as such [Bossé and Rogova 2019]. The latter in particular is essential for risk-orientated applications, e.g., in the medical field [Talbur et al. 2019]. By penetrating various supporting evidence theories, the modeling of application-oriented fusion systems can be considered to be mature [Solaiman and Bossé 2019]. They are applied in various industrial areas such as machine conditioning and predictive and preventive maintenance [Holst and Lohweg 2021] as well as in medical technology [Talbur et al. 2019].

Sensor Orchestration

In the context of sensor orchestration, the primary question is which subset of sensors (n) from an applied universe of sensors (M) are required in a system. If the total amount of sensors M is large, it is given that redundancy will occur. Therefore, a subset n is usually sufficient for a specific application. As of today, it becomes increasingly common that sensors are equipped with communication capabilities and local processing power. The available processing capacities enable the incorporation of local intelligence, which in turn is necessary for a collective of devices to self-organize. A self-organizing system is a system that operates without any central control unit or global state repository. Any decision made by the system, either on a course of action or a change of internal organization, is the result of collective cooperation. Self-organizing systems possess several advantages over systems with a centralized intelligence [Fritze et al. 2017]. A central decision unit always presents a single point of failure and a system without such a unit is overall less error-prone and more robust. Self-organizing systems scale better in comparison and adapt themselves better to changing environments. Consequently, they are more suitable for ad-hoc networks and networks which change often in their structure and number of participants [Dressler 2008]. The trade-offs for these advantages are: (i) self-organizing systems tend to produce more communication load for the organization process; (ii) designing such systems requires an increased effort; and (iii) depending on applied strategies, they are less deterministic [Fritze et al. 2017].

Sensor Conflict Management and Sensor Defect Analysis

It is assumed that the number of smart sensors in the world will continue to increase, especially for IoT applications like healthcare applications, smart homes and agriculture applications [Fitzpatrick 2022; Mukhopadhyay et al. 2021]. Already today, sensors are being installed and connected to sensor networks interconnected into sensor networks. Self-diagnosis and quality monitoring with decentralized cooperating sensor-based systems require diagnostic knowledge and, derived from this, the generation of meaningful characteristics [Zadeh 2008]. In this context, data uncertainty is relevant. The acquired data is prone to uncertainties, which are categorized into aleatory and epistemic uncertainty according to the following definitions. Aleatory uncertainty is characterized by its random and non-deterministic nature and thus represents the inherent randomness of a problem. Epistemic uncertainty is also denoted by subjective uncertainty. Its source is the lack of knowledge due to, e.g., incomplete data or conscious or non-conscious unknowns. Effects resulting from uncertainties can also lead to conflicts in the acquired data. Under practical conditions, this leads to fuzzy and vague information from the sensors [Mönks 2017]. When using sensors in an application, it is generally assumed that it is operating correctly. But sensors can fail and do so during typical operation. This failure can be caused by wrong handling, by wear and tear, or it can be a random failure. Furthermore, measurement data and systems often get stuck gradually, making the detection of anomalies particularly challenging. Therefore, the future will be about learning with so-called drift in the context of robust and explainable computer intelligence (artificial intelligence). Hence, adequate (but also more complex) information fusion algorithms are used for the processing of sensor observations and the generation of a system state.

How to Process Raw Data

Data can be processed in various ways. This strongly depends on the requirements of the specific use case. AI methods are showing up for different use cases, but statistical methods are still in use. Also, with further development

on AI methods, it is expected that statistical analysis will be useful for same data analysis in the future.

Here, we will give a short overview of the different machine learning paradigms, shown in Figure 4.9.

Application-Focused Machine Learning Paradigms

Applications of imitation learning and reinforcement learning are typically strongly connected to a very clearly defined application. For example, an autonomous car should follow the street,

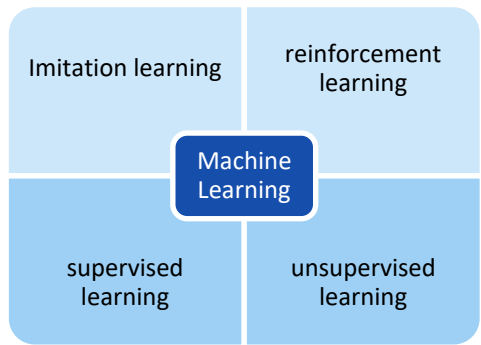


Figure 4.9 Paradigms of machine learning. Unsupervised/supervised learning has a higher relevance for sensor data processing. (Source: Dr. Julia Osten, Fraunhofer IPMS)

or a robot is walking stairs [Eßler 2023]. Imitation learning has the core elements of an agent, the environment, a teacher, and a policy. The goal is to reproduce the observed behavior of the teacher. The improvement is performed by learning from the expert behavior. LiDAR and cameras are used for the environment task of autonomous driving [Le Mero et al. 2022]. Reinforcement learning has, in contrast to imitation learning, a reward and value function. In our example, the learner would be the robot which needs to perform different tasks to walk the stairs all the way up to the top. If it manages to get to the top, it will get a reward. Typical for reinforcement learning is a trial-and-error search and delayed reward phases [Barbierato and Gatti 2024]. Sensors are not directly addressed with reinforcement learning; the focus is on the interaction between actors and the fulfilment of the reward.

Data-Focused Machine Learning Paradigms

The following approaches (supervised and unsupervised learning being compared in Table 4.1) are widely used for different sensor data sets. A requirement of supervised learning is a labeled data set. The supervised learning model is trained on input-output pairs corresponding to the desired output. If the error between the pairs and the desired output is below a certain threshold, the sufficiently trained model will be used to get accurate prediction of unseen data in the future. The disadvantage of supervised learning is its requirement for labeled data during the training phase. Typical applications are image or speech recognition. In contrast to this, unsupervised learning does not depend on labeled datasets. Unsupervised learning works on finding patterns, relationships, and structures in the sensor data without guidance. The algorithm works autonomously. A hybrid form of both approaches is semi-supervised learning, which works with a non-complete labeled dataset [Barbierato and Gatti 2024].

Table 4.1: Comparison of supervised and unsupervised learning based on [Barbierato and Gatti 2024]

Property	Supervised learning	Unsupervised learning
Learning objective	mapping input to output	discover hidden structures
Input data	labeled input/output pairs	unlabeled raw data
Feedback signal	correct output labels	evaluation metrics or criteria
Key mechanism	pattern recognition	clustering, dimensionality reduction
Training approach	self-organization	error minimization

Besides the question of how to process the data, the task of where to process the data is an import issue.

For example, in the federated machine learning approach, the data are trained without explicitly sharing the data samples [Perri 2023]. This approach is more likely for edge computing.

Where to Process the Raw Data

Edge computing refers to processing data geographically closer to the sensor in comparison to transferring the data to a network of remote servers (cloud computing).

Neuromorphic computing, when paired with edge computing, enables local, real-time data processing by mimicking the human brain’s neural networks. This integration facilitates autonomous systems’ rapid decision-making and reduces reliance on cloud data centers, optimizing for speed and energy efficiency. [Fraunhofer IPMS 2024]

An overview of the different properties of data handling in cloud vs. edge is given in Table 4.2.

Table 4.2: Comparison between edge and cloud computing [Beavers 2018; Codeluppi et al. 2021]

Property	Cloud computing	Edge computing
Latency	higher	real time
Amount of data	higher	lower
Data Security	may be an issue	no issue
History data	possible	not possible
Required bandwidth	high	low
Scalability	possible	possible
Privacy	may be an issue	can be addressed by smart sensors
Accessibility	with internet connection	on site

Cloud computing has the advantages of handling higher amounts of data, storing more history data, and better scalability. In contrast to

this, edge computing has a lower latency, and security might not be an issue. Especially data security can be an issue when using cloud computing. Therefore, the chosen data process path depends on the data type and the application requirements.

A matrix of edge vs. cloud computing is depicted in Figure 4.10. Within edge computing, a centralized approach can be distinguished from a distributed approach focusing on smart sensors (which is sometimes also called “edge computing” to avoid confusions).

An example of edge vs. cloud within the automotive domain of autonomous driving is depicted in Figure 4.11. There are various sensors in cars (sea of smart sensors). The computing of the data input from RADAR, LiDAR, ultrasonic, and others can be performed inside the car. (edge). Transforming it to the cloud is not very common because of the higher latency.

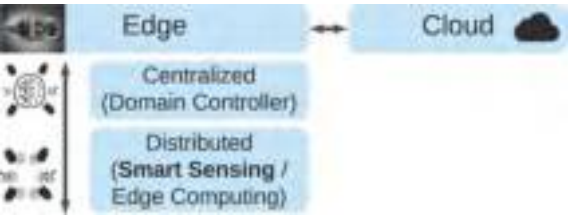


Figure 4.10 Matrix of edge vs. cloud computing

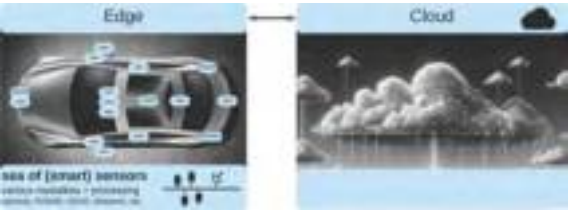


Figure 4.11 Example of edge vs. cloud in the automotive domain

Data can be analyzed directly on the sensor or the sensor chip. In this case, only the already processed reduced data set will be transferred to the cloud afterwards. Edge sensors belong to IoT sensors which are discussed in more detail in Section 4.3.

On the other hand, raw data can be transferred to cloud devices and analyzed there. Depending on the topic, there are different digital ecosystems for connecting machine data and sensors with other data. This does not mean that AI-

methods are always used in this ecosystem. For the agricultural sector in Germany, a feasibility study concluded that a step-by-step implementation of a national data space would be a good idea [Rauch 2020]. The task of a data space is the integration and management of diverse data sources by providing a unified interface across different systems without extensive data centralization. In contrast to a cloud (focus on data centralization), a data space emphasizes data interoperability and consistency. A data space can be part of an ecosystem. The ecosystem refers to an even broader network of interconnected entities, including data providers, consumers, and services.

The GAIA-X project aims to create an ecosystem of interconnected different data spaces [Käuffer 2024b]. Their goal is to overcome the major problems with data spaces, non-matching interfaces and data safety. Of the eleven projects founded, the AI-supported fault tracking solution for vehicles and the Maritime Smart Sensor Data Space X might fit best with the smart sensor topic [Käuffer 2024a].

As mentioned before, cloud computing is not always the solution to a specific application. The chosen data processing path strongly depends on the application requirements and the type of data.

In the following section, the communication towards different networks is addressed.

4.3 Communication Paradigms – (Industrial) Internet of Things

(Wöckel, S.; Reichenstein, T.; Barth, J; Neubert, M;)

Fundamentals IoT and IIOT

The Internet of Things (IoT), better defined as Consumer IoT and Industrial IoT (IIoT), consists of global or local networks of interconnected computing, smart sensing and networking devices that can exchange data and information. IoT solutions require a network, preferably wireless, that can transmit large amounts of data securely and quickly using a variety of data protocols.

It is therefore largely dependent on the communication infrastructure and the availability of and access to local or global networks.

The main technical component of the IoT architecture is the gateway, which either connects the IoT device to the processing service (cloud/enterprise data center) or provides edge processing itself – in the sense of intelligent edge gateways. In addition to handling edge-to-cloud connectivity, the gateway acts as a translator between field and cloud protocols.

Purpose of IoT and IIOT

Independent from communication paths (machine-to-machine, machine-to-human), consumer IoT is about connecting devices, sensors and everyday objects to the internet, allowing them to communicate, share data and be controlled by people from anywhere in the world. In other words, IoT defines the connection between machines and humans.

Thus, from a consumer perspective, the IoT device is strongly constrained by manufacturing costs (customer price) and operating costs (energy, battery), as well as by the technology available (local WIFI and global internet services). This affects the design of components (e.g., antennas) and the operating principle (battery or energy harvesting).

Industrial IoT is a network of connected devices that connects sensors and machines and is an ecosystem of interconnected objects and computing devices. In other words, IIoT defines the connection between machines and machines. Its main purpose is the exchange of real-time data in industrial processes.

While IoT systems use cloud computing to connect and monitor devices, IIoT systems integrate sensors in the field.

The main difference between IoT and IIoT is the intricacy of the solutions. IoT uses inexpensive connected sensors with limited functionalities whereas IIoT uses more sophisticated devices, providing broader visibility, automated controls, and complicated analytics.

While both IIoT and IoT aim to create connected ecosystems, they differ significantly in terms of

scale, reliability, data security and network infrastructure, and are targeted at different applications and industries. The most commonly used parameters that differentiate the IoT from the industrial IoT include: security, safety, interoperability, scalability, precision, low latency, reliability, and resilience.

IIoT focuses on integrating smart sensors, controllers, and devices into industrial processes, prioritizes reliability and robustness to ensure uninterrupted operation in industrial environments, and places a heightened emphasis on data security and privacy due to the sensitive nature of industrial data.

IIoT networks are typically designed with industrial-grade infrastructure capable of withstanding harsh environmental conditions and supporting real-time communication. To ensure timely data transmission and control, these networks often use protocols optimized for low latency and deterministic behavior. Industrial networks may also incorporate redundancy and failover mechanisms to maintain continuity in operations.

In order to control and manage the utilization of (I)IoT-sensor data, the role of security and privacy has become of increasing interest. The reason for advanced access control can either be motivated by competitive reasons, e.g., insights into (production) processes that are part of companies' intellectual property, or privacy reasons, e.g., in the smart home sector.

Communication Protocols

A key component of an intelligent sensor system for IoT or IIoT systems is the ability to communicate and connect wirelessly, providing more flexibility. However, in the industry, there is a need for both wired and wireless communication to realize different types of (I)IoT applications. This decision is discussed in the next chapter. In addition to the physical layers, the communication standard and therefore the protocol are the critical components that define the communication range, transmission rate, interconnectivity, and security of the data. Depending on these factors, a large number of protocols have been developed specifically for IoT. For example, even the IEEE has up to ten working groups for 802.15 (WPAN/Bluetooth, Coex-

istence, High-Rate WPAN, Low-Rate WPAN, Mesh-net, Body Area Network, etc.).

Exemplary the enabling (wired and wireless) technologies for industrial and IoT networks are: Ethernet/IP, PROFINET, CBA, Modbus/TCP, CANopen, NMT, PDO, SDO, Ethernet Powerlink, EtherCAT, not including car connectivity (V2X) and smart energy grid distribution (DLMS/COSEM, DNP3) or building automation systems (e.g., ZigBee, BACnet) [Mansour et al. 2023].

Concerning IoT, the limited hardware resources (CPU, energy) or the costs are often also decisive for the choice of a transmission protocol. Therefore, a variety of lightweight protocols for wireless fidelity (Wi-Fi), Zigbee, and Bluetooth exist [Mansour et al. 2023; Artetxe 2023]. In case of industrial IoT (IIoT), the availability, security, and safety of the data are the most crucial parameters to identify the optimal communication protocol.

Currently, the most common protocols for wireless industrial IoT that fulfil those parameters are: Z-Wave/ZigBee, MQTT, OPC UA, LoRaWAN, LPWAN, NB-IoT, 5G.

IoT communication protocols are typically categorized and classified according to range (short-range, long-range cellular, long-range non-cellular, and wired), data rate, power consumption and industrial safety:

- short-range protocols (RFID, NFC, Bluetooth, Z-Wave, Wi-Fi)
- cellular-based long-range protocols (LTE-M)
- non-cellular IoT protocols with long range (ZigBee, LoRaWAN)

In IoT applications (Figure 4.12), communication technologies include Wi-Fi, RFID, NFC, ZigBee; system mainly include: AMQP, JMS, REST, HTTP/HTTPS, COAP, DDS, MQTT, Bluetooth, LoRa, NB-IoT, GSM, GPRS, 3/4/5G networks, Ethernet, RS232, RS485, USB; and related communication protocols include CDMA/TDMA, TCP/IP, WCDMA, TD-SCDMA, TD-LTE, FDD - LTE, TCP/IP, http [Sari 2023].

The major challenge for the coming years is the interconnectivity and interoperability of IIoT protocols and devices as well as the definition of global regulation. Since IoT devices will succeed in using open global technologies up to satellite communication, the IIoT will stay a local service inside industrial applications with a smart gateway as interconnection to the global network.

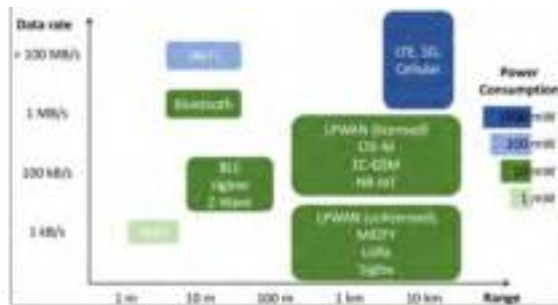


Figure 4.12 Categorization of IOT according to energy consumption, range and data rate

Requirements for Sensors and Communication

The main differences between IoT and IIoT are the higher levels of requirements regarding safety, security, timing, availability, latency, and reliability. In terms of communication, the amount of data that is collected and transferred is different, as well as the overall complexity. For certain industries, these requirements further increase, e.g., in the Ex areas [Khan et al. 2020].

Wireless systems are becoming increasingly important in industry due to the constant increase in production flexibility. However, established wireless standards like WLAN were not primarily developed for industrial use, which often leads to problems. Therefore, new wireless standards should be developed specifically for industrial purposes to counteract these issues [Wollschlaeger et al. 2017].

Furthermore, depending on the use case and usage scenarios, for 5G, different configurations of the communication protocols can be done (the enhanced mobile broadband, massive machine-type communication, or ultra-reliable and low-latency communication). In order to determine the use of wired or wireless communication, the portfolio from [Vukovic 2023] can be used (see Figure 4.13), which shows technology boundaries (wireless: based on 5G and WiFi,

wired: PROFINET, EtherCAT). Motion control applications with sensors and actuators stand out to mostly rely on wired communication due to the requirements regarding latency. Other applications, which rely on the use of sensor (data), are also depicted (e.g., mobile robots, automated guided vehicles, MES coupling, drones, and machine communication) with an increased data rate.

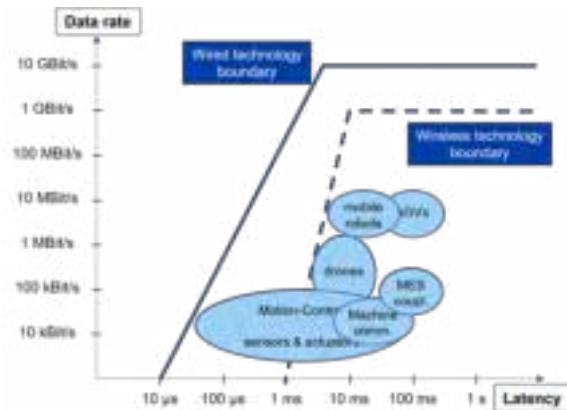


Figure 4.13 Industrial applications in the portfolio for technology boundaries of wired and wireless protocols (adapted from [Vukovic, 2023])

In the context of connecting legacy equipment with sensor and communication technology, i.e., the smart retrofit of legacy systems, [Jaspert et al. 2021] identified three main approaches: (1) add (new) external sensors, (2) tap existing sensor data (e.g., from PLCs), and (3) connect to external data sources. Only partial replacement of equipment is required, i.e., adding new sensors or connectivity solutions [McKinsey & Company 2015].

Depending on the use case, either a raw analog output can be used, pre-processed and aggregated data or sensors with ModbusTCP interfaces, for example, or more intelligence can be brought to the sensor level for special applications, though thereby increasing the costs. Furthermore, for the interoperability regarding (II)IoT-connectivity and communication, new requirements arise. A high level of flexibility in terms of protocols is necessary for a smooth legacy integration. Therefore, future sensors need to be able to be downward-compatible in terms of communication protocols. In addition, developments for a possibility to adjust the communication protocols according to specific use cases would greatly benefit the smart retro-

fit process and the integration of legacy equipment from a communication perspective.

Trends and Outlook

A fundamental principle of IoT is the interconnection of the physical and digital world. This is achieved through the use of sensors, which are either integrated during the production process or subsequently attached to objects such as plant components, machines, vehicles, storage containers, or tanks. The added value of IoT-based applications primarily results from the analysis and processing of data generated by sensors. Therefore, it is crucial that the costs for the required hardware, its assembly or integration, and operation are kept as low as possible. Only in this way, applications can effectively scale and be successful.

An important aspect that influences the architectural decisions for sensors in the IIoT context, especially for retrofit sensors, are the installation costs. To keep these low, a wireless solution is chosen in most cases. However, radio-based sensors bring with them cost-intensive, system-relevant factors. Still, the biggest cost driver is the simple installation and onboarding (as well as the upgradability of the sensors which also influences the choice of wireless standards and communication protocols). Ideally, no battery change should be necessary during operation, but in some cases, this is unavoidable. In such cases, optimization for maximum battery life is essential. Here, the optimal measurement cycle rate, suitable wake-up mechanisms, data transmission according to the use case, the choice of radio standard and protocol play a crucial role, as has been explained in more detail at the start of this subchapter. Another strategy to reduce energy consumption is data compression or preprocessing of the data up to the full interpretation directly on the sensor node. For the latter in particular, neuromorphic hardware structures are increasingly being used (see Chapter 4.2).

A solution established in recent years for cost optimization is the integration of PCB antennas directly on the main board, which incurs hardly any additional costs. The challenge here is to find a compromise between the required antenna performance, the robustness of the con-

nection, energy consumption, and the total cost of the product, with costs being the most significant influencing factor.

Energy harvesting as a permanent solution or for extending battery life is usually only used in the industrial sector for special applications. In the case of cost-effective IIoT sensor solutions, this technology is not used due to still cheaper battery costs. The market expects a lifespan of such sensors of 10 to 15 years.

In many cases, it is possible to achieve the expected lifespan of a sensor (especially for beacons) of 10 to 15 years with only a single battery. Therefore, a potted design is often preferred in the industrial sector. This design method represents the most cost-effective method to meet environmental requirements such as protection class (IP) and explosion protection (Ex) simultaneously. In the course of sustainability and due to the fact that the product's life span can be extended by replacing the battery, solutions with replaceable batteries are increasingly becoming established in the market (e.g., Sushi Sensor [Yokogawa Deutschland GmbH 2024]; IVIB-Series [iQunet 2024]; SI-TRANS MS200 [SIEMENS 2024]). These solutions also meet environmental requirements and thus offer a sustainable alternative to the disposable battery concept, though with higher costs.

4.4 Reliability

(Fleck, S; Trsek, H.)

When sensor systems are developed, constructed, and later placed on the market, they must comply with the general requirements of legal regulations and standards, especially with respect to safety and security.

Safety is defined as the protection of humans, machines, and the environment against harm or danger. It is focusing on preventing accidents and incidents that could cause physical injury or damage. For instance, the safety of typical components in industrial systems is addressed according to standards like IEC 61508 [International Electrotechnical Commission 2010] or ISO 62061 [International Electrotechnical Commission 2021]. In automotive, ISO 26262 [International Organization for Standardization 2018]

is used by major car manufacturers. It is an adaptation of IEC 61508.

Security aims at protecting a system or its components against intentional and unintentional threats as well as external attacks. It focuses on the protection of information assets against malicious activities such as theft, disclosure, and manipulation. The security requirements are specified in terms of confidentiality, integrity, and availability. The availability of data is paramount in the operational technology area, as it is a crucial prerequisite for smooth manufacturing processes. The most relevant international standard is the IEC 62443 series [International Electrotechnical Commission 2009]. It was developed to secure systems in the industrial domain throughout their lifecycle.

One of the main challenges for security is the fact that, unlike with safety, security mechanisms must constantly be adapted to a dynamic threat landscape. At the same time, gaps in security can ultimately impair systems with all its functional elements. Hence, they might also have an influence on the safety of a system. However, the remainder of this section is mainly focused on safety aspects.

Sensor degradation poses a critical challenge to the reliability and functionality of sensor systems in the automotive industry, particularly with the increasing reliance on these systems for autonomous driving and safety features. Modern vehicles are equipped with sophisticated multimodal sensor systems that leverage artificial intelligence (AI) for perception and sensor fusion. Despite their advanced capabilities, these systems are susceptible to various forms of degradation over the vehicle's operational life, leading to potential unpredictability in performance. This degradation, influenced by exposure to different environmental conditions, can result in unforeseen behavior that impacts the vehicle's safety and functionality.

In the realm of sensor technologies, camera, RADAR, LiDAR, and other sensor modalities, both outside and inside the cabin, are fundamental to the operation of modern vehicles. Cameras, in particular, play a vital role in a myriad of applications, from basic navigation and parking assistance to complex autonomous driving functions. However, like all sensor tech-

nologies, cameras are prone to degradation due to factors such as lens wear, dirt accumulation, and exposure to harsh weather conditions, which can significantly diminish their performance. The degradation of camera sensors can lead to a reduction in image quality, affecting the accuracy of AI-driven perception systems and, consequently, the safety and efficiency of autonomous driving features.

A systematic approach to addressing the wide range of degradation effects on automotive sensors is essential. This includes a detailed examination of the specific vulnerabilities of camera sensors and the development of robust countermeasures to mitigate their impact. While design verification (DV) and product validation (PV) processes have traditionally focused on sensor robustness, these measures are often insufficient to fully account for the complex nature of sensor degradation over time.

The intersection of sensor degradation and its impact on AI processing represents a significant challenge, necessitating a comprehensive strategy to ensure the continued reliability of sensor-dependent systems. Recognizing and addressing the multifaceted nature of sensor degradation, particularly in camera technologies, is crucial for maintaining the integrity and safety of autonomous driving systems.

To enhance the resilience and performance of sensor systems in vehicles, it is imperative to explore future analyses and methodologies for detecting and addressing sensor degradation on system level. By adopting a proactive approach to understanding and mitigating the effects of sensor wear and tear, the automotive industry can safeguard the advancements and safety of autonomous driving technologies, ensuring that these systems remain reliable and effective throughout the vehicle's lifecycle.

4.5 Industrial Monitoring and Predictive Maintenance

(Barth, J.; Lohweg, V.; Erdler, A.; Reichenstein, T.; Schäfer, A.; Fischer, M.)

This section explores the evolution of Condition-based Maintenance (CbM) and Predictive Maintenance (PdM), including future trends in prescriptive maintenance. It examines the role of

smart sensors and the technical and economic context of these changes and trends and outlines specific applications.

In the 1960s, to enhance productivity in the manufacturing industry, behavioral (perceptive) data from assets, such as vibration and temperature, were collected. The objective was to optimize maintenance recommendations based on these data, minimizing the risk of machine damage and production downtime. Until the 1980s, the focus was primarily on metrology, with data being systematically collected and analyzed. Key Performance Indicators (KPIs) were developed for specific machine failure cases, resulting in numerous standards for machine condition monitoring. At that time, machine maintenance occurred whenever a problem was identified, i.e., when a defined KPI threshold was exceeded. This approach was robust but required significant investment and expertise. Depending on the frequency of data collection and the elaborate analysis, the risk of machine damage or plant downtime could be reduced accordingly. However, this increased the capital investment, often necessitating an optimum balance. This approach to machine and plant maintenance is reactive in nature and therefore difficult to plan and costly. However, this phase established the foundational knowledge for CbM.

From the 1980s on, with the availability of affordable computing power, advanced data processing, real-time analysis, and stochastic methods were increasingly used to predict asset failure times based on CbM, both off-premise and on-premise. This period marked the beginning of predictive maintenance, enabling better plant maintenance planning and further minimizing downtime.

From 2010 on, several mutually reinforcing trends and technologies emerged. Although cloud computing, various low-power wireless technologies, and low-power computing architectures were already known, they became established due to the success of smartphones and wearables in the consumer sector. This led to a significant price reduction of essential components, making business models based on the Internet of Things (IoT) and Industrial IoT (IIoT)

feasible, and allowing entire plants to be monitored cost-effectively.

The variety of sensor data, from field devices and additional asset condition-describing variables, presented new analysis possibilities and concepts, as well as challenges such as sensor orchestration and data processing. Other developments included sensor fusion, digital twin mapping, and machine learning use for anomaly detection and Remaining Operating Lifetime (ROL) estimation. This section gives particular attention to sensor fusion and machine learning use in the field of CbM and PdM, including the necessary prerequisites and challenges.

The complexity and application of sensors today is extremely diverse. On the one hand, special sensors that work according to various physical or physico-chemical principles are used and required; on the other hand, there is a trend favored by effective and inexpensive electronics that allow the use of sensors suitable for mass production (Chapter 4.3). Nowadays, any sensory weaknesses are usually compensated for using methods of sensor and information fusion with downstream computer intelligence. Furthermore, in the context of edge computing, for example, IoT/IIoT sensors are now the method of choice for many industrial applications with hundreds or even thousands of sensors, as they are cheap to produce [Ferfers et al. 2023].

Artificial Intelligence in the Application for CbM and PdM

State of the Art and Current Challenges

The application of autoencoders has established itself in the field of data processing for CbM and PdM. These are well suited to detect anomalies in large and complex data sets. This is due to the fact that they are capable of efficiently learning patterns and data representations that are characteristic of the normal data distribution and can thus identify deviations. Another significant advantage lies in their generic applicability. They can be applied to different assets and plant components, which allows a broad market access [Raghavendra Chalapathy and Sanjay Chawla 2019].

However, this approach also carries risks. A generic autoencoder may be able to detect anom-

alies, but it can also lead to frequent false alarms, as it was not specifically trained for certain types of errors. This can lead to “alarm fatigue” among users, potentially overlooking real anomalies [Pimentel et al. 2014].

In addition, these models always need to be trained in the real environment, which means a significant effort for the customer. If conditions in the field are changed, e.g., adjustment of the plant or a service was performed, these models must be trained again.

In addition to the desire to detect anomalies, customers are increasingly expressing the need for not only signaling the presence of an anomaly, but also classifying the error cases. This creates added value, as the customer knows not only that a problem exists but can also understand what kind of error it is, enabling a targeted response [Goodfellow et al. 2016].

A pre-trained model that serves as a classifier can indeed recognize and classify specific error cases, but it requires extensive preliminary work to adapt it to the specific conditions of a new field of application. In this context, it is essential to have a large amount of labeled training data that cover all possible error cases, which in practice is often a challenge [LeCun et al. 2015].

In an ideal case, such pretrained models could be delivered to the customer and would function immediately after the installation of the sensors. However, it is shown that the environment of the assets to be examined has a significant effect on the robustness of the prediction. This is easy to understand in the example of pumps that are to be monitored using vibration sensors. The installation of these is often solved differently by each customer and thus the mechanical coupling to the environment. To complicate matters, the environment, which can cause vibrations, is also different for all customers.

This is currently the biggest hurdle for AI-supported CbM and PdM to make the model transfer more robust and is the subject of current research.

Use Cases for Smart Sensors

Condition Monitoring of Filling Process

In the filling and packaging industry, the trend is towards self-diagnosis, optimization, and quality monitoring of processes [Kästner et al. 2017; Bator et al. 2018; Bator et al. 2019]. The aim is to increase production volumes and quality.

These concepts require continuous monitoring and anomaly detection of the filling process. In addition, a root cause analysis of the failure is required because not every failure can be simulated or measured beforehand. In this example, a fusion system is utilized for the detection of the failure source of different unknown anomalies during the filling process. The increasing digitization in the filling and packaging industry is resulting in more and more data being captured by various sensors. Methods of machine learning open up strong potential for optimization, such as increasing the efficiency, flexibility and individuality of the production process. A quick identification of the cause of malfunctions through condition monitoring and anomaly detection enables an increase in the autonomy of filling plants and improves the monitoring of the filling processes. The quick localization of a detected anomaly and the associated repair of the affected plant component are extremely important, as downtimes are often associated with very high costs. This requires diverse sensory functions as well as intelligent autonomous self-diagnostic capabilities of the individual components and processes of the filling plant. Self-diagnosis and quality monitoring require diagnostic knowledge and, derived from this, the generation of meaningful characteristics of the system. New promising concepts for anomaly detection by means of sensory pattern recognition and system diagnosis based on methods of human-centered, context-based, anticipatory multi-sensor and information fusion are hardly used in the environment of Industry 4.0. In addition, quality assessment and subsequent feedback to influence the process and expand the knowledge base is a topic that receives insufficient attention in the environment of intelligent systems.

This example (Figure 4.14) presents an anomaly detection approach which is able to determine the root of the anomaly based on a German research project [BMBF 2024]. The information fusion system MACRO [Mönks 2017] is used to detect abnormal system behavior. Due to the architecture, which summarizes certain properties of the observed process in attributes, it is possible to localize anomalies that occur via the attribute health. Tests were carried out in the context of a real-world example, in which a bottle-filling process was monitored during normal operation and during different abnormal conditions. It was possible to detect the source of failure in the application due to the analysis of the attribute health. It is shown that defect detection is generally possible [Bator et al. 2019].

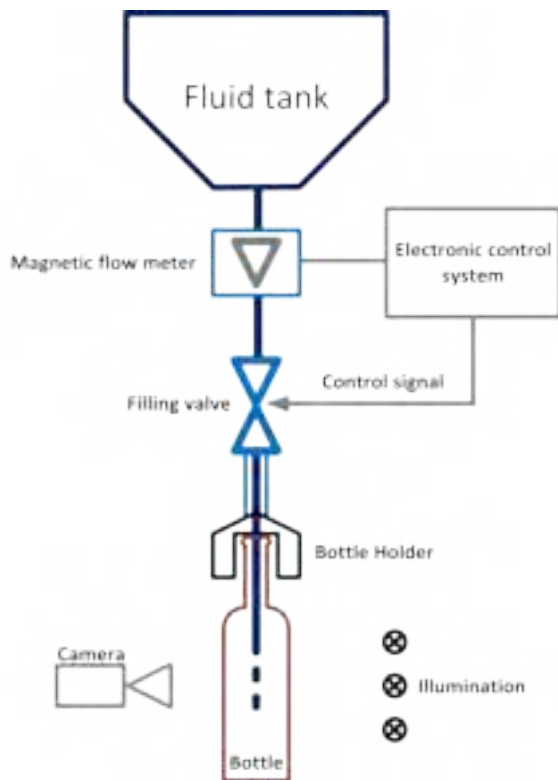


Figure 4.14 Schematic bottling process

Condition monitoring for pumps: Ensuring efficient and reliable operations

Pumps are the widely used machines in chemical plants for fluid handling and there is a huge variety of working principles and media like fluid, gas, and heat. To enhance their performance and prevent unexpected failures, condition monitoring systems have been developed by pump manufacturers. These systems rely on monitoring various parameters such as electrical power consumption, hydraulic power, tempera-

ture, speed, vibrations, and more. The goal is to detect potential issues like dry running, overheating, imbalance, cavitation, and gas entrainment. For pumps, the following operation parameters are important for Condition Monitoring and Predictive Maintenance.

Electrical power consumption: Monitoring the power consumed by the pump motor provides insights into its operational efficiency. Deviations from expected power consumption levels can indicate problems such as wear, blockages, or reduced pump efficiency.

Hydraulic power: Measuring the pressure difference and flow rate of the pumped fluid helps assess the hydraulic performance of the pump. Any significant deviations from the expected values may indicate issues like impeller damage, blockages, or excessive wear.

Temperature: Monitoring temperature at various points in the pump system can help identify abnormal heat generation, which may be indicative of problems such as bearing failure, lubrication issues, or inefficient cooling.

Vibration analysis: Vibration sensors are widely used for condition monitoring of pumps. By analyzing vibration patterns, abnormalities such as unbalance, misalignment, worn bearings, or cavitation can be detected. Vibration analysis can also provide insights into the overall mechanical health of the pump.

Operating-point monitoring: Tracking the pump's operating point on its characteristic curve helps identify any deviations from the optimal operating range. This information is crucial for ensuring efficient pump operation and preventing issues like cavitation or overload.

Maintenance intervals: Monitoring the actual operating hours and the duration of operation under different load conditions (e.g., blocked, partial load, optimum, overload) helps schedule preventive maintenance tasks based on actual usage, ensuring optimal performance, and extending the pump's lifespan.

Energy consumption: Evaluating the energy consumed by the pump provides insights into its overall energy efficiency. By identifying energy-saving opportunities, such as optimizing

pump speed or adjusting impeller diameter, energy consumption can be reduced, resulting in significant cost savings.

Start count: Keeping track of the number of starts helps assess the pump's usage intensity and plan maintenance accordingly. Frequent starts can indicate a higher wear rate, requiring more frequent inspections and preventive measures.

Condition monitoring plays a vital role in optimizing the performance, reliability, and lifespan of pumps. By monitoring parameters such as electrical power consumption, hydraulic power, temperature, vibrations, and operating conditions, potential issues can be detected early, enabling proactive maintenance, and minimizing downtime. Intelligent IOT sensors, combined with advanced analytics and machine learning algorithms, provide valuable insights for predictive maintenance, enabling efficient pump operation and maximizing energy savings. Following relevant norms and standards ensures accurate monitoring and helps benchmark performance against industry standards. Implementing comprehensive condition monitoring systems can significantly benefit pump operators by increasing plant performance, reducing maintenance costs, and ensuring a reliable and efficient pumping process. In Figure 4.15, the Siemens SITRANS SCM IQ IIOT system is shown. The Smart Condition Monitoring System uses IIoT sensors and offers AI-based monitoring functionality for pumps. The system consists of a battery-driven multi-sensor, a cloud gateway for secure and encrypted data transmission, and an app for AI-based detection of deviations from the normal operating status in due time of the pump.

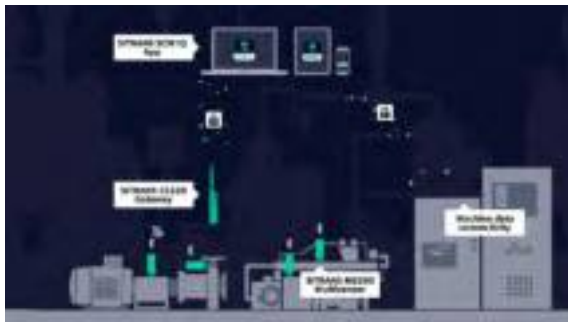


Figure 4.15 Siemens SCM - IQ sensor system for condition monitoring and anomaly detection (Source: Siemens AG)

Condition monitoring of heat exchangers: Key aspects and importance in industrial applications

Heat exchangers are integral components in industrial processes, facilitating efficient heat transfer between fluids. However, fouling, the accumulation of deposits on heat transfer surfaces, can significantly impact their performance. This results in reduced heat transfer efficiency, increased energy consumption, and potential equipment failure. Effective condition monitoring strategies are crucial to ensure optimal heat exchanger performance and prevent costly downtime. In the following, important parameters for condition monitoring are shown.

Heat transfer coefficient (k-value) calculation: The heat transfer coefficient, expressed in Watts per square meter Kelvin ($\text{W/m}^2\text{K}$), represents the efficiency of heat transfer in a heat exchanger. The actual k-value in operation can be determined by comparing the measured k-value with the reference k-value calculated using rigorous models assuming no fouling. Norms such as ISO 16812 [International Organization for Standardization 2019] provide guidelines for the calculation and evaluation of heat transfer coefficients.

Fouling detection and quantification: Regular monitoring of fouling levels is essential to identify potential performance degradation and schedule maintenance activities. The fouling factor, expressed as a percentage, quantifies the extent of fouling on heat transfer surfaces. Various techniques, including direct measurement, indirect estimation, and model-based approaches, can be employed to detect and quantify fouling.

Instrumentation and monitoring systems: Appropriate instrumentation is necessary for effective condition monitoring. Temperature sensors, pressure sensors, flowmeters, and fouling sensors provide valuable data for assessing heat exchanger performance. Advanced IOT monitoring systems, integrated with data acquisition and analysis capabilities, enable real-time monitoring and early detection of fouling-related issues.

Using state-of-the-art condition monitoring functionalities can significantly reduce the life-time costs of heat exchangers. Efficient heat exchanger operation translates into reduced energy consumption. By monitoring fouling levels and promptly addressing fouling-related issues, heat exchanger performance can be optimized. As an example, a 2 % increase in fouling can result in a up to 15 % increase in energy consumption. Regular condition monitoring allows proactive maintenance planning, minimizing the risk of unexpected equipment failures and costly downtime. By monitoring fouling levels, maintenance activities, such as cleaning or replacement of heat exchanger surfaces, can be scheduled based on actual fouling rates, ensuring optimal heat exchanger performance.

In summary, condition monitoring of heat exchangers is crucial for maintaining optimal performance, energy efficiency, and reliability in industrial applications. By calculating heat transfer coefficients, detecting and quantifying fouling, and implementing appropriate instrumentation and monitoring systems, industrial processes can benefit from improved heat exchanger operation and reduced operational costs. Regular condition monitoring enables proactive maintenance planning and minimizes the risk of unexpected failures, ensuring uninterrupted operation and cost savings for industrial processes.

Condition-Monitoring Infrastructure

In Germany, out of approximately 40,000 bridges, 2 % are rated “insufficient” and 11 % “not adequate” [BMVD 2024] while truck traffic increases put even higher demand on structure and health of traffic infrastructure. A similar picture can be drawn for most countries: traffic infrastructure is in a critical state and needs efficient investment.

Structural health monitoring is crucial to extend lifetime and protect bridges from damage and reduce public spending.

Traffic loads have a direct impact on bridge fatigue. Therefore, real traffic load analysis is an important factor in calculating a bridge's remaining lifetime. Moreover, once a bridge is identified as critical, load monitoring can help to

identify overload and heavy vehicles and enforce adequate measures.

The basics of a comprehensive structural - health monitoring of a bridge are sensors: strain gauge sensors and accelerometers for monitoring changes in the bridge's structural behavior to detect faults at an early stage and load monitoring. For load monitoring systems, usually piezoelectric sensors are applied due to their intrinsic overload protection and robustness towards harsh conditions, e.g., salt, temperature, and fatigue due to load cycles.

Sensors are combined with data acquisition systems and edge computers to reduce data traffic. Monitoring data is collected and assessed towards the load conditions (e.g., wind, traffic, temperature) (Figure 4.16) and is used to train data models or digital twins. The actual data can then be compared to the model and help to analyze the actual state of the bridge and remaining lifetime (Figure 4.17). In summary, this helps to detect damage, facilitate inspections and maintenance schedules, and help authorities in decision-making.



Figure 4.16 Vehicle-load monitoring for bridge protection. The load is measured with a so-called weight-in-motion sensor (WIM), which is based on piezoelectric technology (Source: © 2024 Kistler Group)



Figure 4.17 Accelerometer attached to a bridge's structure (Source: © 2024 Kistler Group/Shutterstock.com)

Condition Monitoring for Sustainable Energy

In a soon to be net-zero future, renewable energy generation will soon dominate the landscape, and because of the urgent need for conversion will determine our daily lives one day (Figure 4.18).



Figure 4.18 Condition monitoring for sustainable energy (Source: HBK)

Wind energy is the most important renewable energy source. Wind turbines are huge electrical machines and therefore often require superlatives in terms of their size as a building. If there are many wind turbines, it opens up possibilities to effectively compare them with each other. Condition monitoring can benefit from using exactly that fact. [Schäfer 2015]

For the further development of this resource, offshore wind turbines will be especially important. Since they are outpost to waves and constantly being turned into the wind, and since



Figure 4.19 Influences to offshore wind turbines monitored by a Condition Monitoring System (CMS), Condition monitoring on FBG basis (Source: HBK)

all components of the drive train are installed in the nacelle, a special kind of condition monitoring is required, the so called Structural Health Monitoring, which must be able to rely on both

accelerometers for global observation and strain gauges for local observation as well as to the drivetrain itself. Interestingly, such condition monitoring systems can also be built on an FBG basis, i.e., optically, which meets the desire for stronger lightning protection (see Figure 4.19).

Thus, condition monitoring of wind turbines is a crucial factor of energy transition. [Schäfer 2024]

Trends in CbM and PdM

This subchapter deals with the development and current state of Condition-based Maintenance (CbM) and Predictive Maintenance (PdM). The role of smart sensors and the relevance of IIoT for cost-effective monitoring of entire systems are highlighted. The historical development from reactive maintenance to predictive maintenance through advanced data analysis is demonstrated. Current challenges such as the generation and processing of sensor data, the adaptation of generic models to specific applications, and the need for large training data sets are discussed. Practical examples illustrate the application of condition monitoring in various industries and the importance of real-time monitoring to prevent failures and reduce costs.

Summary on Smart Sensing

Here, we have given an overview of smart sensors, which are devices that can sense, process, and communicate data from the physical world, and their evolution, definition, classification, design, challenges, trends, market, ethics, and future directions. It has been explained how smart sensors use data processing and network technologies, such as sensor and information fusion, sensor orchestration, sensor conflict management, sensor defect analysis, edge computing, cloud computing, and data platforms, to perform analytics. In one subchapter, there was a description about communication paradigms and protocols for smart sensors, such as the Internet of Things and the Industrial IIoT. The differences and challenges between them in terms of range, data rate, power consumption, security, safety, interoperability, and scalability were discussed. There was a discussion on the reliability and resilience of smart sensors, and how they can be affected by sensor degradation, en-

vironmental conditions, and artificial intelligence processing. Examples of sensor systems for applications of condition monitoring and predictive maintenance and how they can optimize the

performance, efficiency, and lifespan of various industrial assets, such as pumps, heat exchangers, filling processes, and wind turbines were presented.

References Chapter 4

- Arino, C.; Cetó, X Serrano, N.: Multivariate Data Analysis for Sensors and Sensor Arrays: Special issue of Sensors, https://www.mdpi.com/journal/sensors/special_issues/mdassa#info (accessed on: March 11th 2025)
- Artetxe, E.; Barambones, O.; Calvo, I.; Fernández-Bustamante, P.; Martín, I.; Uralde, J.: Wireless Technologies for Industry 4.0 Applications, *Energies*, 16, 1349, <https://doi.org/10.3390/en16031349>, 2023.
- Banavar, J.R.; Maritan, A.; Rinaldo, A.: Size and form in efficient transportation networks, *Nature*, 399, 130–132, <https://doi.org/10.1038/20144>, available at: <https://www.nature.com/articles/20144>, 1999. (accessed on: March 11th 2025)
- Barabasi, A.-l.: The Architecture of Complexity, *IEEE Control Syst.*, 27, 33–42, <https://doi.org/10.1109/MCS.2007.384127>, 2007.
- Barbierato, E.; Gatti, A.: The Challenges of Machine Learning: A Critical Review, *Electronics*, 13, 416, <https://doi.org/10.3390/electronics13020416>, 2024.
- Bassler, M.; Deilmann, M.; Ens, W.; Frenzel, F.; Graerlach, M.; Großmann, J.; Grümbel, F.; Heiserkamp, M.; Kaiser, U.; Lambrecht, A.; Maiwald, M.; Ohlenkamp, R.; Pötter, T.; Pyka, P.; Ross, E.; Schmidt, A.; Schünemann, U.; Theuer, M.; Tulke, A.; Weber, N.: Technologie-Roadmap: Prozess-Sensoren 2027+, <https://atpinfo.de/wp-content/uploads/2021/11/Roadmap-Prozess-Sensoren-2027.pdf>, 2021 (accessed on: March 11th 2025)
- Bator, M.; Dicks, A.; Deppe, S.; Lohweg, V.: Anomaly Detection with Root Cause Analysis for Bottling Process, in: 2019 24th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA), Zaragoza, Spain, 9/10/2019 - 9/13/2019, 1619–1622, 2019.
- Bator, M.; Wissel, C.; Dicks A.; Lohweg V.: “Feature extraction for a conditioning monitoring system in a bottling process”, 2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA), pp. 1201–1204, 2018.
- Beavers, I.: Erfassungs- und Messfähigkeiten am Edge Node im IIoT, all-electronics.de, 07.03.2018, available at: <https://www.all-electronics.de/elektronik-entwicklung/edge-node-im-iiot.html> (accessed on: March 11th 2025)
- Bruns, T.; Eichstädt, S.: A smart sensor Concept for traceable dynamic measurements, *J. Phys.: Conf. Ser.*, 1065, 212011, <https://doi.org/10.1088/1742-6596/1065/21/212011>, 2018.
- BMBF: DnSPro – Elektronikforschung: Dezentral kooperierende, sensorbasierende Subsysteme für Industrie-4.0-Produktionsanlagen, <https://www.elektronikforschung.de/projekte/dnspro>, 2024. (accessed on: March 11th 2025)
- BMVD: Zustandsnoten, <https://bmdv.bund.de/SharedDocs/DE/Artikel/StB/zustandsnoten.html> 2024 (accessed on: March 11th 2025)
- Bossé, É.; Rogova, G.L.: Information quality in information fusion and decision making, *Information fusion and data science*, Springer, Cham, 620 pp., 2019.
- Bouhamari, Z.; Clouet, A.; Chalak, A.; Domengie, F.; Virey, E.; Mermet-Lyaudoz, R.: Imaging for Industrial – Machine Vision 2024: Market & technology report, Yole Intelligence, YINTR24399, 2024.
- Chui, M.; Issler, M.; Roberts, R.; Yee, L.: McKinsey Technology Trends Outlook 2023, <https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/the-top-trends-in-tech#tech-trends-2023>, 2023. (accessed on: March 11th 2025)
- Codeluppi, G.; Davoli, L.; Ferrari, G.: Forecasting Air Temperature on Edge Devices with Embedded AI, *Sensors (Basel, Switzerland)*, 21, <https://doi.org/10.3390/s21123973>, 2021.
- De Luca, C.: Five trends in sensor technologies for IoT, <https://network-king.net/five-trends-in->

sensor-technologies-for-iiot/, 2023. (accessed on: March 11th 2025)

Delbos, P.; Midelet, C.; Mouly, J.; Oussalah, D.; Visse, P.-M.: Ultrasound Sensing 2023: Market and Technology Trends, Yole Intelligence, YINTR23386, 2023.

Deutscher Ethikrat: Mensch und Maschine – Herausforderungen durch Künstliche Intelligenz: Stellungnahme, available at: <https://www.ethikrat.org/themen/forschung-und-technik/mensch-und-maschine/>, 2023 (accessed on: March 11th 2025)

Dierauer, P: Smart sensors offer increased functionality, in: InTech, 60–63, 1998.

Dressler, F.: A study of self-organization mechanisms in ad hoc and sensor networks, Computer Communications, 31, 3018–3029, <https://doi.org/10.1016/j.comcom.2008.02.001>, available at: <https://www.sciencedirect.com/science/article/pii/S0140366408000959>, 2008.

Dusun, AIoT in 2024: Examples, Technologies, Implementation Challenges and Practical Solutions, <https://www.dusuniot.com/blog/aiot-artificial-intelligence-of-things/>. 2024 (accessed on: March 11th 2025)

Edge-Power: laufende Ergebnisse im Förderprogramm des BMBF “Elektroniksysteme für vertrauenswürdige und energieeffiziente dezentrale Datenverarbeitung im Edge-Computing” (OCTOPUS) 2024

ECS Community: ECS-Strategic Research and Innovation Agenda: Electronic Components and Systems, <https://ecssria.eu/2024>, 2024 (accessed on: March 11th 2025)

Eßler, J.: Einführung in Reinforcement Learning – Aus Perspektive der Robotik: LAMARR - Institute for machine Learning and artificial intelligence, <https://lamarr-institute.org/de/blog/reinforcement-learning-und-robotik/> (accessed on: March 11th 2025)

Ferfers, T.; Schriegel, S., and Jasperneite, J.: Investigation in automatic fault detection for scheduled traffic and frame preemption in time-sensitive networks, <https://doi.org/10.25673/111737>, 2023.

Fitzpatrick, J.: Sensors: the Gateway to Energy Efficiency, New Electronics, 55, 40–41, [https://doi.org/10.12968/S0047-9624\(23\)60488-2](https://doi.org/10.12968/S0047-9624(23)60488-2), 2022.

Frank, R.: Understanding smart sensors, Artech House, Boston, MA, USA, 2000.

Fraunhofer: KATI: Knowledge Analytics for Technology & Innovation, Fraunhofer, 2024.

Fraunhofer IPMS: Neuromorphic Computing – Fraunhofer IPMS, <https://www.ipms.fraunhofer.de/en/Strategic-Research-Areas/Neuromorphic-Computing.html> (accessed on: March 11th 2025)

Fritze, A.; Mönks, U.; Holst, C.-A.; Lohweg, V.: An Approach to Automated Fusion System Design and Adaptation, Sensors (Basel, Switzerland), 17, <https://doi.org/10.3390/s17030601>, 2017.

Future of Life Institute: EU Artificial Intelligence Act: Up-to-date developments and analyses of the EU AI Act, <https://artificialintelligenceact.eu/de> (accessed on: March 11th 2025)

Giachino, J. M.: Smart sensors, Sensors and Actuators, 10, 239–248, [https://doi.org/10.1016/0250-6874\(86\)80048-8](https://doi.org/10.1016/0250-6874(86)80048-8), available at: <https://www.sciencedirect.com/science/article/pii/0250687486800488>, 1986. (accessed on: March 11th 2025)

Goodfellow, I.; Bengio, Y.; Courville, A.: Deep Learning, MIT Press, 2016.

Grilli, M.; Ménière, Y.; Rudyk, I.; Delanote, J.; Rückert, D.: Deep tech innovation in smart connected technologies: A comparative analysis of SMEs in Europe and the United States April 2022, available at: https://www.eib.org/attachments/publications/eib_epo_deep_tech_smes_en.pdf, 2022. (accessed on: March 11th 2025)

Günes, Ü.: Die 5 wichtigsten IoT-Trends 2024, <https://iot.telekom.com/de/blog/die-fuenf-wichtigsten-iiot-trends-2024> (accessed on: March 11th 2025)

- Hall, D.L.; Llinas, J.: Multisensor Data Fusion, in: Handbook of Multisensor Data Fusion, edited by: Hall, D.L. and Llinas, J., CRC Press, 1–10, 2001.
- Holst, C.-A.; Lohweg, V.: Designing Possibilistic Information Fusion – The Importance of Associativity, Consistency, and Redundancy, *Metrology*, 2, 180–215, <https://doi.org/10.3390/metrology2020012>, 2022.
- Holst, C.-A.; Lohweg, V.: A Redundancy Metric Set within Possibility Theory for Multi-Sensor Systems, *Sensors* (Basel, Switzerland), 21, <https://doi.org/10.3390/s21072508>, 2021.
- Hüllermeier, E.; Waegeman, W.: Aleatoric and epistemic uncertainty in machine learning: an introduction to concepts and methods, *Mach Learn*, 110, 457–506, <https://doi.org/10.1007/s10994-021-05946-3>, available at: <https://link.springer.com/article/10.1007/s10994-021-05946-3>, 2021. (accessed on: March 11th 2025)
- IEEE Standards Association P2020: IEEE P2020 Automotive System Image Quality Draft Standard, <https://sagroups.ieee.org/2020/>, 2020. (accessed on: March 11th 2025)
- International Electrotechnical Commission: Functional safety of electrical/electronic/programmable electronic safety-related systems: IEC 61508, 2nd ed., International Electrotechnical Commission, Geneva, Switzerland, 7 volumes, 2010.
- International Electrotechnical Commission: Industrial communication networks – Network and system security: IEC 62443, International standard / IEC, 62443-1-1, IEC Central Office, Geneva, 81 pp., 2009.
- International Electrotechnical Commission: Safety of machinery – Functional safety of safety-related control systems: IEC 62061, Standard, 2021.
- International Organization for Standardization: ISO 16812:2019: Petroleum, petrochemical and natural gas industries – Shell-and-tube heat exchangers, 2019.
- International Organization for Standardization: Road vehicles – Functional safety: ISO26262, Standard, 2018.
- iQunet: Wireless Sensors, <https://iqunet.com/products/wireless-sensors/#anchor-memsvibrationsensors1>, (accessed on: March 11th 2025)
- Jaspert, D.; Ebel, M.; Eckhardt, A.; Poeppelbuss, J.: Smart retrofitting in manufacturing: A systematic review, *Journal of Cleaner Production*, 312, 127555, <https://doi.org/10.1016/j.jclepro.2021.127555>, 2021.
- Kästner F.; M. Hübner M.; Ohrem J.; Clüsserath L.: “Towards adaptive and efficient bottling plants in a cyber physical production system environment”, 2017 NASA/ESA Conference on Adaptive Hardware and Systems (AHS), pp. 85–92, 2017.
- Käufer, C.: Funding Projects – Gaia-X Hub Germany, Gaia-X Hub Germany, 12.01.2024, available at: <https://gaia-x-hub.de/en/funding-projects/> 2024a. (accessed on: March 11th 2025)
- Käufer, C.: Gaia-X Hub Germany: Welcome to the Website of the German Gaia-X Community!, <https://gaia-x-hub.de/en> (accessed on: March 11th 2025)
- Khan, W.Z.; Rehman, M.H.; Zangoti, H.M.; Afzal, M.K.; Armi, N.; Salah, K.: Industrial internet of things: Recent advances, enabling technologies and open challenges, *Computers & Electrical Engineering*, 81, 106522, <https://doi.org/10.1016/j.compeleceng.2019.106522>, 2020.
- Le Mero, L.; Yi, D.; Dianati, M.; Mouzakitis, A.: A Survey on Imitation Learning Techniques for End-to-End Autonomous Vehicles, *IEEE Trans. Intell. Transport. Syst.*, 23, 14128–14147, <https://doi.org/10.1109/TITS.2022.3144867>, 2022.
- LeCun, Y.; Bengio, Y.; Hinton, G.: Deep learning, *Nature*, 521, 436–444, <https://doi.org/10.1038/nature14539>, 2015.
- Mansour, M.; Gamal, A.; Ahmed, A. I.; Said, L.A.; Elbaz, A.; Herencsar, N.; Soltan, A.: Internet of Things: A Comprehensive Overview on Proto-

cols, Architectures, Technologies, Simulation Tools, and Future Directions, *Energies*, 16, 3465, <https://doi.org/10.3390/en16083465>, available at: <https://www.mdpi.com/1996-1073/16/8/3465>, 2023. (accessed on: March 11th 2025)

Marcus, J.; Fritzsche, F.; Gülden, C. : Where to start reading? Introducing the reference-citation plot in In: ISSI2021: 18th International Conference on Scientometrics & Informetrics. Leuven, Belgium : International Society for Scientometrics and Informetrics (I.S.S.I.); ISSI Society Centre for R&D Monitoring (ECOOM) KU Leuven, edited by: Glänzel, W. Heeffer, S.; Chi, P.-S. and Rousseau, R., 2021., 539–544

McKinsey & Company: Industry 4.0: How to navigate digitization of the manufacturing sector, 2015.

Mönks, U.: Information Fusion Under Consideration of Conflicting Input Signals, Springer Vieweg Berlin, 2017.

Mönks, U.; Trsek, H.; Dürkop, L.; Geneiß, V.; Lohweg, V.: Towards distributed intelligent sensor and information fusion, *Mechatronics*, 34, 63–71, <https://doi.org/10.1016/j.mechatronics.2015.05.005>, 2016.

Morawski, R. Z.: Unified approach to measurand reconstruction, *IEEE Trans. Instrum. Meas.*, 43, 226–231, <https://doi.org/10.1109/19.293425>, 1994.

Mukhopadhyay, S.C.; Tyagi, S.K.S.; Suryadevara, N.K.; Piuri, V.; Scotti, F.; Zeadally, S.: Artificial Intelligence-Based Sensors for Next Generation IoT Applications: A Review, *IEEE Sensors J.*, 21, 24920–24932, <https://doi.org/10.1109/JSEN.2021.3055618>, 2021.

National Research Council: Expanding the vision of sensor materials, National Academy Press, Washington, D.C., 133 pp., 1995.

Perera, Y.S.; Ratnaweera, D.; Dasanayaka, C.H.; Abeykoon, C.: The role of artificial intelligence-driven soft sensors in advanced sustainable process industries: A critical review, *Engineering Applications of Artificial Intelligence*, 121, 105988, <https://doi.org/10.1016/j.en->

[gappai.2023.105988](https://doi.org/10.1016/j.en-), available at: <https://www.sciencedirect.com/science/article/pii/S0952197623001720>, 2023. (accessed on: March 11th 2025)

Perri, L.: What's New in the 2023 Gartner Hype Cycle for Emerging Technologies, <https://www.gartner.com/en/articles/what-s-new-in-the-2023-gartner-hype-cycle-for-emerging-technologies> (accessed on: March 11th 2025)

Pimentel, M.A.; Clifton, D.A.; Clifton, L.; Tarassenko, L.: A review of novelty detection, *Signal Processing*, 99, 215–249, <https://doi.org/10.1016/j.sigpro.2013.12.026>, available at: <https://www.sciencedirect.com/science/article/pii/S016516841300515X>, 2014.

Raghavendra Chalapathy and Sanjay Chawla: Deep Learning for Anomaly Detection: A Survey, <https://doi.org/03407>, 2019.

Rauch, B.: Abschlussbericht Machbarkeitsstudie zu staatlichen digitalen Datenplattformen für die Landwirtschaft, IESE-022.20/D, 521 pp., 2020.

Ruser, H. and Puente León, F.: Methoden der Informationsfusion: Überblick und Taxonomie, in: Informationsfusion in der Mess- und Sensortechnik, edited by: Beyerer, J., Puente León, F., Sommer, Universitätsverlag Karlsruhe, 1–20, 2006.

Sachan, S. and Mutreja, S.: Global Smart Sensor Market: Opportunities and Forecast 2020–2027, <https://www.alliedmarketresearch.com/smart-sensors-market>, 2021. (accessed on: March 11th 2025)

Salicone, S. and Prioli, M.: Measuring Uncertainty within the Theory of Evidence, Springer Cham, 2018.

Sari, A.; Lekidis, A.; Butun, I.: Industrial Networks and IIoT: Now and Future Trends, in: Industrial IoT, edited by: Butun, Springer International Publishing, Cham, 3–55, https://doi.org/10.1007/978-3-030-42500-5_1, 2020.

Schäfer, A.: Structural Health Monitoring of wind turbines- necessity for further progress,

Proceedings of the EWEA Offshore Copenhagen, Denmark, March 2015

Schäfer, A.: Efficiency determination of wind turbines by better capturing huge torque – a crucial factor of energy transition; 22. GMA/ITG – Fachtagung Sensoren und Messsysteme 2024; DOI 10.5162/sensoren2024/C1.1

SIEMENS: SITRANS SCM IQ, <https://www.siemens.com/global/en/products/automation/process-instrumentation/digitalization/smart-condition-monitoring.html> (accessed on: March 11th 2025)

Searle, J. R.: Minds, brains, and programs, *Behav Brain Sci*, 3, 417–424, <https://doi.org/10.1017/S0140525X00005756>, 1980.

Salicone, S.; Prioli, M.: Measuring uncertainty within the theory of evidence. Vol. 2020. Cham, Switzerland: Springer, <https://doi.org/10.1007/978-3-319-74139-0>, 2018.

Solaiman, B. and Bossé, É.: Possibility theory for the design of information fusion systems, Springer, Cham, Switzerland, 2019.

Talbur, J. R.: Pullen, D.; Penning, M.: Evaluating and Improving Data Fusion Accuracy, in: *Information Quality in Information Fusion and Decision Making*, edited by: Bossé, É. and Rogova, G. L., Springer International Publishing, Cham, 295–326, https://doi.org/10.1007/978-3-030-03643-0_14, 2019.

Travis, B.: Smart Sensor, *EDN Magazine*, 05.09.1996, available at: <https://www.edn.com/edn-access-5-09-96-smart-sensor-3> (accessed on: March 11th 2025)

Varak, D.; Charge, D.; Grabill, P.; Kemp, C.: Digital Bus Based Vibration Sensors: Migrating the

Test Cell Inflight, <https://doi.org/10.14339/STO-MP-AVT-306-11-PDF>, <https://www.sto.nato.int/publications/STO%20Meeting%20Proceedings/STO-MP-AVT-306/MP-AVT-306-11.pdf>, 2018. (accessed on: March 11th 2025)

Vukovic, P.: Simulation komplexer Kommunikationssysteme in der Fertigungsautomatisierung, Dissertation, Friedrich-Alexander-Universität Erlangen-Nürnberg, 2023.

Wollschlaeger, M.; Sauter, T.; Jasperneite, J.: The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0, *EEE Ind. Electron. Mag.*, 11, 17–27, <https://doi.org/10.1109/MIE.2017.2649104>, 2017.

Yokogawa Deutschland GmbH: A Wireless IIoT Solution Sushi Sensor, <https://www.yokogawa.com/de/solutions/solutions/asset-management-and-integrity/asset-performance-management/sushi-sensor/#Details>, (accessed on: March 11th 2025)

Zadeh, L.A.: Toward human level machine intelligence – is it achievable?: The Need for a Paradigm Shift, in: 7th IEEE International Conference on Cognitive Informatics, 2008. ICCI 2008, Stanford University, CA, USA, 8/14/2008 - 8/16/2008, 11–22, 2008.

Zhu, S.; Yu, T.; Xu, T.; Chen, H.; Dustdar, S.; Gigan, S.; Gunduz, D.; Hossain, E.; Jin, Y.; Lin, F.; Liu, B.; Wan, Z.; Zhang, J.; Zhao, Z.; Zhu, W.; Chen, Z.; Durrani, T. S.; Wang, H.; Wu, J.; Zhang, T.; Pan, Y.: Intelligent Computing: The Latest Advances, Challenges, and Future, *Intell Comput*, 2, <https://doi.org/10.34133/icomputing.0006>, 2023

5 Packaging, Manufacturing Technologies, and Sensor at Extremes

(Wurz, M.)

In addition to the sensor itself, the design of a suitable housing in combination with innovative manufacturing technology is becoming increasingly important. In particular, measurements under extreme conditions such as temperature and pressure require the use of new manufacturing approaches and innovative materials. This chapter therefore does not focus on the traditional methods used in assembly and connection technology, such as wire bonding and housings such as DIL, TO and BGA. Instead, this chapter provides an overview of new technologies that have already emerged and the possibilities that are expected in the future. The newer processes in housing technology include digital printing techniques, 3D circuit carriers and 3D printing, but also heterointegration as required by modern circuit carriers in microelectronics for chiplets. New housing technologies for the future market of quantum sensors have also been added, in particular technologies for the production of vapour cells or vacuum packages. However, established joining techniques such as soldering are also being supplemented or replaced by processes such as nanoklett or nanofolds.

5.1 Packaging Technology

(Bensch, B.; Eberhardt, W.; Lorenz, L.; Pügner, T.; Zimmermann, A.)

In addition to pure transducers, the field of packaging and connection technology is also increasingly experiencing the trend towards miniaturization. Former classic housings such as DIL (Dual In Line Package), TO (Transistor Outline) or BGA (Ball Grid Array) will be replaced in the future. They will be replaced by solutions for System on Chip (SoC) and System in Packages (SiP). This trend requires an adaptation to the integration and handling technology. For this, it is particularly important to take into account the high requirements in terms of CTE (Coefficient of Thermal Expansion). In addition, new materials such as glass or laser-functionalizable plastics and ceramics are coming onto the market. With their specific properties, these materials

open new possibilities for designing sensors. As a further driver, structuring possibilities of micro- and nanotechnology are now also finding applications in the field of housing and integration technology. Examples of this are stereolithography and the embedding of components. The recording of measured variables goes hand in hand with SmartSensors (Chapter 4), Sensor-Fusion (Chapters 3 and 4) and Self-X (Chapters 2, 3, and 4). In particular, there is a trend towards monitoring our energy consumption combined with energy management. In addition to energy, more recent developments are making it possible to extend the measuring range further and further, thus opening up fields of application where previously only indirect measuring methods were possible. This goes hand in hand with the future market of quantum sensors. These sensors usually place more far-reaching requirements on the housing than conventional sensors. This includes possible hermetic encapsulation, maintenance of an enclosed vacuum or optical accessibility. Further challenges for the production and use of sensors are posed by stricter nature conservation laws. The best-known example at present is the ban on PFAS (perfluorinated and polyfluorinated chemicals), which is leading to the substitution of some plastics.

5.1.1 Mounting and Assembly Technologies

The assembly technologies for sensors rest on the broad technology portfolio for electronic assembly and interconnection technology. However, due to the specific aspects of sensor assembly, there are currently a number of trends which are further described in the following section.

Digital Printing Technologies

Digital printing processes enable the realization of layouts without the need of specific masks or tools. Thus, layouts can be easily adjusted during the development phase. For the production

of sensors, the application of different printing technologies [Keck et al. 2022] paves the way to products with a high number of variants and finally completely individualized solutions [Civelek et al. 2023]. Furthermore, the production can be scaled from small lots to mass production. Since digital printing is based on additive processes, the consumption of resources is reduced. An example for an individualized sensor system used as a functionalized otoplastic is shown in Figure 5.1 [Werum et al. 2022].



Figure 5.1 Pressure sensor with aerosol jet printed wiring on additively manufactured substrate
(Source: Hahn-Schickard/Bernd Müller)

Using drop-on-demand inkjet technology, single droplets are deposited on flat [Mattana et al. 2016] or 2.5-dimensional substrates enabling individualized products. Aerosol jet technology is based on continuous material deposition on two or three-dimensional substrates. For both deposition processes, numerous functional materials are available on the market, e.g., conductive materials like silver, copper, or gold, and dielectric insulating materials like epoxy or polyimide. Inks containing metallic nanoparticles are one widely used material class to realize conductive traces or sensor elements. After printing, a sintering step is required for nanoparticulate inks in order to achieve functional structures (thermal or photonic sintering).

Pick and Place of Sensitive Chips with Vacuum-Free Tools

To cope with the lack of suitable pick-and-place methods for sensitive chips, a new process using a gripper tool from the company INNOCISE called Gecomer® is very promising (Figure 5.2). The tool is designed for the handling of sensitive and/or wavy surfaces. Possible fields of application are handling of optics, fibers, (micro)

electronics, mechanical parts, and different packages in general (Figure 5.3). The tool, made of polymer pillars, is using Van der Waals forces to create adhesion between the gripping tool and the chip surface. Hence, the tool works without any vacuum. While placing, the Van der Waals interactions are reduced by buckling those pillars resulting in a decreased contact area. The challenge is to find the right parameters to avoid a re-gripping of the chip during the Gecomer®-movement away from the chip.

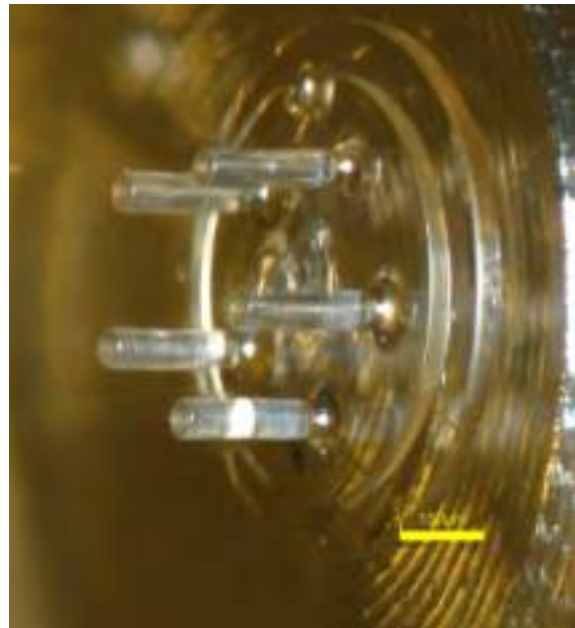


Figure 5.2 Gecomer® tool with five pillars used for chip gripping up to 800 mg (Source: Dr. Lukas Lorenz, Fraunhofer IPMS, [Lorenz et al. 2023])

The Gecomer® gripper allows for safe handling of highly sensitive chip surfaces like membranes or mirrors without using vacuum or edge gripping tools. The achievable placing accuracy is as precise as with standard vacuum tools and is only determined by the xyz portal of the pick-and-place machine. With designing chip-specific gripping tools, it is possible to use areas for gripping which are less sensitive, e.g., bond pads. [Lorenz et al. 2023]

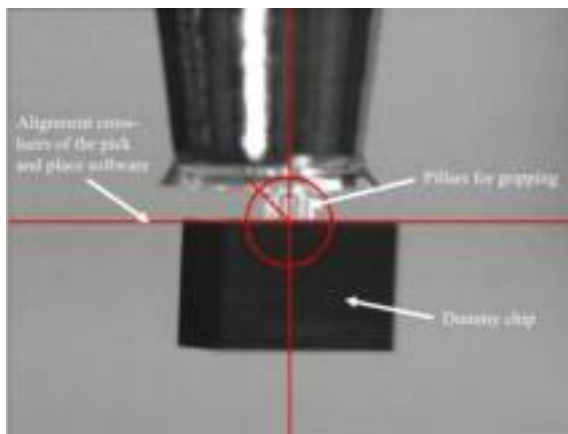


Figure 5.3 Image of a dummy chip attached to the pillars of the Gecomer® tool captured with the monitoring camera built-in in the pick and place machine (Source: Dr. Lukas Lorenz, Fraunhofer IPMS [Lorenz et al. 2023]).

Three-Dimensional Circuit Carriers for Microsystem Packaging and MID

So-called MIDs (mechatronic integrated devices or molded interconnect devices), which are three-dimensional rigid circuit carriers [Franke 2014], can be used for the assembly of sensors. This approach enables to position complete sensors or sensor components in a defined spatial orientation (Figure 5.4). A trend is moving in the direction of standardized sensor carriers. In many cases, the optimal use of a given installation space also makes it possible to miniaturize sensors, as non-electrical functional elements (e.g., mechanical and optical) can be integrated alongside electrical functional elements.

Various process chains are available for the production of spatial circuit carriers, with laser direct structuring (LDS) being the most widely used. The LDS process substitutes traditional photolithographic structuring which is not capable of dealing with three-dimensional parts.

After the 3D base body has been produced by injection molding, selective laser activation is carried out with subsequent electroless plating to create the 3D conductor pattern, followed by the assembly and contacting of components. The freedom of movement of the laser allows complex 3D conductor structures to be created on circuit carriers in a highly flexible and time-saving manner. Selectivity is achieved by laser-induced modification of the substrate material surfaces, whereby special additives are sometimes required for the substrate materials.



Figure 5.4 Three-dimensional circuit carrier with spatially oriented light sensors (Source: Hahn-Schickard/Bernd Müller)

Thanks to a wide range of possible substrate materials [LPKF 2023], spatial circuit carriers can be adapted to the operating conditions of sensors in a wide variety of industries. Thermoplastics such as LCP (liquid crystal polymer) are suitable for the assembly of sensor carriers due to their thermal expansion properties, high temperature stability and good flow properties in the injection molding process. PEEK (polyether ether ketone) is an alternative thermoplastic material, e.g., for use in high-frequency applications. Due to its dielectric properties, PEEK has also the potential to substitute some fluorinated circuit board materials that are being discussed in connection with the PFAS ban.

Thermoset epoxy-based substrate materials are used in particular when functionalized housing solutions are required, e.g., a combination of encapsulation of chips with electrical circuits on the surface of the package (Active Mold Packaging, AMP) [He et al. 2022].

For prototyping and small-scale production, additively manufactured substrate materials can also be functionalized by laser structuring and electroless plating [Vieten et al. 2024].

Another process chain for functionalized substrates is Ensinger Microsystems Technology (EMST) (Figure 5.5). The process chain, which was developed at the Institute of Micro Production Technology (IMPT) at Leibniz Universität Hannover, utilizes plastic substrates based on the LDS-capable TECACOMP PEEK LDS. The material has favorable properties in the field of microsystems technology. The high chemical resistance, temperature resistance and thermal expansion coefficients, which are very close to

metallic PVD thin films, should be emphasized. Using TECACOMP PEEK LDS as a substrate material leads to creating robust microsystems which can offer benefits regarding their physical properties. For instance, flow or temperature sensors can deliver very fast signals due to the thermal properties of the PEEK base material if such sensors are built on TECACOMP PEEK LDS-based substrates. The EMST process chain offers the possibility of building high-precision microsystems on PEEK wafers without the need for lithography. The basis for this is the injection molding of microstructures using high-precision tool inserts, which are produced using lithography and electroplating or milling processes.



Figure 5.5 EMST process chain on wafer substrate from Ensinger GmbH (Source: Ensinger GmbH)

This technology is expected to improve integration capability, adaptability, and functionalization. Figure 5.6 shows a customized solution of a sensor array on a ready-made substrate.



Figure 5.6 Individualized sensor carrier with function integration in component (Source: Ensinger GmbH)

This example clearly shows that EMST creates possibilities that cannot be realized economically with lithography-based processes or even on substrates such as silicon. With EMST, even "large" sensor arrays or varying quantities can be mapped cost-efficiently and can therefore

avoid assembly, joining and cutting processes compared to conventional PCB assembly and connection technology.

EMS technology can be purposefully combined with LDS technology in order to marry the advantages of both process chains. In order to increase integration density and shorten signal paths, the creation of VIAs (Vertical Interconnect Access) in the case of semiconductor components TSVs (Through Silicon Vias) is technically feasible. Via structures are an important topic here. These vias are extremely difficult to realize in other substrates such as silicon and ceramics. TSVs are produced using deep reactive ion etching (DRIE), PECVD (Plasma Enhanced Chemical Vapor Deposition) or atomic layer deposition (ALD) and other thin-film technologies. In comparison, LDS vias can be produced with great benefit using laser drilling and electroless metallization. The dielectric strength of PEEK compared to PECVD insulation layers should also be emphasized (TECACOMP PEEK LDS approximately 17.5 kV/mm). Offering these technological advantages, EMST leads to a re-thinking of packaging for MEMS, neglecting wire bonds and housings for various applications.

Another process for creating three-dimensional molded bodies for use as a carrier system for electronic components is the in-mold structural electronics (IMSE) technology from Tactotek. The process consists of four basic process steps: screen printing, surface mounting, thermoforming and smart film insert molding. The materials used are Polycarbonate (PC) and Thermoplastic polyurethanes (TPU). Areas of application include ambient lighting in the automotive industry.

However, circuit carriers made of polymer can often no longer meet the increased requirements, especially with regard to resistance under extreme conditions and high-frequency properties. Ceramic-based circuit carriers have the necessary properties to meet these challenges and are already being used for example for radar sensors for autonomous driving or lighting technologies. The possibility of hermetic sealing and the chemical resistance make ceramic a suitable material for applications in for example medical technology [Ermantraut et al 2018]. Ceramic materials are particularly attrac-

tive due to their high thermal stability, electrical insulation, good mechanical strength, high chemical resistance and low thermal expansion. Therefore, injection-moldable ceramic materials based on alumina have been increasingly investigated in recent years [Ermantraut et al. 2019; Ermantraut et al. 2018; Zhao et al. 2020; Shafeev 1993], but there are also investigations on aluminum nitride [Yung et al. 2011], diamond [Shafeev 1998], silicon carbide [Shafeev 1998], zirconium oxide [Ninz et al. 2020; Li et al. 2018] and silicon nitride [Shafeev 1998]. The chemical processes that take place during laser activation vary for the materials examined. In the case of aluminum nitride, the high temperatures during laser treatment cause the aluminum nitride compound to break up, leaving a thin film of molten aluminum on the surface, which serves as a catalyst for subsequent electroless deposition. At the same time, this leads to liquefaction and filling of the previously porous surface, which reduces the surface roughness. Previous research results have shown that thin conductor paths ($< 10 \mu\text{m}$) and vias have been successfully created on ceramic surfaces [Bachy et al. 2018; Ermantraut et al. 2018]. The metallization of the machinable composite ceramic aluminum nitride/boron nitride was also investigated for the first time at the Institute of Micro Production Technology in Hanover. Sensor structures, conductor paths and contact pads on 3D milled components were laser-activated and electroless metallized with a Cu/Ni/Au layer structure. Contacting techniques such as wire bonding and soldering could be carried out successfully on the deposited layers. The developments in recent years have led to a higher degree of miniaturization and a higher integration density for universally applicable ceramic three-dimensional circuit carriers.

PCB-Based Integration

According to the state of the art, sensors are often mounted on PCBs in the form of SMDs (surface mounted devices). However, it is also possible to realize sensor elements directly using PCB technology.

The need for costly investments in production facilities poses a major difficulty for small and medium-sized enterprises (SMEs) when entering the market. The direct integration of sensor

functions in printed circuit boards is a concept that enables SMEs to benefit from the large predicted growth of the sensor market by increasing vertical integration (reuse of existing SMD assembly machines, use of cost-effective production technologies). Thanks to the low initial costs and design flexibility, customized sensor solutions can also be produced economically in small quantities.

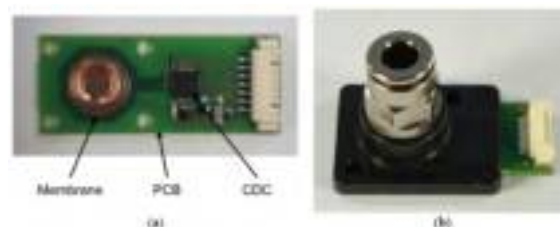


Figure 5.7 Capacitive pressure sensor with membrane mounted on the PCB, a) without housing, b) with housing for differential pressure measurement (Source: Hahn-Schickard)

The integration of functions in printed circuit boards (e.g., passive and active components) is a trend that has been pursued for some time and from which the integration of sensor-relevant functions can also benefit [Kostelnik 2015]. Sensor structures such as electrodes or coils can be integrated in addition to the printed circuit board layout [Hella 2017]. Other components required for the sensor, such as membranes for pressure sensors, can be mounted on the PCB using conventional assembly technology (Figure 5.7) [Schwenck et al. 2021]. Different capacitive, resistive and inductive sensors can be realized with these integration concepts [Büla 2024].

Heterogeneous Integration with Flexible Carrier Material (System-in-Foil)

Polymer foils are already widely used as flexible circuit carriers. However, there is currently a trend to realize sensors via heterogeneous integration with mechanically flexible substrates [Saleh et al. 2021], so called system-in-foils [Koyuncu et al. 2015; Elsobky et al. 2021]. This includes the possibility to integrate discrete components such as ultra-thin flexible chips and direct integration of functions on polymer foils, e.g., by printing or thin film technology. One advantage of this approach is given by the overall reduced thickness in the order of $100 \mu\text{m}$ which enables sensor integration in flat

structures. Depending on the substrate material, sensor application on curved structures can be achieved due to stretchability or bendability. One example for the capabilities of foil-based sensors is the temperature sensor for diabetes patients shown in Figure 5.8 [Polzinger 2017].

Silicon chips become flexible when the thickness is reduced to a value below 50 μm . Special pick-and-place tools are required to mount these ultrathin chips on flexible substrates. Several process chains are available for face-up or face-down assembly of the chips. Thin film and printing technologies can be utilized to integrate transducers or passive components directly on the flexible substrate.

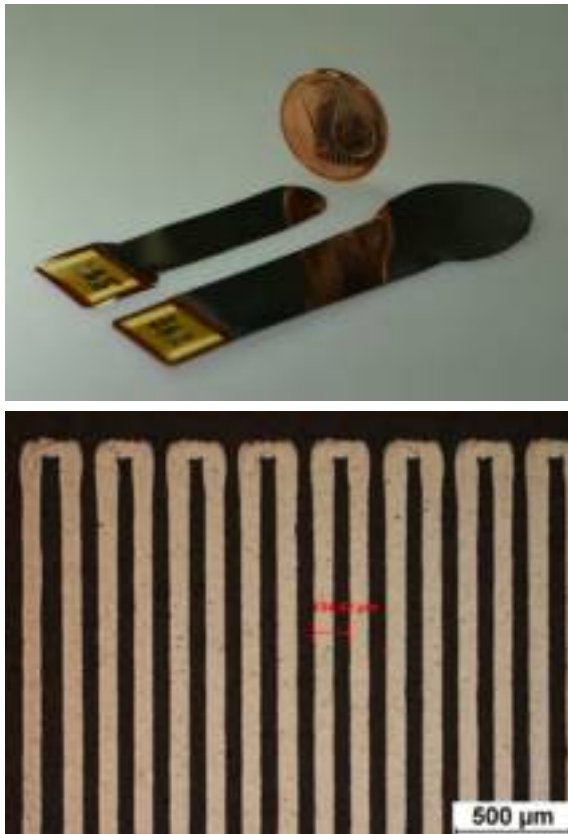


Figure 5.8 Foil based temperature sensor for shoe soles for diabetes patients (Source: Hahn-Schickard)

Polymer Technologies for Optical Sensors

Optical sensors offer several advantages such as touchless measurements and high accuracy. While optical components in the past were mainly manufactured using inorganic materials, there is currently rising interest in polymer-based optical components. Since replication techniques for polymer parts have gained a high

maturity level, the use of polymers enables significant cost reduction of optical components for mass production.

Figure 5.9 shows an optical encoder as an example of an optical microsystem which uses a diffraction-based principle. The light of a laser diode is diffracted at a micro-structured polymer disc and detected via photo diodes [Seybold et al. 2019]. Another example would be a micro-lens array for hyperspectral imaging applications.



Figure 5.9 Optical encoder with micro-structured polymer components (Source: Hahn-Schickard/Bernd Müller)

For manufacturing of optical polymer components, several processes such as injection molding, injection compression molding or hot embossing can be chosen [Roeder et al. 2019]. Quality criteria include high molding accuracy for diffractive components and low surface roughness for refractive components. The assembly of optical components demands high accuracy as well. One approach to achieve the requested accuracy level is the so-called active alignment which uses light sources and image processing to ensure precise positioning of optical components during assembly processes.

Since sensors based on quantum effects often require optical detection principles, polymer technologies offer high potential for miniaturized quantum sensors as well.

SLA Printing for Component Embedding

Fan-out wafer-level packaging is increasingly developing into a serious packaging solution. With the help of 3D printing, special and individual solutions can be developed that make it possible to embed active and passive components and thus achieve an extremely high packing density in a multi-chip module. This miniaturization is of particular interest for sensor applications. Stereolithographic (SLA) printing is particularly suitable for achieving high precision. Figure 5.10 shows the basic process flow for a 3D additively manufactured package. In both cases, the components are placed on a temporary carrier in order to be subsequently embedded using SLA printing. The advantage of this is a particularly low temperature input compared to injection molding processes [Tiedje 2017]. The differences in the process flow result from the way in which the RDL is produced. This can either be created on the temporary carrier or applied to the finished printed package afterwards.

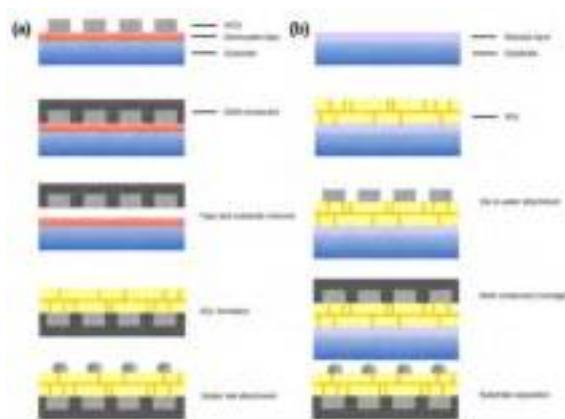


Figure 5.10 Two typical RDL processes in FOWLP: a) chip-first process flows; b) chip-last process flows (Source: [Mo et al 2023])

5.1.2 Heterogeneous Integration

(Behrmann, O.; Bertke, M.; Dubey, V.; Diex, K.; Gojdka, B.)

Heterogeneous integration is the approach to integrating separately manufactured components into higher level system which is commonly referred to as a System-in-Package (SiP) which in its holistic form provides enhanced functionality with improved operating characteristics. The SiP can be a final product (e.g., Arduino board, Raspberry Pi, or a working com-

puter) or a sub-system which may lead to easy assembly to a final product (such as solid-state memory, CPU, graphics card). The complete system may differ for a given technology (e.g., optimization in terms of size, while another component is optimized for a low-power or a high-temperature application) or functionality (e.g., MEMS device, memory, specialized processing units such as NPU, CPU, or GPU) or system level (such as complete packaged systems or a sub-system).

There are several advantages of heterogeneous integration over a monolithic integration. Using heterogeneous integration, chips of different sizes, fabricated with different technology nodes, can be integrated on a common substrate. As the chips are getting larger with increasing transistor count reaching almost 1 trillion with decreasing transistor gate length, it becomes more difficult to integrate such large chips with other technologies. In this case, heterogeneous integration can provide a solution by enabling tighter integration. At the same time, this approach essentially maintains progress toward higher performance, lower latency, smaller form factor, lighter weight, low power and cost and better thermal performance. Heterogeneous integration is enabled by several key packaging technologies, such as bumping, interconnect, wire bonding, 2.5D/3D integration, flexi-connectors, several embedded technologies, fan-in or fan-out chips, interposers, wafer-level-packaging (WLP), etc.

The largest players in the heterogeneous integration technologies are:

- Intel
- TSMC
- Samsung
- ASE
- EV Group

Some of the key industry players that are taking advantage of heterogeneous integration are Apple, Nvidia, AMD, Samsung, BBK electronics, Microsoft, Google, Asus, Qualcomm, Intel. There is growing demand for applications such as artificial intelligence, internet-of-things, high-per-

formance computing (HPC), 5G, medical health and wearables, MEMS and Sensors. Among the regions which are leading to the growth of the heterogeneous integration are [Precisionreports 2024]:

- Europe (Germany, Belgium, UK, France, Russia, Italy)
- North America (United States, Canada),
- Asia (China, Japan, Taiwan, South Korea, Singapore, India, Philippines, Vietnam, Thailand)
- South America (Brazil, Argentina, Columbia)
- Middle East and Africa (UAE, Saudi Arabia, Egypt and South Africa)

One of the key technologies enabling advanced 3D heterogeneous integration is wafer level packaging. This is further described in the next section.

3D Advanced Packaging W2W

Wafer-to-wafer bonding is a key technology to enable the packaging of components at the wafer level. There are several key advantages of wafer level packaging, such as use of existing process modules that are at wafer level, e.g., testing, cleaning, inspection, handling, alignment, and bonding. Cleaning and handling of chips are critical and have downsides in terms of alignment accuracy. The state of the art for chip alignment is 1 μm , while it is 50 nm for wafer alignment. Figure 5.11 shows the trend for 3D interconnect scaling which is key towards realizing the further process challenges that would be necessary for the hybrid bonding on the wafer level. In research and development (R&D), the alignment accuracy for W2W bonding is at 400 nm pitch (with interconnect density of 10 million/ mm^2), while in the industry, it is still at 1 μm (with interconnect density of 1 million/ mm^2). For chip-level assembly in R&D, the alignment accuracy is 2 μm pitch, while the industry is still at 40 μm pitch. Additionally, there are challenges with scaling processes which are described in the next section.

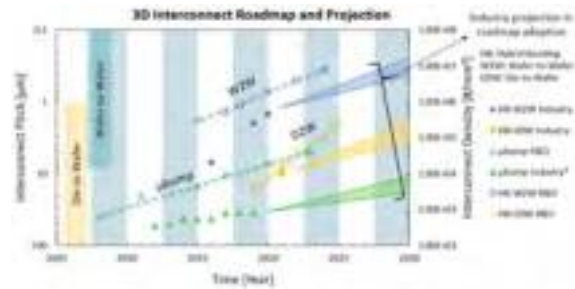


Figure 5.11. Trends for the μbump scaling along with interconnects pitch for D2W and W2W bonding [Source: [imec 2024]].

Wafer-to-Wafer Hybrid Bonding

Wafer-to-wafer hybrid bonding is a mature technology compared to die-to-wafer hybrid bonding. The first industrial application of W2W hybrid bonding is demonstrated by Sony in their stacked backside illuminated CMOS image sensor (BI-CIS) [Haruta 2017]. This work was demonstrated in 2017. This technology helps deal with the distortion in the acquired image created by the rolling shutter effect of a fast-moving object. Here, when the image is captured, a delay in the information is created at the output interface (I/F) when the signal is transmitted serially from the image sensor to the logic and then to the output interface (I/F). This is resolved by adding a high-speed dynamic random-access memory (DRAM) chip which captures and stores the information parallel to the image sensor. Then, it is transmitted to the substrate-output interface. [Haruta 2017] shows the 3-layer sensor architecture (pixel/DRAM/logic substrate) which greatly decreases the distortion in the final image due to the rolling shutter effect. In this heterogeneous integration scheme, the DRAM wafer is flipped and bonded to the logic substrate face to face (F2F). The DRAM wafer is then thinned down to 3 μm thickness, then through silicon vias (TSVs), and the required metal wiring is fabricated connecting the substrate. The pixel wafer is flipped and bonded to the DRAM/logic substrate wafer, and then the TSV are formed to connect the pixel wafer to the bottom DRAM/logic wafer. This is subsequently realized using 6 μm low resistance Cu-Cu hybrid bonding [3Urata 2024].

As of 2024, the W2W hybrid bonding has been successfully demonstrated for 400 nm pitch in research [Chew 2024]. For such a small inter-

connect pitch size, the overlay accuracy has to be below 100 nm, which requires advanced wafer-bonding equipment with a vision system that can enable such high alignment accuracy. This is realized using the SmartView® alignment by EVG Group [EVGROUP 2024]. The scaling of the interconnect for hybrid bonding is motivated mostly by the CMOS scaling needs. The advantage of scaling for fine pitch Cu-Cu hybrid bonding is that there are fewer masks required for fan-out of the interconnects from the transistor level to the outside, which in turn contributes to the decreasing cost and time required in realizing such a complex technology. Additionally, with the advent of system technology co-optimization (STCO), circuit portioning is realized at a lower hierarchy. This leads to several interesting mix matches of devices for advanced heterogeneous integration. The need for W2W hybrid bonding also holds key importance in several applications, such as sensor integration for smartwatches and AR/VR glasses. The smartwatches and wearables are currently designed with a multitude of sensors like temperature sensors, strain sensors, pressure sensors, physical sensor, biosensors, accelerometers, and infrared sensors. Integration of these sensors is realized using advanced heterogenous integration technology.

For sub-micron pitch, there is also a possibility that the copper might re-sputter in the oxide region during the plasma pre-treatment, leading to electrical pathways between subsequent copper vias. This would affect the electrical performance and the reliability of the finally bonded wafers [Hahn 2023]. The O₂ plasma leads to oxidation of the bond interface with a bond strength of 1.65 J/m², and the N₂ plasma leads to a bond strength of 1.80 J/m² [Hahn, 2023]. O₂ plasma also shows the formation of an oxide layer at the copper surface, while N₂ plasma does not lead to any oxide formation in between the copper interface.

The design and density of the copper vias can have a significant impact on the bond surface that needs to be realized for hybrid bonding. It is shown in the work [Dubey (ECTC) 2023] that the copper via density and pitch size can have an impact on the bond surface topography, dishing and roll-off. However, there are two ways in which this can be mitigated: by inclu-

sion of dummy vias (vias that do not connect to the underlying circuitry) and by using compatible dielectric film.

Die-to-Wafer

For D2W bonding research, the current interconnect pitch in research is 3 µm, while in the industry it is still at 10 µm pitch. The key rationalization for such a large pitch at the chip level are the challenges that come with alignment, placement accuracy, surface quality and bonding. The technology for D2W hybrid bonding is in the nascent stage with most of the equipment reaching maturity since 2019. However, with a chip, there are additional challenges when compared to the wafer-level process, such as cleanliness after dicing on a dicing tape, and surface activation, which is realized using the plasma cleaning and de-ionized water rinse and then flip chip bonding. Alternatively, there are other concepts that are in the research phase, such as an innovative collective D2W bonding (cD2W) approach. Here, the chips are stacked picked on a carrier wafer and then transferred to the target wafer, thereby ensuring the sanity of the surface quality needed for D2W hybrid bonding. Additionally, the technology of interest also adheres to the thickness of the chip, wherein the chips are thinned to expose the TSV on the backside for RDL and pad processing or to make an interconnect across the thickness of the chip for multichip stacking.

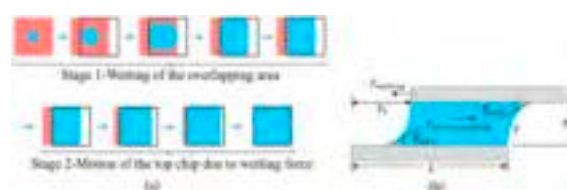


Figure 5.12: Stage 1 and 2 of the self-aligned assembly process. Stage 1 shows the wetting of the overlapping chip, stage 2 shows the motion of the chip during the alignment process (Source: Reprinted from [Dubey et al. 2018])

To realize high integrity of the alignment accuracy, self-aligned assembly is an innovative assembly technology that is foreseen as an option to further improve the alignment accuracy to sub 100 nm [Dubey (EPTC) 2023]. Self-aligned assembly (Figure 5.12) is a stochastic technique when compared to standard pick-and-place approach that is realized using direct bonding,

which is a deterministic approach. The details and fundamentals of this approach are described in detail in the work done by [Dubey et al. 2018].

Another technique which is used is the bumpless technology wherein the chips are fabricated and the microbumps are embedded in the wafer-level photo-patternable underfill (WLPUF) [Derakhshandeh et al. 2016], which, after CMP planarization, leads to effective isolation and high bond strength between the chip and wafer. One advantage of this approach over standard flip chip bonding is the improvement in planarization of the placed chips, leading to high yield and better alignment accuracy. This approach is helpful for fine pitch interconnects with solder. It is essential to maintain a good solder volume which leads to high solder interconnects which in turn are supported by WLPUF. This technique is demonstrated for 5 μm pitch microbumps for N>2 stack [Derakhshandeh et al. 2022].

Hybrid Bonding with TSV Integrated

Two critical processes are required for the realization of a TSV for 3D heterogeneous integration. Firstly, the deep silicon etch, and secondly, the metallization fill, which is TSV-conformal seed layer deposition, and then the electro-chemical deposition of the copper fill in the vias. To enable the scaling of the TSVs, the scaling needs to rely on a 1:10 (via diameter:etch depth) aspect ratio. With regard to this for 10 μm -diameter TSVs, the etch depth can go to 100 μm . However, challenges arise for the diameter scaling of the TSVs from 10 μm to 1 μm as the thickness of the silicon will translate from 100 μm to 10 μm , which is challenging and requires innovations in the handling of chips.

Chiplets

The slowdown of Moore's Law is increasingly shifting the focus to packaging and assembly when it comes to achieving further increases in performance. In this context, chiplets have become increasingly important and can be found in almost all packaging concepts for highly integrated heterogeneous systems [Lau 2021].

The integration of sensors also benefits from this development. For example, sensor chips can be integrated together with the control

electronics in a very small footprint in a system-in-package (SiP). The advantage of this "near-sensor computing" is the significantly more efficient exchange of data between the sensor unit and the processing electronics. The close proximity alone means that unnecessary data transfer can be avoided, and energy efficiency is increased [Zhou et al. 2020].

The most recent option for chiplet integration developed at Fraunhofer IPMS is the quasi-monolithic integration (QMI) (Figure 5.13). The idea is to combine several chiplets (e.g., sensors/MEMS together with ASICs) on a passive interposer and an RDL on top of them. For that, the chiplets are bonded onto the interposer already in the backend of line (BEoL). Afterwards, the redistribution layer (RDL) is fabricated with frontend instead of packaging technologies in the BEoL as well. Hence, the chiplets are integrated with the wafer, and from the outside, it looks like a monolithic integration of sensor and computing functions directly on a chip. Among other things, challenges are the die-to-wafer bonding, which needs to be highly accurate, and the fabrication of the interposer with its pockets.

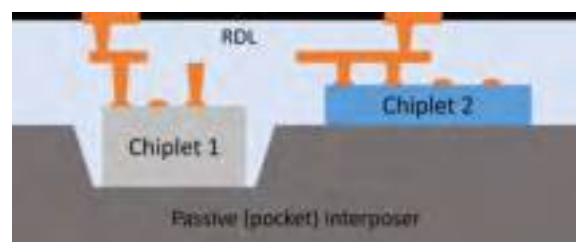


Figure 5.13: Schematic of a quasi-monolithic integration (QMI) of two chiplets on a passive interposer with a redistribution layer (orange) fabricated in the BEoL on top of the chiplets ((Source: Dr. Lukas Lorenz, Fraunhofer IPMS)

One advantage of bumping vs. bumpless integration of multi-chip stacking is the thermal efficiency of the stack. The bumping process and the underfill material sandwiched between the chips lead to additional spacing compared to hybrid bonding technology. This leads to improved thermal efficiency in terms of heat dissipation for the stack, realized by using a bumpless process instead of a bumping process. The bumping is created using tin-based solder which is realized using thermo-compression bonding and then closing the open space with non-conducting film (NCF). This is shown by Samsung for their memory chips realized for

high-bandwidth memory (HBM) stack for a 12-plus chips stack [Kim et al. 2023].

Glass as Functional Material

Glass possesses a unique set of properties that make it increasingly favorable for sensing applications. Its optical, mechanical, chemical, and thermal characteristics render it ideal for microsensor fabrication [Weigel et al. 2023; Yu et al. 2024; Tang et al. 2021]. Glass's isotropic structure, low thermal conductivity and low internal friction reduces thermal noise and thermoelastic damping, enhancing sensor sensitivity [Zeng et al. 2021], while its excellent dimensional stability ensures long-term accuracy [Rocheleau et al. 2013]. The low dielectric constant and loss tangent ensure minimal signal loss and distortion at radio frequencies. Due to its versatility as a carrier substrate, packaging material, or functional microsystem, glass is increasingly employed across various sensing applications such as environmental monitoring [Glukhovskoy et al. 2021], lab-on-a-chip [Sandström et al. 2022], medical sensing [Han et al. 2023], industrial process control, RF or radar sensors [Galler et al. 2021] and high-performance inertial sensing [Su et al. 2023; Li et al. 2020]. Besides traditional sensor principles, quantum or photonic integrated sensors are actively researched [Hänsel et al. 2020; Quack et al. 2023]. They offer a promising platform for developing compact, sensitive, and multiplexed sensor systems [Broquin et al. 2021; Schröder et al. 2021]. Photonic integrated circuits (PICs) based on glass substrates offer several advantages, including low optical loss, high thermal stability, and compatibility with existing microfabrication processes [Schröder et al. 2021].

Ensuring the functionality and performance of glass-based microsystems hinges on meticulous control of precise sensor fabrication, surface roughness and defect minimization. This attention to detail is vital during fabrication processes [Weigel 2023]. Glass microstructures are intricately formed through selective etching using wet or dry techniques, creating channels or cavities. Yet, challenges persist in achieving uniformity and high aspect ratios across large areas [Yu 2024]. While some glass microfabrication methods promise high-quality results, they may prove costly or time-consuming, limit-

ing scalability for mass production [Hamed 2023]. However, laser-induced deep etching (LIDE) emerges as a potent solution, propelling the advancement of glass in microsystems and sensors. This technique enables the creation of high aspect ratios structures, precise defect-free feature resolution (Figure 5.14), and scalability, effectively addressing the challenges inherent in traditional fabrication methods [Bertke 2024; Santos 2022]. Additional techniques like photolithography, wet etching, thin-film deposition, and anodic bonding are commonly used in microsystem processing, and glass is highly compatible with most materials, though process integration is part of current developments [Karl 2023].



Figure 5.14: a) 5 μm through holes in a 30 μm glass-membrane anodic bonded to a micro-structured handle wafer for environmental sensing applications; b) glass-based micro opto-electro-mechanical system (MOEMS) (Source: LPKF Laser & Electronics SE)

Integration of Functional 3D Microstructures

The fabrication of “bulky” three-dimensional (3D) microstructures with dimensions between several tens to several hundreds of micrometers is of considerable interest to enable new degrees of freedom for the design of microsystems. Integrated permanent micromagnets can be applied, e.g., in magnetic field sensing and quantum components, whereas porous 3D structures can contribute to environmental sensors and microfluidic devices. Several substrate-level technologies emerge with integration characteristics potentially suitable for industrial fabrication of sensor components.

The company Magnetfab offers a sputtering process for NdFeB magnets with lateral dimensions between 50 μm and 300 μm at a maximum thickness of 50 μm . [Keller 2022]. While silicon is the typical substrate, other substrates like titanium, glass, and sapphire can also be

used. Such magnets offer a high remanence of 1.3 T out of the substrate plane.

A wide material choice and low process temperatures can be achieved using powder-based techniques. While not integrated within the silicon substrate, Infineon's integrated back bias (ibb) technology is an example of polymer-bonded magnets for magnetic field sensors. [Elian et al. 2014] Widely used for 3D microstructure fabrication is the filling of mold patterns with particle-loaded inks or pastes via spin coating or squeegee coating. [Pallapa et al., 2014] The properties of such 3D microstructures can be tailored within a broad range. However, the geometric precision and minimal structural dimensions of these methods are limited; due to the viscosity of highly loaded organic matrices and trapped air, proper filling of micro-molds is challenging.

A technique from Fraunhofer ISIT called PowderMEMS offers an organic-free approach for a wide range of magnetic and non-magnetic materials. [Lisec et al. 2022] Microfine powder is dry-filled into pre-formed micro-molds and solidified by atomic layer deposition. In this way, porous and magnetic structures can be fabricated with lateral dimensions from 30 μm to millimeters and thicknesses of several hundreds of micrometers (Figure 5.15).



Figure 5.15: 200 mm silicon wafer with integrated NdFeB magnets. The magnets have lateral dimensions between 40 μm and 2 mm and are 500 μm thick. (Source: Bodo Schmidt)

Thanks to process temperatures below 100 $^{\circ}\text{C}$, the structures can be integrated into pre-processed substrates like silicon, glass and even PCB. A monolithically integrated back-biased hall sensor was demonstrated by wafer-level integration of NdFeB magnets into the silicon

substrate of the sensors (Figure 5.16). [Gojdka et al. 2023] Non-magnetic porous membranes realized with the PowderMEMS technique were applied for the functionalized capping of environmental sensors on wafer-level. [Behrmann et al. 2023]



Figure 5.16: 3D Hall sensor with NdFeB magnets integrated into the substrate at wafer level on the back (Source: Florian Ziegler)

5.1.3 Joining Technologies for the Heterointegration of Quantum Sensors

(Droese, N.; Kassner, A.)

Classic joining technologies for wafer-level-based joining or heterointegration include eutectic bonding, anodic bonding, and direct silicon bonding. Eutectic bonding is a joining process in which a strong bond is created between two materials using a eutectic alloy. This alloy melts at a lower temperature than the individual components and forms a strong bond when it solidifies. During anodic bonding, an electrical voltage is applied between a glass wafer and a silicon wafer. This causes sodium ions to migrate in the glass, creating an electrostatic attraction that firmly bonds the two materials together at relatively low temperatures. In direct silicon bonding, also known as Si-Si bonding, two clean, flat silicon surfaces are bonded together at the atomic level. This is usually achieved by pressure and sometimes heat, creating strong covalent bonds without intermediate layers. When selecting joining technologies for the heterointegration of quantum sensors, however, a number of boundary conditions must be taken into account. Quantum sensors

such as vapor cell-based magnetometers, atomic clocks, or ion and atom traps are sensitive to external magnetic fields, so the use of non-magnetic material pairings must be given priority in the joining process. In addition, many quantum sensors are operated under high vacuum (HV) or ultra-high vacuum (UHV) conditions. Consequently, the outgassing rate of the joint is of paramount importance. Another aspect concerns the maximum temperature resistance of the quantum sensors during the joining process. Atom chips, which are used in gravimeters and gyroscopes, should be mentioned here as an example. These consist of different materials with different thermal expansion coefficients. Temperature input during joining can lead to delamination of layers. Two promising joining processes at this point are transient liquid phase (TLP) bonding (Figure 5.17) and bonding using silver sintering paste.

TLP bonding is a form of eutectic bonding [Kassner et al. 2023; Kassner et al. 2024].

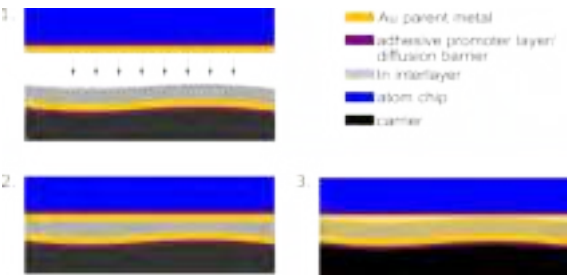


Figure 5.17: TLP bonding process sequence

With a suitable choice of material pairing, it is characterized by comparatively low process temperatures with a higher re-melting temperature. It also offers the possibility of compensating for unevenness in the joint. The material pairing Au-In has proven to be particularly advantageous at this point. The melting point of indium is 156 °C, while the re-melting temperature of the alloy AuIn2 is 540.7 °C. Like the substrate, the quantum sensor to be joined is coated with the base metal gold by sputtering. The indium intermediate layer can be applied in the form of a foil, for example. The components are then brought into contact under the influence of pressure and temperature. The latter must be at least as high as the melting temperature of the intermediate layer. This is followed by melting and homogenization of the intermediate layer. This leads to a reaction with the base metal, resulting in the formation of inter-

metallic compounds with a higher melting point. When the interlayer is completely transformed, isothermal solidification follows. This joining process is tolerant of superficial oxides or defects and is also characterized by high thermal conductivity, high tensile and shear strength and low mechanical stresses.

Alternatively, silver sintering paste can be used as a non-adhesive joining technique for applications that exclude pressure during joining. At 235 °C, the temperatures are higher than with Au-In TLP bonding. During the joining process, the solvent outgasses so that a silver framework is finally formed. Application to silver or gold surfaces guarantees appropriate adhesion. The melting point of this compound is 961 °C. A comparative measurement carried out by the PTB of the outgassing rates and the residual gas composition of a quantum sensor and a quantum sensor joined using silver sintering paste proves the vacuum compatibility of this joining process.

Table 5.1: Outgassing measurement of the quantum sensor with joining [Kassner et al. 2023].

Outgassing rate in mbar·l/s	Residual gas analysis, composition in %					
	H ₂	CO ₂	H ₂ O	CO	CH ₄	other
4,26E-13	81	7	6	4	1	1

Atomic Clocks/Vapor Cells

Quantum technologies are considered one of the key technologies of the 21st century, and their application in sensor technology and metrology has opened up new possibilities in terms of sensitivity in fields such as medicine, communication, and navigation technology. This includes highly stable and precise time and frequency standards. With current atomic clocks, frequency accuracies and stabilities of less than 10⁻¹¹ can be achieved [Kitching 2018]. Quantum systems with the best current sensitivity also have a frequency uncertainty of less than 10⁻¹⁸ [Kitching 2018; Ludlow et al. 2015]. In contrast, conventional systems such as quartz crystal and MEMS oscillators provide less accurate refer-

ences and suffer from insufficient long-term frequency stability in the 10^{-4} range due to aging and environmental changes such as temperature and mechanical vibrations. While temperature or oven-compensated systems can increase stability in the 10^{-10} range, they require high power consumption and a relatively long switch-on time [Taitien 2021; ITU 1997; Ludlow et al. 2015]. As a result, the stability of oscillators is no longer sufficient for many applications. Highly stable and accurate time and frequency measurements are required, for example, for GPS navigation and telecommunications. In the case of modern mobile telephony, a relative deviation of the clock of $3 \cdot 10^{-12}$ is required over a period of 24 hours. The requirements for satellite navigation are even higher, with a time difference of 10 ns corresponding to a location error of approximately 3 m, and deviations of less than 10^{-14} being necessary [Almat 2020]. As frequency standards improve, the spatial resolution of these systems also improves. If the accuracy is too low, the clock must be reset at regular intervals.

To achieve economic use, it is necessary to miniaturize the overall system and shift from laboratory operation to mobile applications in the field or on-board aircraft or satellites. Atomic clocks are based on either the principle of optically pumped atomic vapor or the generation of ultracold atoms in a magneto-optical trap (MOT). MOT atomic clocks achieve the best accuracy, but their high complexity makes them mainly suitable for laboratory operation. Atomic vapor cells, on the other hand, can be produced in compact dimensions at a low price and still have good long-term stability in the range of 10^{-12} , making them interesting for commercial time and frequency standards. In an atomic vapor cell, which is often filled with an alkali metal in a specific atmosphere, a laser of the corresponding wavelength λ_0 is used to selectively depopulate the lower hyperfine structure level of alkali atoms by optical pumping. With further microwave irradiation, electromagnetic waves with characteristic oscillation frequency f_0 are absorbed. The better the resolution or the smaller the line width of the resonance signal, the better the accuracy of the atomic clock. The stability of atomic clocks based on atomic vapor cells is influenced by various physical effects, such as changes or deviations in pressure con-

ditions, magnetic field, microwave power, light intensity, and light frequency, which can reduce long-term stability [Almat 2020]. The basic components for a chip-scale atomic clock are shown in Figure 5.18, which include light source (e.g., laser), optics, vapor cell, detector and analyzing electronics. The alkali vapor cell represents the core element of the sensor.



Figure 5.18: Schematic principle of an alkali vapor cell

The current state of technology and science involves the production of micro-integrated atomic vapor cells, primarily in an academic context. Vapor cells come in various configurations with different contents, atmospheres, and manufacturing methods. Among the commonly used components are alkali metals, which are vaporized by heating during operation. One advantage of alkali metals is that they generate a sufficient vapor density even at relatively low temperatures of $-50\text{ }^{\circ}\text{C}$ to $150\text{ }^{\circ}\text{C}$. Different alkali metals, such as rubidium [Limes et al. 2018; Limes et al. 2019; Lucivero et al. 2022; Gerginov et al. 2020; Kennedy et al. 2016; Almat et al. 2020], cesium [Abdullah et al. 2015; Maurice et al. 2017; Hafiz et al. 2015; Woetzel 2017], potassium [Chen et al. 2007], or mixtures of alkali metals like rubidium-potassium [Chen et al. 2007; Huang et al. 2021] have been employed. In addition to alkali metals, buffer gases like nitrogen [Lucivero et al. 2022; Gerginov et al. 2020; Almat et al. 2020] or argon [Almat et al. 2020], or functional gases such as noble gases like xenon-129 [Kennedy et al. 2016; Limes et al. 2018; Limes et al. 2019], neon [Abdullah et al. 2015], or helium-3 [Huang et al. 2021; Limes et al. 2018; Masuda et al. 2005] may be used to reduce excited atom relaxation processes or increase magnetic activity. The pressure within the vapor cell can also vary, ranging from high/fine vacuum [Woetzel 2017; Lucivero et al. 2022] to rough vacuum/atmospheric [Gerginov et al. 2020] or overpressure [Limes et al. 2018; Limes et al. 2019].

Earlier, gas cells were produced through glass blowing or prefabricated glass cells with a pinch-off system. However, with the advent of miniaturization, vapor cells are now primarily manufactured using microtechnology. This approach enables the production of cells with adjustable geometry in various sizes and a significantly reduced volume in the mm³ range. Furthermore, the production method is attractive for industrial applications due to the prospect of high quantities and relatively low production costs. The vapor cells are created by bonding structured silicon and glass substrates with a glass lid in a controlled atmosphere, which hermetically encapsulated the previously dosed alkali metal. There are different bonding methods which already demonstrate the ability to produce such hermetic packaging for this application. These include anodic bonding, eutectic bonding or thermocompression bonding. The common method in the state of the art is anodic bonding, which seals glass to silicon or metal without introducing an intermediate layer though electric fields and temperatures.

On the industrial side, there are a few commercial partners known to offer atomic vapor cells for use in atomic clocks and other quantum sensor technologies. Microchip Technology Incorporated was one of the first companies to release a commercial chip-scale atomic clock with a frequency stability of 10^{-11} at an averaging time of 1,000 seconds, using the optical resonance D1 line of atomic cesium [Microchip 2024]. Similarly, Stanford Research Systems offers a rubidium oscillator with similar stability for precision frequency measurements [Thinkers 2023]. Vapor Cell Technologies and Twinleaf are two additional companies that offer integrated atomic cells. Vapor Cell Technologies, a spin-off from NIST, offers customized vapor cells as the “heart of quantum standards” for length measurement, optical frequency measurement, and high-resolution optically pumped magnetometers (OPMs) [VCT 2021]. OPMs can be used in magnetoencephalography (MEG) to analyze brain activity and have potential applications in the treatment of epilepsy and as a biomarker for Alzheimer’s dementia. Other potential fields of application for OPMs include geology and safety. The measurement resolution of atomic vapor cells is sufficient to detect magnetic fields of landmines or raw-material depos-

its [Woetzel 2017]. Twinleaf, a Princeton spin-off company, offers an optically pumped magnetometer based on Rb vapor with a magnetic sensitivity of $< 0.2 \text{ pT/Hz}^{1/2}$ [Twinleaf 2023]. QuSpin Incorporated also provides such systems [QuSpin 2024]. In addition, CSEM, a semi-commercial Swiss research and development center, is active in the field of atomic vapor cells for quantum technology.

Atomic vapor cells are increasingly important for the industry due to their potential in improving time and frequency standards for communication and navigation. Current research focuses on enhancing sensor performance to the limit of possibility. The European MacQsimal Project, coordinated by CSEM, should be mentioned here. Involving 14 partners and based on alkali vapor cells, it aims to develop a chip-scale atomic clock, miniature magnetometer for brain imaging, compact shoebox-size NMR gyroscope, novel GHz spectrum analyzer demonstrator, and novel THz imaging technique with a budget of 10.2 million euros [MacQsimal, 2024]. In addition to improving performance, another research focus is the transition to an industrial product. While commercially available systems already exist, they are still expensive compared to conventional sensor technology and cannot be produced in large quantities. Therefore, various challenges related to low-cost production of high-quantitative systems need to be addressed to fully exploit the potential of atomic clocks or, in general, atomic vapor cells for quantum sensor technology.

5.1.4 New Materials for Joining

Assembly and connection technology (ACT) is primarily used for the connection of micro-technical components with a higher contacting level. There are various extreme environmental conditions (harsh environments) with different requirements, such as wear, high and low temperature, chemicals, radiation, forces and acceleration, high and low pressure (vacuum), flow, EMC (high frequency), humidity, vibration, dust. Here, the focus is on the presentation of a selection of ACT processes suitable for the high temperature range starting at 125 °C [Wilde 2022].

High-Temperature Assembly and Connection Technology

Various methods are employed for chip bonding. Eutectic bonding is conducted thermocompressively and is characterized by the fact that the melting temperature of the alloy of the bonding partners, and thus the bonding process temperature, is significantly lower compared to the pure elements.

The distinction from Transient Liquid Phase (TLP) Bonding lies in the fact that one bonding partner is melted and subsequently, through diffusion, forms an alloy with the other bonding partner thermocompressively. The re-melting temperature here is above the utilized process temperature.

For the connection of (metal ion-containing) glasses and silicon, usually anodic bonding is carried out, requiring high pressure, temperature, and electrical voltage.

Another approach involves reactive multi-layer foils. They consist of an alternating nanolayer stack of two metals, such as Al and Ni, and are placed between the components to be bonded. Activation can be electrically induced, causing the foil to exothermically react to form an alloy, generating short-term (within milliseconds) temperatures above 1000 °C, enabling the connection of components without subjecting them to temperature stress.

In high-performance electronics, silver sintering is particularly utilized for mechanical and electrical chip contacting. The thermocompressive process (200 °C to 300 °C) leads to degassing, compression, and sintering of the applied silver paste.

For mechanical bonding while ensuring electrical isolation, ceramic adhesives are employed. They dry by solvent evaporation and are characterized by extremely high maximum operation temperature ranges.

Wire bonding is the most commonly used method for chip level contacting. The methods include ultrasonic, thermocompression and thermosonic wire bonding. The primary parameters for creating a permanent connection are force, ultrasonic power, temperature, and dura-

tion. The quality of the bond results from the production yield and the bond strength achieved and is largely dependent on the material pairing between the bond wire and the bond pad (compare Table A1). The bond strength is determined, for example, by shear or tensile tests. The challenges are a loss of adhesion and an increase in contact resistance.

Soldering is used to create material-to-material connections between two materials. In contrast to welding, the liquidus temperature of the solder is exceeded during fusion soldering, but not that of the two materials to be joined. Soft soldering (liquidus temperature $TL < 450\text{ °C}$) is most commonly used in electronic contacting, rarely hard soldering ($450\text{ °C} < TL < 900\text{ °C}$) and high-temperature soldering ($TL > 900\text{ °C}$). Common processes are reflow soldering, wave soldering or laser beam soldering. Glass solders are used in packing and are used to bond glasses or glass with metal or ceramics. The process belongs to the category of adhesive bonding.

A summary of these processes is given in the Table A1 (Annex) including maximum temperature ranges.

Application of High-Temperature Connection Technology

Often, a combination of the mentioned methods is employed, such as in the case of strain measurement utilizing directly deposited thin-film sensors [Kayser et al. 1993; Lei et al. 1997; Ottermann et al. 2023; Klaas et al. 2020]. Exemplifying this, a schematic representation of the electrical contacting setup, as utilized by Ottermann et al. [Ottermann et al. 2023], is depicted in Figure 5.19. Initially, a ceramic board was applied onto a steel substrate using a reactive multi-layer foil. Subsequently, contact pads were deposited through cathode sputtering, establishing a connection to the thin-film sensors via gold wire bonds. Additionally, nickel wires were affixed through spot welding to facilitate the transmission of electrical signals from the strain sensors. Consequently, successful strain measurements were achieved at 515 °C.

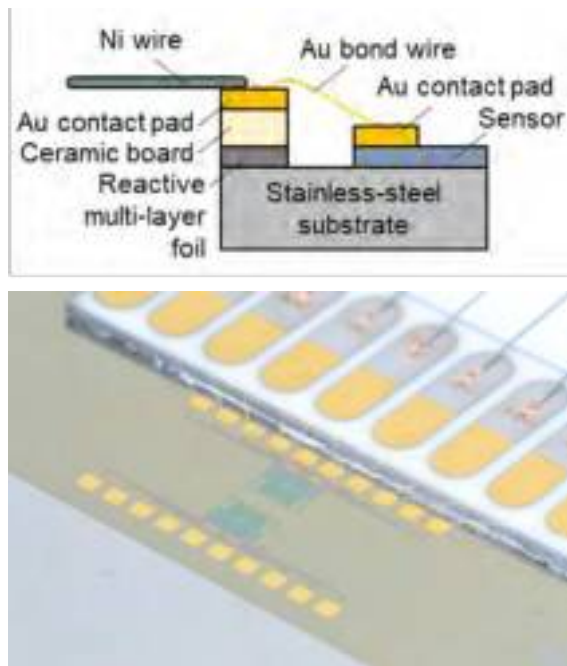


Figure 5.19: High-temperature contacting with reactive multi-layer foil, ceramic board, spot-welded Ni wire and Au wire bonding for thin-film strain gauges (top: scheme, bottom: photo) (Source: [Otermann et al. 2023])

Nanofoils

For the system integration or packaging of microelectronics, bonding processes such as anodic bonding, thermal compression bonding and transient liquid phase bonding are used at temperatures of at least 200 °C, which can lead to a high heat input into the temperature-sensitive components. A reduction offers further potential for the three-dimensional integration of components that have different requirements depending on their optical, mechanical or electrical function [Braeuer 2012]. One solution is offered by reactive bonding, which is achieved using reactive material systems (RMS) in the form of foils or thin-film-based layer systems (integrated Reactive Material System – iRMS) and results in two components being connected within milliseconds without an external heat source at room temperature [Vogel et al. 2021a]. The films were first commercialized in 2001 by the Indium Corporation under the brand name Nanofilm® [Rogachev et al. 2016]. The foils consist of a multilayer system of at least two components and are produced in various combinations such as Ti/Al, CuO/Al, Pt/Al, Pd/Al, Ni/Al with thicknesses of up to 300 µm. While foil-based RMS have limitations in structuring and pose challenges in handling at wafer

level, iRMS show greater potential for integration into the process chains of microsystems.

The reaction is activated by a low energy pulse, for example from a 5-9 V battery or of an optical or thermal origin. It runs independently and exothermically along the entire layer system [Vogel et al. 2021]. The process is based on the reduction of chemical energy within the multi-layer system, which is promoted by the thin layer thicknesses and the short diffusion path of the materials. Speeds of up to 80 m/s and temperature peaks of over 1200 °C are achieved within the layers, which only occur locally within the film due to the brief reaction time of 40 ms to 80 ms, making an external heat source unnecessary [Wang et al. 2003]. The high localized heat leads to the bonding of the multilayer system with the solderable layers on the substrates. These can be realized from gold or tin, for example. The reaction is therefore flux-free, without outgassing, and can also be carried out under vacuum. Notably, foils are also used to bond stainless steel, aluminum, titanium and metallic glasses [Qiu et al. 2009].

Nanoklett

Another method for joining two substrates at room temperature is bonding using nanowires, which is developed at the Technical University of Dresden and by the company NanoWiring GmbH [Strahringer et al. 2021; Roustaei et al. 2016]. The principle behind the process is comparable to a miniaturized Velcro fastener, in which the nanowires tilt within a flat nanogrid during joining and the individual wires form a positive connection as in cold welding (Figure 5.20). The process is therefore a competitor to traditional bonding processes, but also to gluing and soldering. For nanowires to grow on surfaces, they must be conductive or first be functionalized with a conductive layer. Polymers, glass, ceramics, and semiconductors (and others) can be used as substrates, but the application is also suitable for wafer-to-wafer and chip-to-wafer bonding [Roustaei et al. 2020]. After the metallization, the nanowires can be grown on the desired surfaces, which are usually structured using photolithography. For this purpose, a sponge with the desired electrolyte is pressed onto the area and the wires grow galvanically in the pores of the sponge. Nan-

owires can be produced from copper, gold, nickel, silver and others.

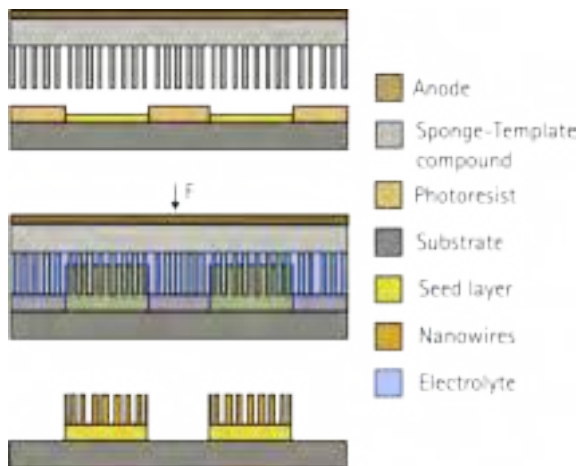


Figure 5.20: Growing Nanowires [Roustaie et al. 2020]

There are different variants of the joining process: KlettWelding, KlettWelding+, KlettSintering, KlettSintering+, KlettGlueing and KlettGlueing+. These differ fundamentally in their temperature, whether the nanowires are only applied to one joining partner (KlettSintering) or via a film between the joining partners and whether a supporting adhesive is used (KlettGlueing). For a bond between copper nanowires, contact pressures of approximately 20 MPa are required with a process time of 100 ms. This achieves shear strengths of 12 MPa and a temperature resistance of $-50\text{ }^{\circ}\text{C}$ to $500\text{ }^{\circ}\text{C}$ [Roustaie et al. 2021; Roustaie et al. 2020]. KlettWelding is shown in Figure 5.21.

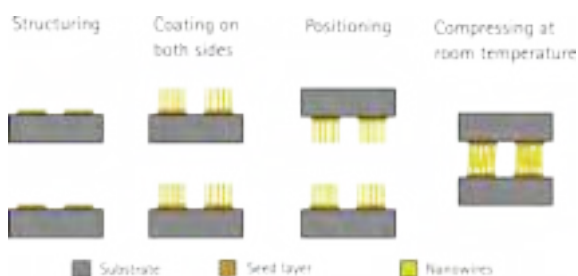


Bild 1. Figure 5.21. Bond process with NanoKlett [adapted from <https://nanowired.de/klett welding>]

5.2 Measuring in the Extremes

(Fischer, M; Hoheisel, D.; Müller, J.; Steller, A.; Bramlage, S., Hild, R; Droese, N.)

Due to exceptionally demanding requirements, the aerospace industry is a driver for innovation

and new technologies for sensors. This comprises equipment testing, sensorics for monitoring and data acquisition (e.g., imagery). Equipment and thus sensorics need to be functional in extreme environments: wide temperature ranges from cryogenic to highest temperatures, large pressure fluctuations, shocks, and different vibration levels.

Space applications require the handling of cryogenic fluids, such as liquid hydrogen, methane or oxygen which are used for propulsion. In this applications, temperature ranges down to $-196\text{ }^{\circ}\text{C}$. In this region, piezoelectric crystals for accelerometers need to exhibit a low temperature coefficient of sensitivity and high sensitivity in order to reduce mass. Less element mass leads to higher resonance frequencies and better frequency response and allows smaller overall housing designs. Also, sensor electronics need to withstand the low temperature levels, which is usually ensured by adequate coatings.



Figure 5.22. Sensor providing reliable measurement data under extreme conditions (red glowing metal casing). Temperatures of $700\text{ }^{\circ}\text{C}$ for long-lasting pressure and acceleration measurements are highly demanding requirements for a suitable sensor design. In some cases, even higher temperatures for short-term measurements are possible. (Source © Kistler Group 2024)

In rocket engine monitoring, pressure pulsation is key to ensure stable combustion and in turn safe operation. For this, measurements are taken directly in the combustors. Here, the sensor element needs to withstand extreme condi-

tions and needs provide reliable measurements at high temperatures of 700 °C or – for short time periods – up to 1000 °C. (Figure 5.22) This is only possible when the sensor housing is made of Ni-based high-temperature alloys and the (usually) piezoelectric sensing element is made of crystal material developed for very high temperatures. Here, it is essential that the crystal material does not exhibit a pyroelectric or popcorn effect, which is present in many sensor elements based on ceramic materials. The popcorn effect is caused by the accumulation of charge on a sensor element's surface due to pyroelectric effect and results in noise spikes in the electric signal. Also, cabling needs to be high-temperature safe; usually, a mineral-insulated hardline cable is used. Similar requirements are present in stationary gas turbines and jet engines, where dynamic pressure sensors are installed in the combustors [Ćosić et al. 2022; Li et al. 2006; Kim et al. 2021]. Here, for example, the sensors help in the understanding of thermoacoustics instabilities, i.e., the coupling of flame (thermal) and pressure fluctuation (acoustics) and in turn help to increase combustion stability and efficiency and the reduction of unwanted vibrations and excitation of downstream components.

In detonation engines, the combustion takes place in a rotating shock wave regime in an annular channel. This fairly new propulsion system is a promising technology for space applications (Figure 5.23) or even as a replacement of gas turbines as it exhibits the potential of increasing thermal efficiency while profiting from a substantial simplification of engine design [Armbruster et al. 2024; Kindracki et al. 2011].

Satellite Jitter & Micro-Vibrations

Recent years have seen a dramatic increase in the need to measure the earth's surface and atmosphere with ever greater precision. The quality of such images would have been unimaginable only a few years ago. Critical steps in achieving this progress include the reduction of micro-vibrations on board of satellites. Satellite jitter, or blurring of the images originating from micro-vibrations, is a severe deviation source that affects the geometric accuracy of high-resolution imagery. Every satellite requires numerous drives, position controls, reaction wheels,

actuators and cryocoolers, and so on. These devices consist of mechanical components that cause vibrations when they operate. Micro-vibrations consist of extremely small accelerations of very low intensity. Measuring them is a challenging task (Figure 5.24).

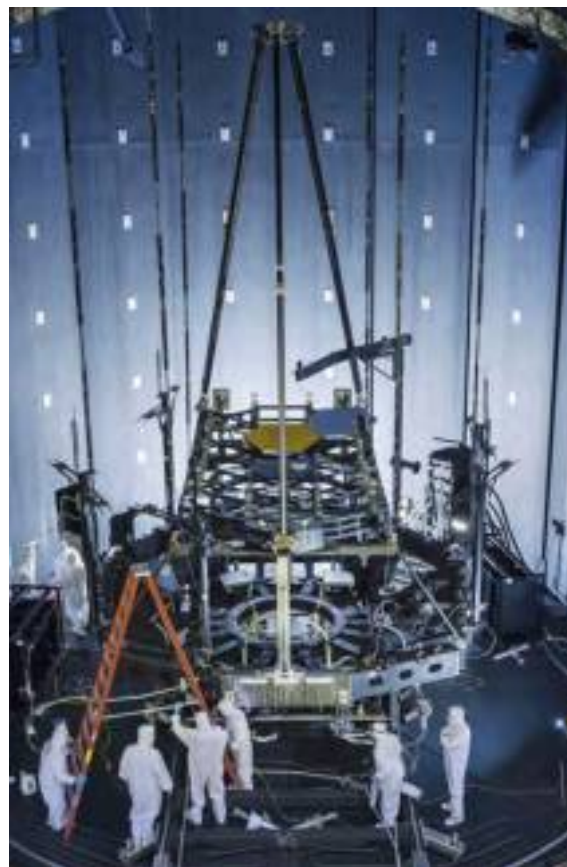


Figure 5.23. Inside NASA's giant thermal vacuum chamber, called Chamber A, at NASA's Johnson Space Center in Houston, the James Webb Space Telescope's Pathfinder backplane test model is being prepared for its cryogenic test. (Source: [NASA])

For example, reaction wheels are used for attitude control of satellites without the need to use thrusters and propellant, which are in limited supply. The operation of a reaction wheel uses an electrical motor to rotate a flywheel at various rotational speeds, causing the satellite to counterrotate proportionately due to the conservation of angular momentum. As the flywheels rotate, jitter couples onto the structure and can affect imaging precision [Cavalloni et al. 2020].

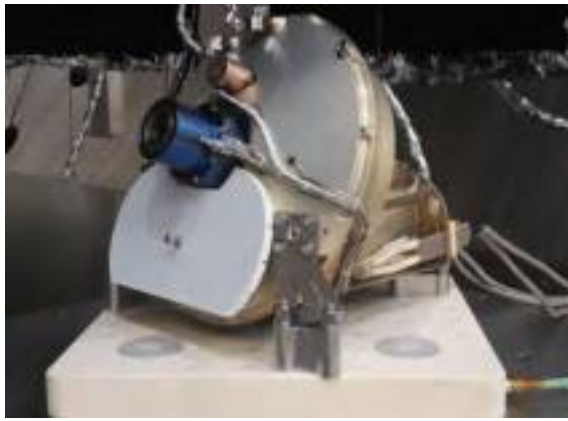


Figure 5.24: Micro-vibration testing on an optical payload with a Force Plate (Source © 2024 Kistler Group)

Pressure Sensing in H₂ industry

But not only in space industry, extreme conditions, and thus challenging requirements to sensorics are present. Pressure sensors play a fundamental role in monitoring and control in hydrogen production, distribution and storage and its related infrastructure. In production and compression pressure ranges extend between 25 bar and 1,000 bar, where temperatures are up to 200 °C. In the course of the transformation towards hydrogen industry, sensors also need to be adapted to be operational in H₂.

In hydrogen environment, technical challenges arise due to the embrittlement of steel parts and the permeation (diffusion) of hydrogen into the sensor, making state-of-the-art sensor designs unsuited for long-term pressure monitoring.

First of all, oil-filled pressure sensors are by design unsuited for application in H₂ environment, as H₂ can potentially diffuse through the membrane into the oil-filled cavity (Figure 5.25), leading an expansion of cavity volume and in turn faulty measurement signals or membrane fracture. Thus, “dry” packaging technologies need to be followed. However, care also has to be taken here, as, e.g., standard Ni-Cr metal thin-film strain gauges bonded on a thin steel membrane are very sensitive to interaction with H₂ permeating into the sensor [Matsuo 2014]. The technology, shown in Figure 5.25, is tested and proven to be a robust solution for high temperatures. Here, the pressure is transferred via a steel diaphragm as a force acting on a silicon-on-insulator (SOI) bulk sensing chip [Gramich et al. 2023].

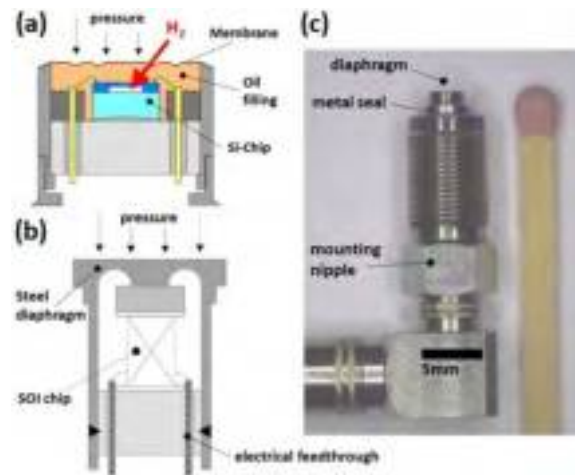


Bild 2. Figure 5.25: a) Typical oil-filled piezoresistive sensor: H₂ can diffuse through the thin membrane into the oil filling and silicon cavity, causing measurement errors; b) Principle of “dry” block-type piezoresistive sensor technology: pressure is transferred to stress in a Silicon-on-insulator (SOI) block-type chip, measured via piezoresistors on both sides of the chip; c) Picture of the sensor prototypes, with a 3 mm diameter diaphragm [Gramich et al. 2023]. (Source © 2024 Kistler Group)

3D Printing for Vacuum Chambers

The additive manufacturing of ceramics, metals and polymers for vacuum applications is currently under investigation in research. It has been demonstrated that it is already possible to produce hermetically sealed chambers or components with low outgassing using various materials (Figure 5.26) [Povilus et al. 2014; Wolf et al. 2019; Vovrosh et al. 2018; Eickenscheidt et al. 2021]. Additive manufacturing for vacuum components enables significant savings in size, weight, and power, which makes the systems even more transportable. The use of polymers offers a range of applications in a rough vacuum, but is less suited for lower pressure ranges due to the solvents dissolved in the components from the manufacturing processes. However, the printing of housings in the packaging technology of MEMS systems is intriguing [Lifton et al. 2014]. Plastic processes with wall thicknesses below 100 µm can be used for encapsulating individual sensor structures or finished components, where a wafer could serve as the starting layer.



Figure 5.26: Additively manufactured vacuum chamber for cold-atom experiments with a gyroid lattice for weight reduction (Source: IMPT)

Vacuum encapsulation with conventional manufactured ceramics is already widespread, such as the use of Low Temperature Cofired Ceramics (LTCC), which can be sealed in a joining process under vacuum and have a low outgassing rate [Keusseyan et al. 2002; Kopola et al. 2001; Tanaka et al. 2015]. Vacuum chambers made of Al_2O_3 are also used and initial investigations show that Al_2O_3 can be produced vacuum-tight with a low outgassing rate of no more than $3.3 \cdot 10^{-10}$ mbar/s using the FDM process, a debinding step and a final sintering process [Burrow et al. 2021; Eickenscheidt et al. 2021]. This raises the prospect of using fully 3D-printed ceramic vacuum chambers.

The Laser Powder Bed Fusion process can be used to print a steadily increasing number of metals, such as stainless steels, aluminum, nickel alloys, copper, and various types of titanium. Metal components can be produced with a high density ($> 99.9\%$) and are already being used in ultra-high vacuum applications, including in particle accelerators or miniaturized vacuum tubes [Grazzi et al. 2021; Deng et al. 2018]. Fully printed chambers have already been produced from stainless steel and aluminum, some of which have integrated channels that enable heating and subsequent cooling [Wolf et al. 2019]. The aluminum chamber achieved a vacuum pressure range of 10^{-10} mbar and enables the use of a magneto-optical trap based on ultra-cold atoms [Cooper 2021]. The outgassing rate was a maximum of $3.3 \cdot 10^{-13}$ mbar l/(s mm²), which is presumably influenced by the magnesium-rich oxide layer that forms on the surface during the manufacturing process using LPBF. In conclusion, it can be said

that there is still a lot of potential in the use of additive manufacturing in vacuum technology and the first milestones have been set.

Fiber-Optic Acoustic Measurement System

For characterization of downhole geothermal reservoirs, a cost-effective, high-temperature (i.e., higher than 170 °C) measurement technology was developed. The technology is suitable for fracture system characterization while drilling, in terms of fracture distribution, direction, length, and thickness. This characterization of downhole geothermal reservoirs is important for an optimized well placement and efficient usage of geothermal energy. With the measurements result, it is possible to derive the fracture's position and at the same time draw conclusions about the rock type and porosity. These are important parameters for the construction of a geothermal borehole and an enabler for optimized automatic well placement.

Current receiver sections are built with arrays of piezoceramic hydrophones. A new approach is to replace the piezoceramic receivers with fiber-optic hydrophones using fiber Bragg gratings (FBG). Fiber Bragg gratings are based on intentionally generated periodically defects in the fiber core (Figure 5.27).

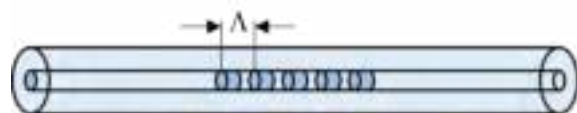


Figure 5.27: Fiber Bragg grating with periodic distance Λ , as per [Kruspe et al. 2016] (Source: Baker Hughes)

These defects are locally changing the refractive index of the core material. By this, a certain portion of the input light is reflected (Figure 5.28). The wavelength of the reflected light is proportional to the periodic distance. By stretching or compressing the FBGs, its periodic pattern is changed and as result of this, the reflected light wavelength is shifted. This effect is used to transduce the acoustic pressure wave into optical wavelength shifts of the FBG reflected light. By coupling spectral broadband light into the fiber and using FBGs with individual wavelength for each hydrophone, multiple hydrophones can be read out with only one optical fiber.

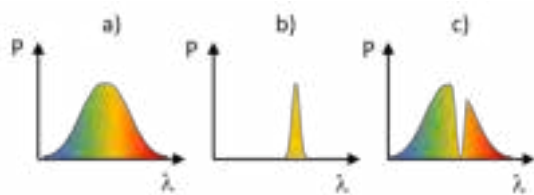


Figure 5.28: Fiber Bragg grating principal; a) coupled broadband light; b) reflected light by the FBG; c) further transmitted light (Source: Baker Hughes)

The developed fiber-optic acoustic measurement system consists of a superluminescent light emitting diode (SLED) as light source, a fiber-optic coupler, a fiber-optic feedthrough (FOFT), a hydrophone array with sensing FBGs, and a fiber-optic interrogator, using an arrayed waveguide grating (AWG), photodiodes (PD) and necessary readout electronics. Figure 5.29 shows a schematic overview of the optical system.

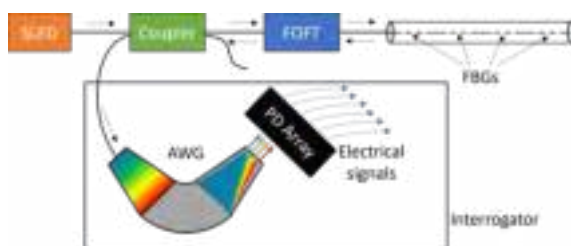


Figure 5.29: Schematic overview of the fiber-optic measurement system, as per [Kruspe, 2016] (Source: Baker Hughes)

The SLED is emitting broadband light which is coupled via a fiber-optic coupler into the hydrophone array. The hydrophone array is located at the outer diameter of the drill string and faces the extreme environmental conditions of high-pressure and high temperature. All other components are stored inside the tool and shielded against the pressure. Because of that, there is a special FOFT installed between the coupler and the hydrophone array withstanding the pressure difference. Inside the hydrophone array, each hydrophone FBG is reflecting a different wavelength of the incoming light. The reflected light is transmitted backward through the FOFT and through the fiber-optic coupler to the fiber-optic interrogator, including the AWG. The AWG splits the incoming light in spectral separated channels. The light signals are converted into electrical signals by a photodiode array (Figure 5.42). The signals are finally processed in the evaluation electronics and output via a digital interface.

Fiber-Optic Hydrophone

The hydrophone array is assembled of individual hydrophones in a row featuring one common optical single-mode-fiber. The array is oil-filled and pressure compensated. A metal membrane separates the oil filling from the drilling fluid in the borehole allowing at the same time acoustic signals to enter the hydrophone array. Each hydrophone converts the acoustic pressure waves into optical signals. For that conversion of pressure amplitudes into spectral wavelength shifts, a transducer element was developed (see Figure 5.30). To avoid multi-material composition with signal disturbances coming from different thermal expansion coefficients, the transducer element with a beam-like shape is formed by etching of a glass chip. The gap between the transducer element and the glass chip provides a built-in high pass filter against drilling noise. The fiber with the FBG is glued to the transducer element as shown in Figure 5.30. For spectral separation of the hydrophone positions, the reflecting profile of each FBG has a slightly different central wavelength. When an incoming acoustic wave is moving the transducer element, the FBG is hence stretched or compressed. This is modulating the central wavelength of the FBG and the acoustic pressure signal is converted into an optical signal.

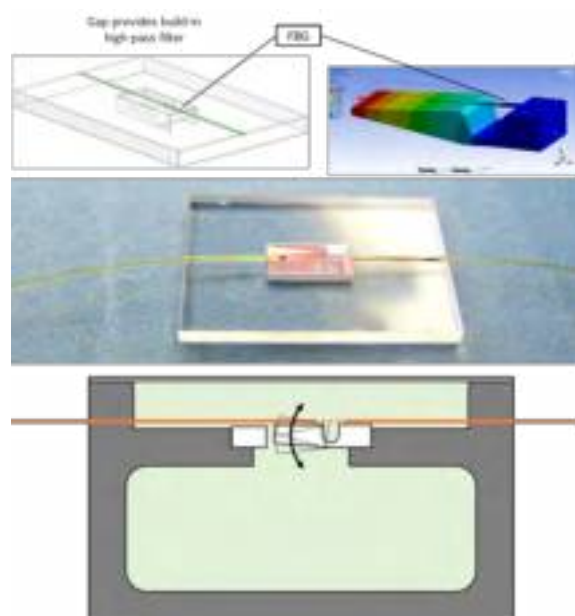


Figure 5.30: Acoustic pressure transducer element; (top left) sketch; (top right) Simulation of deformation; (middle) Photograph, for illustration with a red laser; (bottom) Schematic cross-section of a fiber-optic hydrophone [Jung et al. 2019]

By using the fiber-optic technology, it was possible to design very slim hydrophone arrays. This enables a more cost-effective design and manufacturing of the whole tool, e.g., by reduced manufacturing time and material costs. Furthermore, this fiber-optic hydrophone array can be used in tools with very different outer diameters without the need for any design modifications (e.g., changed dimensions). Another advantage of the fiber-optic sensing approach is the resistance against electromagnetic interference during sensing as well as during information transmission. With that, there is no need for a preamplifier closely to the receivers. The sensed signals are converted to spectral information, transmitted within only one fiber compared to a bundle of cables used for piezoceramic hydrophones. This further reduces the number of pressure feedthroughs needed to a minimum and results in increased reliability. The measured optical signals are centrally converted into electrical signals and digitalized within one interrogator. This minimizes the introduction of electronic noise and improves the signal-to-noise ratio.

Fiber-Optic Interrogator

The fiber-optic interrogator is designed to convert the optical signals coming from the hydrophones to electrical signals. Furthermore, the interrogator electronics is performing digitization and initial data processing. Inside of the interrogator, an AWG is used to spectrally differentiate the incoming signals. Each optical signal is differentiated by its wavelength. The optical intensity signals are converted to electrical signals using photodiodes in combination with transimpedance amplifiers. The converted electrical signals are digitized with analog-to-digital converters (ADCs) and processed with a digital processor (see Figure 5.31). All signals are synchronically digitized and processed. The processed data is transferred via digital high-speed data bus for further downhole processing.

To achieve a higher grade of integration and an extended lifetime, a multi-chip module (MCM) design approach was chosen. Figure 5.32 shows the integration step from first prototype in classic printed circuit board assembly (PCBA) technology to the final design in MCM technology.

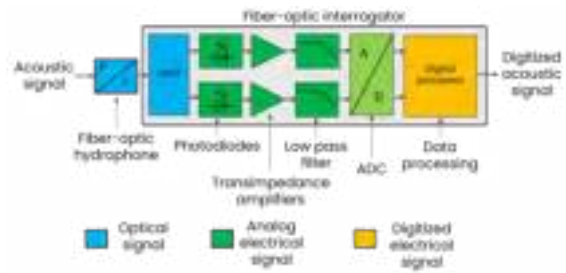


Figure 5.31: Schematic overview about signal conversion and processing (Source: Baker Hughes)

In addition to the reduced size, the MCM technology features increased reliability and lifetime at downhole conditions including strong vibrations with amplitudes higher than 20 g rms and shocks with several hundred g. The electronics components are bare dies glued on a ceramic substrate to achieve low thermal expansion mismatch. The used wire bonds are matched to the bare-die metallization. For increased reliability, the components are hermetically encapsulated within an inert gas atmosphere.

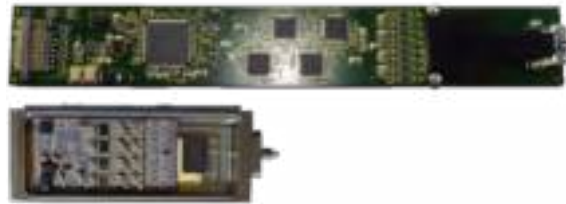


Figure 5.32: Fiber-optic interrogator comparison; (top) PCBA technology; (bottom) MCM technology (Source: Baker Hughes)

High-Temperature Electronics Packaging

To understand why a specific high-temperature packaging technology is required, the knowledge about the limits of conventional packaging is essential: What failure modes are observed when standard packaging is exposed to high temperatures?

There are two major areas of concern: One is related to mechanical properties and the linear coefficient of thermal expansion (CTE). The other one is related to material selection and chemical interaction. At higher temperatures, chemical reactions can be triggered that cannot take place at lower temperatures due to their required activation energy.

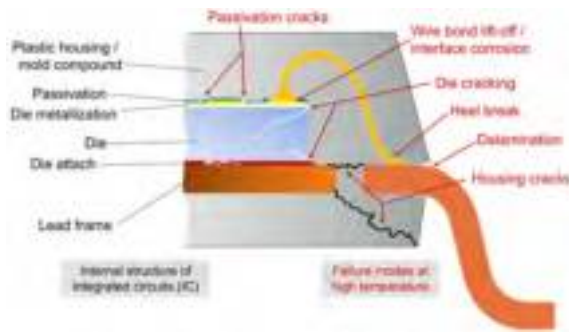


Figure 5.33: Internal structure of a plastic molded integrated circuit and the typical failure modes for high-temperature operation

CTE Mismatch and Thermomechanical Stress

A typical integrated circuit (IC) in standard packaging contains a semiconductor die mounted on a die attach pad, uses wire bond connections from the die bond pads to the lead frame and is protected by a mold compound covering the die and wire bonds. The CTEs of this assembly range from 2.6 ppm/K for silicon as the predominant semiconductor material over 17 ppm/K for copper as typical lead frame base material to the epoxy-based mold compound which can have a strong variation depending on its formulation, but values between 10 ppm/K and 30 ppm/K are typical. Glass filler particles are used to engineer the mold compound's CTE. Most critical for high-temperature applications is that the partially crystalline polymers have a significantly higher CTE above the glass transition temperature (T_g) which is approximately three times higher. T_g of standard mold compounds is in the range of 100 °C to 125 °C. Under temperature cycles, these different CTEs cause high mechanical stress which can result in delamination, cracking or fracturing (Figure 5.33).

Thermomechanical stress at the wire bond heel can lead to a fractured wire bond on the lead frame side. The typical electrical behavior is an electrical interruption ("open") under high-temperature conditions while at room temperature (RT), the device is fully functional because the mold compound keeps the fractured wire in place. For failures like this, the component-internal CTE mismatches as well as the board level interaction are important, and pin geometry and component stand-off play a role as well.

Chemical Interaction and Diffusion

Especially the polymer materials like the mold compounds, but also the printed circuit board material and conformal coatings are a highly complex material mix that can not only contain fillers and coupling agents, but numerous other additives like curing agents, accelerators, flame retardants, ion-getter additives, and coloring agents.

Multiple options for chemical interactions arise from this material mix.

But even at simple systems like the interface of two solids, high temperature can dramatically change the behavior. Typical diffusion processes can be described by the Arrhenius equation, which means they show an exponential dependency on temperature. See, for example, the interdiffusion of gold and aluminum at a wire-bond interface on the die bond pad. Au/Al shows several intermetallic phases (IMP) that differ in volume. By these, voids at the interface are created until the Au ball has lost the contact (so-called Kirkendall voiding). This is a typical end-of-life failure, where the lifetime at high temperature is drastically reduced. Together with chlorine residues in an epoxy mold compound and humidity, a highly accelerated corrosion of this Au/Al IMP occurs (so called Horsting voids).

Approach for Reliable HT-Electronics

Material selection is crucial: materials in contact must be selected by their diffusion properties, and diffusion barriers can be essential. The same applies for the involved CTEs, respectively the CTE mismatch between materials. An approach to completely eliminate mold compounds and the second-level interconnects is to build multi-chip modules (MCM) using bare dies and ceramic substrates in hermetic housings.

High Temperature Substrate Materials

Substrate materials for high-temperature applications need to consider both the temperature stability of the material itself and the interaction with other parts of the electronic assembly. Often, additional factors such as thermal conductivity or high frequency properties need to be taken into account.

Circuit board materials can be divided into two major material groups: organic and inorganic circuit boards, the first of which is most widely used in standard electronics and generally known as printed circuit boards (PCB).

In this technology, copper-clad organic laminates are structured through etching and plating processes to receive the final electronic design. Most of these materials are epoxy-based and not suitable for operating temperatures above 125 °C. However, there are polyimide or hydrocarbon-based PCB materials that tolerate temperatures up to 200 °C. Since these materials can be processed in the same way as standard PCB materials, they are very cost-efficient and readily available.

But even if generally suitable for high-temperature applications, those materials add a wide range of organic components to the system, which might reduce the overall lifetime of the package e.g., by outgassing, especially if used in hermetic housings.

The second group, inorganic materials, include everything from ceramic and glass to silicon to ceramic coated metals, with aluminum oxide (Al_2O_3) ceramic as the most commonly used substrate material.

Opposed to PCB technology, conductive tracks are added to ceramic substrates using additive processes, mostly screen printing, plating or sputtering. Screen-printed thick film materials are generally fired at temperatures above 800 °C, which also ensures that no organic contaminations are present in the final product.

The wide material range of ceramics allows solutions tailored to various thermal and electrical needs.

Due to the high firing temperatures (1,500 °C) required for HTCC (High Temperature Cofired Ceramic), only a very limited selection of materials is available as conductors for the inner layers, namely tungsten and molybdenum, with tungsten most commonly used. An overview of ceramic substrate materials and some specific advantages is shown in Figure 5.34.

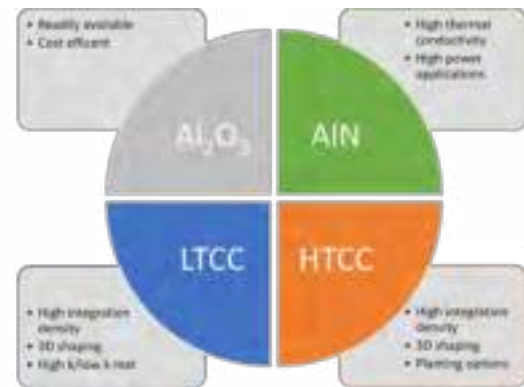


Figure 5.34: Overview of properties of different ceramic substrate materials. (Source: Baker Hughes)

Compared to copper used at organic substrates, the specific conductivity of tungsten is significantly lower, which must be considered in the design /geometry of the conductor layers (three times higher resistivity for tungsten).

Additionally, tungsten is not suited for wire bonding and will oxidize at air without building a diffusion-tight oxide layer, which means unlimited oxidation of the volume. Therefore, the tungsten has to be protected.

Analog to the coating of copper at the organic substrates, the combination of a nickel diffusion barrier and a gold top layer for oxidation protection is widely used.

But the choice of coating system also offers the opportunity to optimize the material system for the wire bonding material or make it suitable for a broad range of materials. Thin immersion palladium and immersion gold over nickel (ENIPIG), for example, result in highly reliable wire-bond connections for both gold and aluminum wire on the same surface.

In contrast to HTCC, LTCC substrates (Low Temperature Cofired Ceramic) contain a certain amount of glass, which reduces the firing temperature to 800 °C. Benefits of this modification are the possibility to match the CTE of the substrate to the CTE of silicon and the use of gold and silver based thick-film pastes for all substrate metallization layers. On the downside, the glass material reduces the thermal conductivity and the metallization is not suitable for Aluminum wire bonding: on gold thick-film aluminum, wire bonding will result in void-induced wire bond lift-offs (= Kirkendall effect); alumi-

num wires on AgPd and AgPt thick-film are extremely sensitive to humidity.

Component Attach Technology

Attaching components to a substrate is one of the important aspects of packaging technologies for electronic applications. The primary function of attach materials is to provide reliable mechanical, thermal and, if required, electrical interconnect between component and substrate to prevent detach or fracture when exposed to high temperature, changes in temperature, high power and/or mechanical loads. The choice of attach technology depends on several aspects, for example component type, substrate metallization, design complexity, and reliability requirements. Figure 5.35 illustrates some of these factors in more detail.

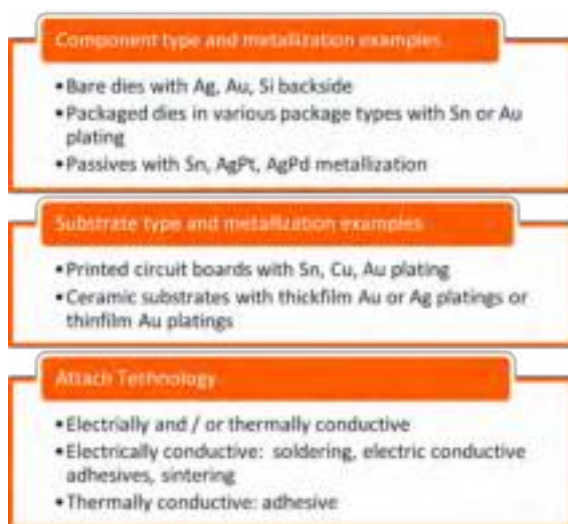


Figure 5.35: Examples of influencing factors for the choice of a component attach technology (Source: Baker Hughes)

A very common attach technology is the solder connection. As a rule of thumb, a solder material can function reliably up to a homologous temperature of 80 % of its melting temperature before creep leads to quick degradation. For the most commonly used lead-free near eutectic solder alloys like SnAgCu and SnAg, this means a maximum allowable temperature of approximately 125 °C for long lifetime applications. Higher temperatures will reduce the lifetime. Adding additional elements like Bi, In and Sb can increase thermomechanical fatigue life, altering the microstructure of the solder connections and leading to solid solution and precipitation strengthening [Choudhury et al. 2022].

For higher temperature requirements, eutectic AuSn and Pb90Sn10 with melting temperatures in the range of 280 °C can be used. Though high-melting PbSn solder is still exempt from the Restriction of Hazardous Substances (RoHS), lead-free, more environmentally friendly materials should be preferred. AuSn on the other hand needs very high soldering temperatures which might pose a risk for components to be attached. Additionally, it shows a very high stiffness which can lead to reliability concerns [Sousa et al. 2014]. It is not compatible with a wide variety of component metallization systems, making it useful for certain die attach applications but limiting its application for complex electronics where also passives need to be attached.

Electrically conductive adhesives (ECAs) provide an alternative to solder materials. Their advantages are easy processing, higher resolution printing, lower processing temperature, and environmental friendliness [Aradhana 2020]. Adhesives are suitable for a wide variety of component metallization, like Ag, Au, but also non-metallized component surfaces like ceramics and bare silicon.

The main components of ECAs are polymer and electrically conductive fillers. The polymer matrix can consist of thermoplastics like polyimide and thermosets like silicon, epoxy, or acrylate resins. The most commonly used filler is micro silver, used in the form of powder, flakes, spheres, nanowires or dendrites [Latko-Durątek et al. 2020].

The type of polymer matrix used determines the temperature range in which adhesives can be used. Epoxy-based adhesives can work up to 200 °C continuous operating temperature, while silicone-based adhesives also withstand temperatures up to 260 °C [McCluskey et al. 1997].

While ECAs can withstand higher temperatures compared to solders, their thermal conductivity is comparatively low. Thermal conductivity can be a critical factor, for example, for high power applications. It can be altered by the amount and type of filler content and processing conditions. Hybrid sinter adhesives combine the advantages of a silver-filled adhesive (thermal-mechanical stability, low sensitivity to surfaces) with the high conductivity of a sintered Ag ma-

terial. The remaining resin content is a key factor determining the physical properties of the material. The transition from an adhesive with very low resin content to a pure Ag-sinter material is gradual.

Sintered die-attached connections show highest thermal conductivity. Processing is more complex because pressure needs to be applied to the components for the connections material to properly sinter.

Pressure assisted sintering thus gives the best high-temperature and high-power performance but is limited to a certain type of components and complicates production processes.

5.3 The Future of Production Systems and Energy Distribution

(Lohweg, V.)

This section provides an overview of the need for various sensor technologies in the area of future sustainable production and energy supply in the context of a climate-neutral view of various technical systems.

Many countries face two fundamental changes at the same time: digitalization and Artificial Intelligence (AI), and the conversion of the economy to climate neutrality and sustainability. The associated pressure to innovate also harbors a great opportunity to increase competitiveness. However, manufacturing companies are faced with the challenge of ensuring production quality and quantity at the highest level despite transformative changes.

Industry 4.0 and Cyber-Physical Production Systems. To increase sustainability in production, many companies focus on the innovative approach of combining production machine retrofitting [Hemmelgarn et al. 2021], multi-sensory approaches [Kancharla et al. 2021] and AI-based analyses on effective production [Ehrhardt et al. 2022]. In specific applications, process parameters are optimized in order to reduce waste, minimize energy and maximize performance.

Individualized production is usually placed in the context of Industry 4.0 [Terzimehić and Zoitl 2023] or cyber-physical production systems

(Pérez et al. 2015). However, in order to enable existing production machines to be used in an Industry 4.0 ecosystem, it is essential to equip machines with sensors that record the physical properties of the system. As a rule, hardly any special sensors are used, but rather mass-produced, inexpensive elements to detect current, voltage, forces, movement, structure-borne noise, etc.

Large-scale industrial machinery applies complex processes to cover the demands put on them [Otto et al. 2018]. Such processes range from car manufacturing over newspaper printing up to garment weaving, to name just a few. The complexity of the machinery applied in such processes puts subsequent demands on their handling. In the engineering phase, modularization approaches are followed to divide complex plants into smaller, less complex parts forming the desired process when operated in the appropriate combination. During operation, the machineries' control, supervision, and service have to be guaranteed reliably.

Within various scenarios mentioned above, there are of course challenges arising when it comes to machine condition monitoring with multiple sources. Besides sensors, hundreds or thousands of actuators and other sources are inside those systems [Holst et al. 2021]. Thus, industrial production processes are clearly to be categorized as big data applications. Manual human condition monitoring processing all the data generated is therefore impossible and is today to be carried out by multisensory information fusion systems (see Chapter 4). Since signal sources are distributed over the complete application, all data is to be communicated over an appropriate network to the condition monitoring system [Catenazzo et al. 2018].

Energy distribution. It can be assumed that major changes are expected in energy distribution systems and for the society and manufacturing by 2030, both throughout Europe and worldwide. Following the paradigms of sustainable, resource-circulating production, a corresponding energy supply with exclusively renewable forms of energy will be necessary, even if these are subsequently used for hydrogen generation, for example. This necessarily means that measurement and sensor technol-

ogy must be implemented in the aforementioned processes. The market for sensor technology will have greatly expanded by 2030.

Essentially, sensors are required for high-current and high-voltage measurements as well as sensors for temperature and power measurement. Here are three examples of the directions that will drive change processes in the coming years.

In the United Kingdom, high-voltage direct current (HVDC) applications driven by the wind power industry are on the way. A 443-megawatt wind farm was set to power Shetland and parts of Scotland by mid-2024 [Fairley et al. 2024].

The German government supports companies and research institutions in the development of innovative technologies that drive the achievement of international climate targets. In particular, the energy research programs of the Federal Ministry for Economic Affairs and Energy support the industrial and production landscape in Germany. The main focus is on energy supply of

industrial plants via intelligent, open DC (direct current) grids and on DC infrastructure being implemented. The output of these systems ranges from a few kilowatts to 2 megawatts [DC Industry 2024].

Furthermore, the German Commission for Electrical, Electronic & Information Technologies [DKE] defined guidelines and goals in 2022 to work on the fastest and most comprehensive energy transition possible by means of electrical standardization – with the aim of achieving a sustainable energy supply. It defines the All Electric Society (AES) as follows: The DKE's target image is the All Electric Society – a world that is digitally networked and produces electricity sustainably. The DKE interprets the All Electric Society as the scientifically based vision of a CO₂-neutral and sustainably developing world whose energy requirements are covered entirely by electricity generated from renewable sources [DKE 2022]. For example, Phoenix Contact in Blomberg, Germany, an electric component supplier, is one of the first companies to demonstrate what is already technologically possible today [Phoenix 2024].

References Chapter 5

Digital Functional Printing Based on Nano Metal Inks

J. Keck, K. Glaeser, D. Juric, W. Eberhardt, and A. Zimmermann in W. Zapka (Ed.) *Inkjet Printing in Industry*, Wiley-VoH, <https://doi.org/10.1002/9783527828074.ch53>, 2022

Product Development Processes for Individualized Products: A Case Study

F. Civelek, A. Brem, K.-P. Fritz, and A. Zimmermann *IEEE Transactions on Engineering Management*, <https://doi.org/10.1109/TEM.2023.3277019>, 2023

Aerosol Jet Printing and Interconnection Technologies on Additive Manufactured Substrates

K. Werum, E. Mueller, J. Keck, J. Jaeger, T. Horter, K. Glaeser, S. Buschkamp, M. Barth, W. Eberhardt, and A. Zimmermann *J. Manuf. Mater. Process*, 6, 119, <https://doi.org/10.3390/jmmp6050119>, 2022

Recent Advances in Printed Sensors on Foil

G. Mattana, and D. Briand *Materials Today*, 19, 88, <https://doi.org/10.1016/j.mat-tod.2015.08.001>, 2016

Pick and Place of Sensitive Chips with Vacuum-Free Gecomer® Tools

Lorenz, L., Ludewig, T., Swiecinski, K., Ollmann, H., Razkordanisharahi, A., & Bock, V. (2023, September). In 2023 24th European Microelectronics and Packaging Conference & Exhibition (EMPC) (pp. 1-6). IEEE.

Three-Dimensional Molded Interconnect Devices (3D-MID) – Materials, Manufacturing, Assembly and Applications for Injection Molded Circuit Carriers

J. Franke (Ed.) Carl Hanser, 2014

https://www.lpkf.com/fileadmin/media-files/user_upload/LPKF_LDS_Polymers_Approva_List_2023-04.pdf (accessed on: March 11th 2025)

Laser Direct Structuring of Semiconductor Liquid Encapsulants for Active Mold Packaging

C. He et al. 2022 IEEE 72nd Electronic Components and Technology Conference (ECTC),

1277–1281,

<https://doi.org/10.1109/ECTC51906.2022.00205>, 2022

Integration of Mechatronic Functions on Additively Manufactured Components via Laser-Assisted Selective Metal Deposition

T. Vieten, S. Weser, A. Schilling, K. Gläser, and A. Zimmermann *Adv. Funct. Mater.*, 2312833, <https://doi.org/10.1002/adfm.202312833>, 2024

Laser Induced Selective Metallization of 3D Ceramic Interconnect Devices

Ermantraut E, Zimmermann A, Muller H et al. (2018 - 2018). In: 2018 13th International Congress Molded Interconnect Devices (MID). IEEE, pp 1–5

New Process for Selective Additive Metallization of Alumina Ceramic Substrates

Ermantraut E, Muller H, Eberhardt W et al. (2019). *IEEE Trans. Compon., Packag. Manuf. Technol.* 9(1): 138–145. doi: 10.1109/TCPMT.2018.2881410

Research on laser-assisted selective metallization of a 3D printed ceramic surface

Zhao F, Jiao C, Xie D et al. (2020). *RSC advances* 10(72): 44015–44024. doi: 10.1039/d0ra08499a

Laser activation and metallisation of oxide ceramics

Shafeev GA (1993). *Adv Material for Optics Elec* 2(4): 183–189. doi: 10.1002/amo.860020405

Laser induced activation of circuit lines and vias on AlN for electroless metal plating

Yung KC, Chen C, Lee CP (2011). *Applied Surface Science* 257(15): 6601–6606. doi: 10.1016/j.apsusc.2011.02.085

Laser-assisted activation of dielectrics for electroless metal plating

Shafeev GA (1998). *Applied Physics A: Materials Science & Processing* 67(3): 303–311. doi: 10.1007/s003390050775

Selective laser induced autocatalytic metallization of NiO and Cr2O3 doped alumina zirconia ceramic substrates

- Ninz P, Kern F, Petillon S et al. (2020). Journal of the European Ceramic Society 40(11): 3733–3743. doi: 10.1016/j.jeurceramsoc.2020.01.026
- Microstructure and mechanical properties of Al₂O₃-ZrO₂ ceramic deposited by laser direct material deposition
Li F, Zhang X, Sui C et al. (2018). Ceramics International 44(15): 18960–18968. doi: 10.1016/j.ceramint.2018.07.135
- Novel Ceramic-Based Material for the Applications of Molded Interconnect Devices (3D-MID) Based on Laser Direct Structuring
Bachy B, Süß-Wolf R, Wang L et al. (2018). Adv Eng Mater 20(7). doi: 10.1002/adem.201700824
- Multi-Funktionale Boards – MFB – mit embedded Components
J. Kostelnik 18. EE-Kolleg, Saint Jordi, 2015
<https://www.hella.com/soe/de/News/CIPoS-Technologie-4164> (accessed on: March 11th 2025)
- Characterization of a PCB Based Pressure Sensor and Its Joining Methods for the Metal Membrane
A. Schwenck, T. Groezinger, T. Guenther, A. Schumacher, D. Schuhmacher, K. Werum, and A. Zimmermann Sensors, 21, 5557, <https://doi.org/10.3390/s21165557>, 2021.
- Bülau, A.: Leiterplattenbasierte Sensoren mit Ausleseelektroniken auf Basis von Zeitmess-technik, <http://dx.doi.org/10.18419/opus-14480>, Universität Stuttgart, 2024.
- Bending Setups for Reliability Investigation of Flexible Electronics
R. Saleh, M. Barth, W. Eberhardt, and A. Zimmermann Micromachines, 12, 78, <https://doi.org/10.3390/mi12010078>, 2021
- Advanced Interconnection Technologies for Flexible Organic Electronic Systems
M. Koyuncu, E. Lorenz, and A. Zimmermann in S. Logothetidis (Ed.) Handbook of Flexible Organic Electronics - Materials, Manufacturing and Applications, Woodhead Publishing, <https://doi.org/10.1016/B978-1-78242-035-4.00006-3>, 2015
- Hybrid Systems-in-Foil
M. Elsobky, and J. N. Burghartz Cambridge University Press, 2021
- Inkjetdruck von Silberleiterbahnen zur Anwendung als Temperatursensor
B. Polzinger Verlag Dr. Hut, 2017
- Miniaturized Optical Encoder with Micro Structured Encoder Disc
J. Seybold, A. Buelau, K.-P. Fritz, A. Frank, C. Scherjon, J. Burghartz, and A. Zimmermann Applied Sciences, 9(3), 452, <https://doi.org/10.3390/app9030452>, 2019
- Fabrication of curved diffractive optical elements by means of laser direct writing, electroplating, and injection compression molding
M. Roeder, S. Thiele, D. Hera, C. Pruss, T. Guenther, W. Osten, and A. Zimmermann Journal of Manufacturing Processes, 47, 402–409, <https://doi.org/10.1016/j.jmapro.2019.10.012>, 2019
- Will Low-Cost 3D Additive Manufactured Packaging Replace the Fan-Out Wafer Level Packages?
T. Tiedje, S. Lungen, M. Schubert, M. Luniak, K. Nieweglowski and K. Bock, ", 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2017, pp. 1065–1070, doi: 10.1109/ECTC.2017.276
- Temporary Bonding and Debonding in Advanced Packaging: Recent Progress and Applications
Z. Mo, F. Wang, J. Li, Q. Liu, G. Zhang, W. Li, C. Yang, R. Sun Electronics 2023 12(7) <https://doi.org/10.3390/electronics12071666>
<https://www.precisionreports.co/>; 2022 2029 Global Heterogeneous Integration Professional Market – Industry Reports, 2024 (accessed on: March 11th 2025)
<https://www.imec-int.com/en/articles/view-3d-technology-landscape>, 2024 (accessed on: March 11th 2025)
- 4.6 A 1/2.3inch 20Mpixel 3-layer stacked CMOS Image Sensor with DRAM
T. Haruta et al., 2017 IEEE International Solid-State Circuits Conference (ISSCC), San Fran-

cisco, CA, USA, 2017, pp. 76-77, doi:
10.1109/ISSCC.2017.7870268

Novel three-layer stacking process with face-to-back CoW 6 μm -pitch hybrid bonding
A. Urata et al., 2024 IEEE 74th Electronic Components and Technology Conference (ECTC), Denver, CO, USA, 2024, pp. 56-61, doi:
10.1109/ECTC51529.2024.00018

Wafer-to-wafer hybrid bonding at 400-nm interconnect pitch
Chew, S.A., De Vos, J. & Beyne, E.. Nat Rev Electr Eng 1, 71–72 (2024).
<https://doi.org/10.1038/s44287-024-00019-8>

<https://www.evgroup.com/products/bonding/bond-alignment-systems/smartview-nt>, 2024 (evgroup.com) (accessed on: March 11th 2025)

Contamination-Free Cu/SiCN Hybrid Bonding Process Development for Sub- μm Pitch Devices with Enhanced Bonding Characteristics
S. H. Hahn et al., 2023 IEEE 73rd Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2023, pp. 1390-1396, doi: 10.1109/ECTC51909.2023.00238

Impact of Dielectric and Copper Via Design on Wafer-to-Wafer Hybrid Bonding
V. Dubey et al. 2023 IEEE 73rd Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2023, pp. 795-799, doi:
10.1109/ECTC51909.2023.00138

Advancing Fine Pitch ($< 5\mu\text{m}$) Interconnects through Self-Aligned Die-to-Wafer Hybrid Bonding for Chiplet Integration
V. Dubey et al., 2023 IEEE 25th Electronics Packaging Technology Conference (EPTC), Singapore, 2023, pp. 469-473, doi:
10.1109/EPTC59621.2023.10457767

Physics of self-aligned assembly at room temperature
V. Dubey, E. Beyne, J. Derakhshandeh, I. De Wolf,. Physics of Fluids 1 January 2018; 30 (1): 012001. <https://doi.org/10.1063/1.5004797>

Die to wafer 3D stacking for below 10 μm pitch microbumps
Derakhshandeh et al., 2016 IEEE International 3D Systems Integration Conference (3DIC), San

Francisco, CA, USA, 2016, pp. 1-4, doi:
10.1109/3DIC.2016.7969993

Low temperature backside damascene processing on temporary carrier wafer targeting 7 μm and 5 μm pitch microbumps for N equal and greater than 2 die to wafer TCB stacking
J. Derakhshandeh et al., ", 2022 IEEE 72nd Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 2022, pp. 1108-1113, doi:
10.1109/ECTC51906.2022.00179

Semiconductor Advanced Packaging
John H. Lau, Springer, 2021, ISBN 9811613753

Near-sensor and in-sensor computing
Feichi Zhou, Yang Chai; Nature Electronics volume 3, pages664–671 (2020)

Thermal Improvement of HBM with Joint Thermal Resistance Reduction for Scaling 12 Stacks and Beyond
T. Kim et al., ", 2023 IEEE 73rd Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2023, pp. 767-771, doi:
10.1109/ECTC51909.2023.00133

Ultralow Expansion Glass as Material for Advanced Micromechanical Systems
C. Weigel, V. Cherkasova, M. Holz, H.B. Phi, C. Görner Tenorio, B. Wilbertz, L. Voßgrag, T. Fröhlich, and S. Strehle Adv. Eng. Mater., 25: 2201873,
<https://doi.org/10.1002/adem.202201873>, 2023

Application of Through Glass Via (TGV) Technology for Sensors Manufacturing and Packaging
C. Yu, S. Wu, Y. Zhong, R. T. Yu, J. Zhao, and D. Yu, Sensors 2024, 24, 171,
<https://doi.org/10.3390/s24010171>, 2024

Glass based micro total analysis systems: Materials, fabrication methods, and applications
Tao Tang, Yapeng Yuan, Yaxiaer Yalikun, Yoichiro Hosokawa, Ming Li, and Yo Tanaka Sensors and Actuators B: Chemical, Volume 339, 129859,
<https://doi.org/10.1016/j.snb.2021.129859>, 2021

Fused silica cylindrical shell resonators with 25 million Q factors

Libin Zeng et al J. Phys. D: Appl. Phys. 54 495104, <https://doi.org/10.1088/1361-6463/ac2447>, 2021

Long-term stability of a hermetically packaged MEMS disk oscillator

T. O. Rocheleau, T. L. Naing, and C. T.-C. Nguyen 2013 Joint European Frequency and Time Forum & International Frequency Control Symposium (EFTF/IFC), Prague, Czech Republic, 209–212, <https://doi.org/10.1109/EFTF-IFC.2013.6702095>, 2013

Proof of Concept: Glass-Membrane Based Differential Pressure Sensor

A. Glukhovskoy et al. 2021 IEEE 71st Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 1563–1570, <https://doi.org/10.1109/ECTC32696.2021.00248>, 2021

Live single cell imaging assays in glass microwells produced by laser-induced deep etching

N. Sandström, L. Brandt, P. A. Sandoz, C. Zambarda, K. Guldevall, M. Schulz-Ruhtenberg, ... & B. Önfelt Lab on a Chip, 22(11), 2107–2121, <https://doi.org/10.1039/D2LC00090C>, 2022

Advances in high-performance MEMS pressure sensors: design, fabrication, and packaging

X. Han, M. Huang, Z. Wu et al. Microsyst Nanoeng 9, 156, <https://doi.org/10.1038/s41378-023-00620-1>, 2023

Glass Package for Radar MMICs Above 150 GHz

T. Galler et al. IEEE Journal of Microwaves, vol. 2, no. 1, 97–107, <https://doi.org/10.1109/JMW.2021.3122067>, 2022

Micromachining Fused Silica Micro Shell Resonator with Quartz Glass Mold by Thermal Re-flow

Z. Su, B. Luo, Q. Tang, L. Zhu, and J. Shang 2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS), Munich, Germany, 889–892, <https://doi.org/10.1109/MEMS49605.2023.10052274>, 2023

Frequency split suppression of fused silica micro shell resonator based on rotating forming process B. Li, X. Xi, K. Lu. et al. Microsyst. Technol. 27, 789–799, <https://doi.org/10.1007/s00542-020-05034-x>, 2021

Opportunities for photonic integrated circuits in optical gas sensors

A. Hänsel & M. J. Heck Journal of Physics: Photonics, 2(1), 012002, <https://doi.org/10.1088/2515-7647/ab6742>, 2020

Integrated silicon photonic MEMS

N. Quack, A.Y. Takabayashi, H. Sattari et al. Microsyst Nanoeng 9, 27, <https://doi.org/10.1038/s41378-023-00498-z>, 2023

Integrated Photonics on Glass: A Review of the Ion-Exchange Technology Achievements

J.-E. Broquin, and S. Honkanen Appl. Sci. 2021, 11, 4472. <https://doi.org/10.3390/app11104472>, 2021

Hybrid photonic system integration using thin glass platform technology

Henning Schröder, Julian Schwietering, Gunnar Böttger, and Vanessa Zamora, J. Optical Microsystems 1(3) 033501 <https://doi.org/10.1117/1.JOM.1.3.033501>, 2021

Applications, materials, and fabrication of micro glass parts and devices: An overview

Hazem Hamed, Marwan Eldiasty, Seyed-Mahmoud Seyedi-Sahebari, and Jana D. Abou-Ziki Materials Today, Volume 66, 194–220, <https://doi.org/10.1016/j.mattod.2023.03.005>, 2023

Glass as A Functional Material for Micro Electromechanical Systems

M. Bertke, S. Schudak, and R. Ostholt, 2024 IEEE 37th International Conference on Micro Electro Mechanical Systems (MEMS), Austin, TX, USA, 646–649, <https://doi.org/10.1109/MEMS58180.2024.10439553>, 2024

Fabrication of Panel-Level Glass Substrates with Complete Design Freedom Using LIDE

Rafael Santos, Nils Anspach, Norbert Ambrosius, Stephan Schmidt, and Roman Ostholt

IMAPSource Proceedings 2022 (IMAPS Symposium), Boston: 000371–77,
<https://doi.org/10.4071/001c.74577>, 2023

Laser-Induced Structuring of Glass as a Promising Manufacturing Technology for Lab-on-Chip Devices: Opportunities and Challenges
Werner J. Karl, Nagashree B. Jagadesh, and Roy Knechtel Proceedings of MikroSystemTechnik Kongress 2023, Dresden, 382–388, VDE-Verlag. ISBN: 978-3-8007-6203-3, 2023

Batch Fabrication of 50 μm -Thick Anisotropic Nd-Fe-B Micro-Magnets
Frederico O. Keller, IEEE Transactions on Magnetics (Volume: 58, Issue: 2, February 2022), DOI: 10.1109/TMAG.2021.3101911

Integration of polymer bonded magnets into magnetic sensors
Klaus Elia; Horst Theuss; Proceedings of the 5th Electronics System-integration Technology Conference (ESTC), 2014,
10.1109/ESTC.2014.6962754

A review of the hybrid techniques for the fabrication of hard magnetic microactuators based on bonded magnetic powders
M Pallapa and J T W Yeow 2015 Smart Mater. Struct. 24 025007, 10.1088/0964-1726/24/2/025007

PowderMEMS—A Generic Microfabrication Technology for Integrated Three-Dimensional Functional Microstructures
Thomas Lisec , Ole Behrmann and Björn Gojdka; Micromachines 2022, 13, 398.
<https://doi.org/10.3390/mi13030398>

Fully Integrated Back-Biased 3d Hall Sensor with Wafer-Level Integrated Permanent Micro-magnets
Björn Gojdka et al, 2023 IEEE 36th International Conference on Micro Electro Mechanical Systems (MEMS),
DOI: 10.1109/MEMS49605.2023.10052184

Gas Permeable Protection Caps for Wafer Level Chip Scale Packaging (WLCSP) of MEMS Environmental Sensors
Ole Behrmann et al, 2023 24th European Microelectronics and Packaging Conference & Exhibition (EMPC);
DOI:10.23919/EMPC55870.2023.10418326

Miniaturized quantum systems for inertial measurement units

Kassner, A., et al. in 2023 DGON Inertial Sensors and Systems (ISS), Braunschweig, Germany, 2023, pp. 1-20, doi:
10.1109/ISS58390.2023.10361909

Entwicklung eines mehrschichtigen Atomchip-Systems mit integrierter Temperatur-Sensorik für den Einsatz unter Weltraumbedingungen.
Kassner, A., and Wurz, M. C. (Ed.) in Berichte aus dem impt, 2024, Band 1, TEWISS Verlag, 2024, doi: 10.51202/9783959009508

Chip-scale atomic devices
J. Kitching Applied Physics Reviews Vol. 5,
<https://doi.org/10.1063/1.5026238>, 2018

Optical atomic clocks
Andrew D. Ludlow, Martin M. Boyd, Yun Ye, E. Peik, and P. O. Schmidt Rev. Mod. Phys. 87 (2), 637–701, <https://doi.org/10.1103/RevModPhys.87.637>, 2015

Double Oven OCXO Series - NI-10M-3500 Type
TAITIEN ELECTRONICS CO.,LTD
<https://www.taitien.com/ti-products/double-oven-ocxo-series-ni-10m-3500-type>, 2021
(accessed on: March 11th 2025)

ITU: Handbook Selection and Use of Precise Frequency and Time Standards
International Telecommunication Union 1997

Long-Term Stability Analysis Toward <10-14 Level for a Highly Compact POP Rb Cell Atomic Clock
Nil Almat, Mohammadreza Gharavipour, William Moreno, Florian Gruet, Christoph Affolderbach, and Gaetano Miletì IEEE transactions on ultrasonics, ferroelectrics, and frequency control 67 (1), 207–216.
<https://doi.org/10.1109/TUFFC.2019.2940903>, 2020

^3He - ^{129}Xe Comagnetometry using ^{87}Rb Detection and Decoupling
M. E. Limes, D. Sheng, and M. V. Romalis, Physical review letters 120 (3), S. 33401,
<https://doi.org/10.1103/PhysRevLett.120.033401>, 2018

M. E. Limes, N. Dural, M. V. Romalis, E. L. Foley, T. W. Kornack, A. Nelson et al. Dipolar and scalar He3–Xe129 frequency shifts in stemless cells. *Phys. Rev. A* 100 (1), <https://doi.org/10.1103/PhysRevA.100.010501>, 2019

Laser-written vapor cells for chip-scale atomic sensing and spectroscopy
Lucivero, Vito G.; Zanon, Andrea; Corielli, Giacomo; Osellame, Roberto; Mitchell, Morgan W. (2022): In: *Optics express* 30 (15), S. 27149–27163. DOI: 10.1364/OE.469296

Below 100 fT/Hz^{1/2} in a Microfabricated Cell
Gerginov, Vladislav; Pomponio, Marco; Knappe, Svenja (2020): *Scalar Magnetometry I*. In: *IEEE sensors journal* 20 (21), S. 12684–12690. DOI: 10.1109/JSEN.2020.3002193.

An optimized microfabricated platform for the optical generation and detection of hyperpolarized 129Xe
Kennedy, Daniel J.; Seltzer, Scott J.; Jiménez-Martínez, Ricardo; Ring, Hattie L.; Malecek, Nicolas S.; Knappe, Svenja et al. (2017): In: *Scientific reports* 7, S. 43994. DOI: 10.1038/srep43994.

Aging studies on micro-fabricated alkali buffer-gas cells for miniature atomic clocks
Abdullah, S.; Affolderbach, C.; Gruet, F.; Mileti, G. (2015): In: *Applied Physics Letters* 106 (16), Artikel 163505. DOI: 10.1063/1.4919009.

Microfabricated vapor cells filled with a cesium dispensing paste for miniature atomic clocks
Maurice, V.; Rutkowski, J.; Kroemer, E.; Bargiel, S.; Passilly, N.; Boudot, R. et al. (2017): In: *Applied Physics Letters* 110 (16), Artikel 164103. DOI: 10.1063/1.4981772.

Characterization of Cs vapor cell coated with octadecyltrichlorosilane using coherent population trapping spectroscopy
Hafiz, Moustafa Abdel; Maurice, Vincent; Chutani, Ravinder; Passilly, Nicolas; Gorecki, Christophe; Guérandel, Stéphane et al. (2015): In: *Journal of Applied Physics* 117 (18), Artikel 184901. DOI: 10.1063/1.4919841

Mikrosystemtechnisch integriertes, optisch gepumptes Magnetometer
Woetzel, Stefan. (2017). <https://www.db-thuer->

[ingen.de/receive/dbt_mods_00032071](https://www.db-thuer-ingen.de/receive/dbt_mods_00032071) (accessed on: March 11th 2025)

Spin-exchange optical pumping of He3 with Rb-K mixtures and pure K
Chen, W. C.; Gentile, T. R.; Walker, T. G.; Babcock, E. (2007): In: *Phys. Rev. A* 75 (1). DOI: 10.1103/PhysRevA.75.013416.

Development of a Spin-Exchange Optical Pumping-Based Polarized 3 He System at the China Spallation Neutron Source (CSNS)
Huang, Chuyi; Zhang, Junpei; Ye, Fan; Qin, Zecong; Amir, Syed Mohd; Buck, Zachary Norris et al. (2021): In: *Chinese Phys. Lett.* 38 (9), S. 92801. DOI: 10.1088/0256-307X/38/9/092801.

He 3 polarization via optical pumping in a birefringent cell
Masuda, Y.; Ino, T.; Skoy, V. R.; Jones, G. L. (2005): In: *Applied Physics Letters* 87 (5), Artikel 053506. DOI: 10.1063/1.2008370

CSAC-SA45S
Available online: <https://www.microchip.com/en-us/product/CSAC-SA45S2024> (accessed on: March 11th 2025)

PRS10 - Rubidium Frequency Standard (2023).
Available online: <https://www.thinksrs.com/products/prs10.html>, last updated: 20.06.2023 (accessed on: March 11th 2025)

Vapor Cell Technologies VCT (2021):
Vapor Cell Technologies. Available online: <https://vaporcelltechnologies.com/>, last updated: 20.07.2021 (accessed on: March 11th 2025)

Twinleaf — Precision magnetic field sensors (2023).
available online: <https://twinleaf.com/>, last updated: 15.12.2023 (accessed on: March 11th 2025)

Technology – QuSpin (2024).
available online: <https://quspin.com/technology/>, last updated: 09.01.2024, (accessed on: March 11th 2025)

macQsimal (2024): Overcoming the limits of conventional sensing with quantum technolo-

gies - macQsimal project.
available online: <https://www.macqsimal.eu/>,
last updated: 05.01.2024, (accessed on: March
11th 2025)

Hochtemperatur-Elektronik: Stand und Herausforderungen
J. Wilde VDE/GMM. Frankfurt am Main 2002

High-temperature thin-film strain gauges
P. Kayser, J. C. Godefroy, L. Le Sensors and Actuators A: Physical, Volume 37–38, 328–332, 1993

Advances in Thin Film Sensor Technologies for Engine Application
J.-F. Lei, L. C. Martin, H. A. Will Nasa Lewis Research Center, Cleveland, Ohio, 1997

Direct-Deposited Thin-film Strain Gauges for High-temperature Applications
R. Ottermann, N. Kyoushi, M.C. Wurcz, MikroSystemTechnik Kongress, Dresden, 2023

Development, Characterisation and High-Temperature Suitability of Thin-Film Strain Gauges Directly Deposited with a New Sputter Coating System
D. Klaas, R. Ottermann, F. Dencker, M. C. Wurcz MDPI Sensors 2020, 20, 3294, 2020

A novel technique for MEMS packaging: Reactive bonding with integrated material systems
J. Braeuer, J. Besser, M. Wiemer, T. Gessner, Sensors and Actuators A: Physical, Volume 188, 212–219, ISSN 0924-4247, <https://doi.org/10.1016/j.sna.2012.01.015>, 2012

Reactive chip level bonding based on CuO/Al reactive multilayer systems
K. Vogel, R. Schachler, F. Roscher, M. Wiemer, and H. Kuhn 2021 23rd European Microelectronics and Packaging Conference & Exhibition (EMPC), Gothenburg, Sweden, 2021, 1–6, <https://doi.org/10.23919/EMPC53418.2021.9585012>, 2021a

Combustion in reactive multilayer Ni/Al nanofoils: Experiments and molecular dynamic simulation
A. S. Rogachev, S. G. Vadchenko, F. Baras, O. Politano, S. Rouvimov, N. V. Sachkova, M. D. Grapes, T. P. Weihs, A. S. Mukasyan, Combustion and Flame, Volume 166, 158–169, ISSN 0010-2180, <https://doi.org/10.1016/j.combustflame.2016.01.014>, 2016

Reactive Bonding K. Vogel, S. Braun, C. Hofmann, M. Weiser, M. Wiemer, T. Otto, and H. Kuhn in M. Esashi (Ed.) 3D and Circuit Integration of MEMS, <https://doi.org/10.1002/9783527823239.ch14>, 2021

Room-temperature soldering with nanostructured foils
J. Wang, E. Besnoin, A. Duckham, S. J. Spey, M. E. Reiss, O. M. Knio, M. Powers, M. Whitener, T. P. Weihs Appl. Phys. Lett., 83 (19): 3987–3989. <https://doi.org/10.1063/1.1623943>, 2003

Reactive multilayer foils for MEMS wafer level packaging
X. Qiu, J. Zhu, J. Oiler and H. Yu 2009 59th Electronic Components and Technology Conference, San Diego, CA, USA, 1311–1316, <https://doi.org/10.1109/ECTC.2009.5074181>, 2009

Optimizing the Nano Wiring and KlettSintering parameters for low-temperature die to DCB attach of power electronic chips
D. Strahringer, F. Roustaie, F. Weissenborn, S. Quednau, and J. Wilde 2021 16th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), Taipei, Taiwan, 31–34, <https://doi.org/10.1109/IMPACT53160.2021.9696635>, 2021

In situ synthesis of metallic nanowire arrays for ionization gauge electron sources
Farough Roustaie, Sebastian Quednau, Florian Dassinger, Helmut F. Schlaak, Marcel Lotz, Stefan Wilfert J. Vac. Sci. Technol. B; 34 (2): 02G103. <https://doi.org/10.1116/1.4939756>, 2016

Room Temperature Interconnection Technology for Bonding Fine Pitch Bumps Using NanoWiring, KlettWelding, KlettSintering and KlettGlueing
F. Roustaie, S. Quednau, F. Dassinger, and O. Birlem 2020 15th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), Taipei, Taiwan, 168–171, <https://doi.org/10.1109/IMPACT50485.2020.9268570>, 2020

Room Temperature Interconnection Technology for Bonding Fine Pitch Bumps Using NanoWiring, KlettWelding, KlettSintering and KlettGlueing
F. Roustaie, S. Quednau, F. Dassinger, and O. Birlem 2020 15th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), Taipei, Taiwan, 168–171, <https://doi.org/10.1109/IMPACT50485.2020.9268570>, 2020

Room Temperature Interconnection Technology for Bonding Fine Pitch Bumps Using NanoWiring, KlettWelding, KlettSintering and KlettGlueing
F. Roustaie, S. Quednau, F. Dassinger, and O. Birlem 2020 15th International Microsystems, Packaging, Assembly and Circuits Technology Conference (IMPACT), Taipei, Taiwan, 168–171, <https://doi.org/10.1109/IMPACT50485.2020.9268570>, 2020

- Room Temperature KlettWelding Interconnect Technology for High Performance CMOS Logic
F. Roustaei et al., 2021 IEEE 71st Electronic Components and Technology Conference (ECTC), San Diego, CA, USA, 371–376, <https://doi.org/10.1109/ECTC32696.2021.00069>, 2021
- <https://nanowired.de/klett welding/> (accessed on: March 11th 2025)
- Development and integration of the dual fuel combustion system for the MGT gas turbine family
Ćosić, Bernhard, et al., *Journal of Engineering for Gas Turbines and Power* 144.2 (2022): 021021.
- Experimental study of flameless combustion in gas turbine combustors
Li, Guoqiang, et al., 44th AIAA Aerospace Sciences Meeting and Exhibit. 2006.
- Modal dynamics of high-frequency transverse combustion instabilities
Kim, Jeong-won, et al., *Proceedings of the Combustion Institute* 38.4 (2021): 6155-6163.)
- Experimental Investigation of a Small-Scale Oxygen-Hydrogen Rotating Detonation Rocket Combustor
Armbruster, Wolfgang, et al., AIAA SCITECH 2024 Forum. 2024.
- Experimental and numerical study of the rotating detonation engine in hydrogen-air mixtures
Kindracki, Jan, et al., *Progress in propulsion physics* 2 (2011): 555-582.
- <https://www.nasa.gov/nasa-brand-center/imagesand-media/> – https://images.nasa.gov/details/GSFC_20171208_Archive_e000745) (accessed on: March 11th 2025)
- A4. 1 Measuring Considerations for Jitter Characterization on Small Satellite Reaction Wheels
Cavalloni, C., M. Dumont, and B. Zwolinski., *SMSI 2020-Sensors and Instrumentation* (2020): 67-68.
- Development of New Strain Gage for High-Pressure Hydrogen Gas Use
T. Matsuo, J. Yamabe, H. Furukawa, K. Seki, K. Shimizu, S. Watanabe, S. Matsuoka, , *Experimental Mechanics* 54, 431-442 (2014), [doi:10.1007/s11340-013-9816-4](https://doi.org/10.1007/s11340-013-9816-4)
- Piezoresistive Pressure Sensor Technology for Hydrogen Applications at High Temperatures
J Gramich, O Braun, M Rohner, R Rodrigo, T Candonau SMSI 2023
- Vacuum compatibility of 3D-printed materials
Alexander P. Povilus, Caroline J. Wurden, Zak Vendeiro, Marcelo Baquero-Ruiz, and Joel Fajans J. *Vac. Sci. Technol. A* 32 (3): 033001, <https://doi.org/10.1116/1.4873556>, 2014
- 3D Printing for High Vacuum Applications
C. R. Wolf, F. B. Beck, L. Franz, and V. M. Neumaier *Proc. Cyclotrons'19*, Cape Town, South Africa 317–320, <https://doi.org/10.18429/JA-CoW-Cyclotrons2019-THC04>, 2019
- Additively manufactured ultra-high vacuum chamber for portable quantum technologies
N. Cooper, L.A. Coles, S. Everton, I. Maskery, R.P. Campion, S. Madkhaly, C. Morley, J. O'Shea, W. Evans, R. Saint, P. Krüger, F. Oručević, C. Tuck, R.D. Wildman, T.M. Fromhold, L. Hacker-müller *Additive Manufacturing*, Volume 40, 2021, 101898, ISSN 2214-8604, <https://doi.org/10.1016/j.addma.2021.101898>.
- Additive manufacturing of magnetic shielding and ultra-high vacuum flange for cold atom sensors
J. Vovrosh, G. Voulazeris, P. G. Petrov et al. *Sci Rep* 8, 2023 <https://doi.org/10.1038/s41598-018-20352-x>, 2018
- 3D-Printed Hermetic Alumina Housings
M. Eickenscheidt, M. Langenmair, A. Dbouk, D. Nötzel, T. Hanemann, and T. Stieglitz *Materials* 2021, 14, 200, <https://doi.org/10.3390/ma14010200>, 2021
- Options for additive rapid prototyping methods (3D printing) in MEMS technology
V. A. Lifton, G. Lifton, and S. Simon *Rapid Prototyping Journal*, Vol. 20 No. 5, 403–412, <https://doi.org/10.1108/RPJ-04-2013-0038>, 2014
- A new approach for opto-electronic/MEMS packaging
R. Keusseyan, J. Sosnowski, M. Doyle, D. Amey,

and S. Horowitz 52nd Electronic Components and Technology Conference 2002. (Cat. No.02CH37345), San Diego, CA, USA, 259–262, <https://doi.org/10.1109/ECTC.2002.1008104>, 2002

MEMS sensor packaging using LTCC substrate technology
Harri K. Kopola, Jaakko Lenkkeri, Kari Kautio, Altti Torkkeli, Outi Rusanen, and Tuomo Jaakola Proc. SPIE 4592, Device and Process Technologies for MEMS and Microelectronics II, <https://doi.org/10.1117/12.448960>, 2021

Wafer-level hermetic packaging technology for MEMS using anodically-bondable LTCC wafer
S. Tanaka, S. Matsuzaki, M. Mohri, A. Okada, H. Fukushima, and M. Esashi 2011 IEEE 24th International Conference on Micro Electro Mechanical Systems, Cancun, Mexico, 376–379, <https://doi.org/10.1109/MEMSYS.2011.5734440>, 2011

Stand-alone vacuum cell for compact ultracold quantum technologies
Oliver S. Burrow, Paul F. Osborn, Edward Boughton, Francesco Mirando, David P. Burt, Paul F. Griffin, Aidan S. Arnold, and Erling Riis Appl. Phys. Lett. 119 (12): 124002, <https://doi.org/10.1063/5.0061010>, 2021

A multi-technique tomography-based approach for non-invasive characterization of additive manufacturing components in view of vacuum/UHV applications: preliminary results
F. Grazi, C. Cialdai, M. Manetti et al. Rend. Fis. Acc. Lincei 32, 463–477, <https://doi.org/10.1007/s12210-021-00994-2>, 2021

A 3D-printed miniature magnetron gauge for ultra-high vacuum environments
Shiyang Deng, Scott R. Green, and Yogesh B. Gianchandani Vacuum, Volume 156, 264–270, ISSN 0042-207X, <https://doi.org/10.1016/j.vacuum.2018.07.039>, 2018

Kruspe et al.: US 9,448,312 B1 (2016)

Jung et al.: US 10,444,063 B2 (2019)

Unveiling High Performance Solder Alloys for Automotive Applications

Choudhury, P., Rangaraju, R., Ribas, M. and Sarkar, S., in: IMAPSource Proceedings 2022 (HiTEN), Oxford, UK, 18 – 20 Jul 2022, 10.4071/001c.89682, 2022.

Thermo-mechanical simulation of sintered Ag die attach for high temperature applications
Sousa, M., van Dijk, M., Walter, H., Weber, C., Hutter, M., Oppermann, H., Wittler, O., and Lang, K.D., in: IMAPSource Proceedings 2014 (HITEC), International Conference and Exhibition on High Temperature Electronics, Albuquerque, New Mexico USA, May 13-15 2014. 2014.

A review on epoxy-based electrically conductive adhesives
Aradhana, R., Mohanty, S., Nayak, S. K. International Journal of Adhesion and Adhesives, Volume 99, 2020, ISSN 0143-7496, <https://doi.org/10.1016/j.ijadhadh.2020.102596>

Relationship between Viscosity, Microstructure and Electrical Conductivity in Copolyamide Hot Melt Adhesives Containing Carbon Nanotubes
Latko-Duratek, P., Kozera, R., Macutkevič, J., Dydek, K., and Boczkowska, A.: , Materials, 2020, 13 (20), <https://doi.org/10.3390/ma13204469>.

High Temperature Electronics
McCluskey, F. P., Grzybowski, R. and Podlesack T. (Eds.): , CRC Press, 1997.

Evaluation of different additive manufacturing technologies for MIDs in the context of smart sensor systems for retrofit applications
F. Hemmelgarn et al. 14th International Congress Molded Interconnect Devices (MID), Amberg, Germany, 1-8, <https://doi.org/10.1109/MID50463.2021.9361628>, 2021

Augmented Reality Based Machine Monitoring for Legacy Machines: a retrofitting use case
C. R. Kancharla et al. XXX International Scientific Conference Electronics (ET), Sozopol, Bulgaria, 1-5, <https://doi.org/10.1109/ET52713.2021.9579936>, 2021

An AI benchmark for Diagnosis, Reconfiguration & Planning
J. Ehrhardt et al. IEEE 27th International Con-

ference on Emerging Technologies and Factory Automation (ETFA), Stuttgart, Germany, 1-8,
<https://doi.org/10.1109/ETFA52439.2022.9921546>, 2022

Landscape of Architectural Design Decisions in Industry 4.0
T. Terzimehić, A. Zoitl, A. IEEE 28th International Conference on Emerging Technologies and Factory Automation (ETFA), Sinaia, Romania, 1-4,
<https://doi.org/10.1109/ETFA54631.2023.10275678>, 2023

A CPPS Architecture approach for Industry 4.0
F. Pérez et al. IEEE 20th Conference on Emerging Technologies & Factory Automation (ETFA), Luxembourg, Luxembourg, 1-4,
<https://doi.org/10.1109/ETFA.2015.7301606>, 2015

Automatic Parameter Estimation or Reusable Software Components of Modular and Reconfigurable Cyber-Physical Production Systems in the Domain of Discrete Manufacturing
J. Otto, B. Vogel-Heuser, and O. Niggemann IEEE Transactions on Industrial Informatics, 14(1), 275–282,
<https://doi.org/10.1109/TII.2017.2718729>, 2018

A Redundancy Metric Set within Possibility Theory for Multi-Sensor Systems

C.-A. Holst, V. Lohweg Sensors, 21(7):2508.
<https://doi.org/10.3390/s21072508>, 2021

On the use of Wireless Sensor Networks in Preventative Maintenance for Industry 4.0
D. Catenazzo, B. O'Flynn, and M. Walsh 12th International Conference on Sensing Technology (ICST), Limerick, Ireland, 256–262,
<https://doi.org/10.1109/ICSensT.2018.8603669>, 2018

High-Voltage DC Power Roars Ashore in Europe: Scotland's next-generation transmission network foreshadows a global grid transformation
P. Fairley IEEE Spectrum, 61(1), 28-31,
<https://doi.org/10.1109/MSPEC.2024.10380470>, 2024

DC Industry, <https://dc-industry.zvei.org/en/publications/direct-current-power-for-sustainable-factories>, (accessed on: March 11th 2025)

DKE German Commission for Electrical, Electronic & Information Technologies,
<https://www.dke.de/resource/blob/2198422/582099a381a99cc7d6dcb8a1193c91b8/commitment-2030---pdf-englisch-data.pdf> (accessed on: March 11th 2025)

Phoenix Contact All-Electric-Society-Park,
<https://www.phoenixcontact.com/en-pc/company/all-electric-society/all-electric-society-park> (accessed on: March 11th 2025)

6 AMA Innovation Awards

(Schütze, A.)

AMA, the Association for Sensors and Measurement, has granted the AMA Innovation Award (Figure 6.1) for ground-breaking innovations in sensors and measurement science since 2000 [AMA, 2024]. These innovations combine invention, i.e., excellent scientific and technological advances, with clear market potential, thus mirroring the main trends in the field. The award comes with a prize money of 10,000 € each year, which is awarded not to the companies, but to the people responsible for the innovations. Since 2013, a special innovation award is presented to young enterprises to recognize and honor new market entries, often spin-offs from research institutions, and provide wide visibility for multifaceted developments taking their first commercial steps.

This chapter reviews the AMA Innovation Awards presented since 2017, both the award for young enterprises and the main innovation award. The structure follows the main chapters of this study. However, the innovations highlight the fact that sensors and measurement science is very system and application oriented, thus most innovations actually cover multiple technological fields to address a specific market need.



Figure 6.1 AMA Innovation Award (Source: AMA)

6.1 Physical Measurands

Probably one of the last innovations for conventional diesel and gasoline engines before the

transition to e-mobility took hold in the research departments was awarded with the AMA Innovation Award in 2017, namely the particulate filter monitoring technology based on radio frequency (RF) sensing by CTS Corporation and Filter Sensing Technologies with MIT for on-vehicle applications to meet the latest regulations. Note, however, that RF and radar sensing solutions are repeated winners with two awards for young enterprises (Sykno, 2pi-Labs) and one further innovation award (Scantinel Photonics) (Figure 6.7) as well as several nominations. Two other innovation awards in the area of physical measurements show that even well-known and established sensor technologies offer potential for groundbreaking innovations, if their fit for the intended application is perfect. This certainly holds for the iTherm TrustSens TM37x by Endress+Hauser Wetzer, a thermometer with automatic in-situ and in-process calibration function, which obviates having to re-calibrate temperature sensors outside the process and, thus, avoids problems during transport and re-installation. This is highly relevant especially for sterilization applications in the biomedical and food industries. Similarly, FAMAS, a fast magnetic angle sensor by Senis, improves existing angle sensors by integrating a novel algorithm for digitization of the measurement results for practically unlimited rotational speed. All three innovations also show the importance of combining sensor principle and data analysis to fit the application. The final innovation in this field, which also received an award for a young enterprise, the first magnetic quantum sensor for industrial applications (QT-RH105 by Quantum Technologies) indicates the increasing importance of quantum technologies 2.0 for sensing, where further leaps in improvement are expected especially for magnetic and gyro sensors (Figure 6.2).

Four further awards in this field were given to young enterprises, two of which use foil based thin-film sensors, one with nanotechnology layers (CeLaGo), the other making use of electroactive polymers (matelligent iDEAS, Figure 6.3), while the other two both address high-resolution position measurements, but for very differ-

ent applications with very different technical solutions. AIM Systems offers a novel measuring system for non-contact inline measurement of the coating thickness of Li ion batteries based on thermo-optical interference, while Sykno measures vital parameters – heartbeat, respiration rate and even heart sounds – with radar-based distance measurement as an alternative to adhesive electrodes used in conventional ECG.



Figure 6.2 AMA Innovation Award 2023 Quantum Technologies GmbH. From left to right: Prof. Dr. Andreas Schütze (Jury Chairman), Dr. Lutz Langguth, Romy Müller, Dominik Rajspp, Dr. Robert Staacke (all Quantum Technologies GmbH), Peter Krause (AMA Chairman of the Board). (Source: AMA)



Figure 6.3 FlexSense – Electroactive Polymer (EAP) stretch and pressure sensors (Source: Alexander York, matelligent IDEAS)

2017: Radio Frequency Diesel and Gasoline Particulate Filter Sensor (CTS Corporation / Filter Sensing Technologies, Inc./Massachusetts Institute of Technology)

2018: Thermometer with automatic in-situ and in process calibration function (Endress+Hauser Wetzler GmbH + Co KG/TU Ilmenau)

2020: FAMAS – FASt Magnetic Angle Sensor (SENIS GmbH)

2023: Innovation Award and Young Enterprise: QT-RH105: First magnetic quantum sensor for

industrial applications (Quantum Technologies GmbH)

2018, Young Enterprise: Customized thin film foil strain gauges with high sensitivity (CeLaGo Sensors GmbH with University of Applied Sciences Saarland)

2023: Young Enterprise: Photothermal inline measurement for battery electrodes (AIM Systems GmbH)

2023: Young Enterprise: Non-contact measuring system for breathing, heartbeat and heart sounds (Sykno GmbH)

2024: Young Enterprise: FlexSense – Electroactive Polymer (EAP) stretch and pressure sensors (matelligent IDEAS GmbH with ZeMAG GmbH and Saarland University, Figure 6.3)

6.2 Biochemical and Chemical Measurements

Seven innovations received the AMA Innovation Award in this field, almost one in every year. This is an indication of the wide spectrum in this field, but perhaps also of the greater maturity of solutions in the physical domain. The awards are evenly spread between the gas and the liquid phase with three and four awards respectively. The great difference is that all four innovations for gas sensing offer a broad application spectrum, while the three innovations for the liquid phase are fairly specific with two addressing monitoring of brewing processes (Plan B by Senorics, also honored as winner in the category Young Enterprise, and InQGuard Brew QWX43 by Endress+Hauser), the third targeting lubrication and hydraulic oils (fluid-FOX by MicroResonant Technologies, also double winner as Young Enterprise). The first three innovation awards for gas sensor solutions seem to indicate that this is a field for large companies (the highly integrated BME680 multisensor by Bosch Sensortec and dielectric excitation gas sensing by GE Research) or consortia (NDIR gas sensor technology platform by Micro-Hybrid Electronic, Siegert TFT and 5microns together with CiS Forschungsinstitut) which also reflects the complexity in gas sensing with large concentration ranges and highly complex gas matrices. However, in 2024, Faradaic Sensors received the award for Young Enterprises

with their Micro-Electro-Chemical Sensor (MECS) (Figure 6.4) technology showing that even in this field, novel solutions find their way from research institutes to the market via spin-offs.

2018: Bosch BME680 – first miniaturized, integrated chemical gas sensor (Bosch Sensortec GmbH)

2019: Innovation Award and Young Enterprise: Plan B – a compact analytical system for microbreweries (Senorics GmbH)

2020: Innovation Award and Young Enterprise: fluidFOX – the clever online fluid analyser (MicroResonant Technologies GmbH)

2021: Dielectric excitation gas sensing (General Electric Research Center)

2021: InQGuard Brew QWX43 – multiparameter measurement as a cloud-based sensor for fermentation (Endress+Hauser SE+Co. KG)

2022: Technology platform for highly reliable NDIR gas sensor systems (Micro-Hybrid Electronic GmbH, CiS Forschungsinstitut, Siegert Thin Film Technology GmbH, 5microns GmbH)

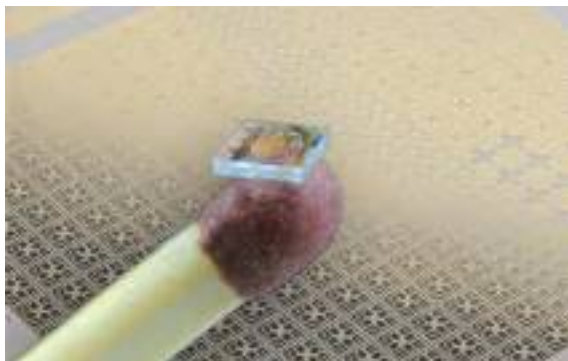


Figure 6.4 Micro-Electro-Chemical Sensor (MECS) technology (Source: Faradaic Sensors GmbH)

2024: Young Enterprise: Micro-Electro-Chemical Sensor (MECS) technology (Faradaic Sensors, Figure 6.4)

6.3 Electronics, Information Technologies, Communication

This field is obviously a domain for young enterprises, which is mainly due to the fact that, here, we find enabling technologies applicable for various markets and applications and some-

times with seemingly narrow applications such as the THz absolute power detectors by SLT Sensor und Lasertechnik. But this technology contributes significantly to extending the use of THz sensing and spectroscopy by enabling comparison of different THz sources and systems. Similarly, the innovations by 2pi-Labs and Ackision enable technologies allowing new applications. These then address primarily physical measurands in the case of the D-Band FMCW Software Defined Radar – such as μ m-accurate distance measurements, high-resolution thickness measurements, radar imaging for NDT or precise material characterization for process control – and (bio-)chemical measurands with the FUSE technology, a fast and low-noise current measurement down to femtoampere with large dynamic range. The latter is especially interesting for different GC and IMS detectors to improve the overall system performance in terms of detection limits, linearity, and resolution. Other innovative solutions result from the use of advanced signal processing and analysis, making use of machine learning for measurement applications. Two examples are the innovations by SENVISYS and HCP Sense: vibration analysis in combination with AI is used to increase safety at railroad crossings while the “sensor bearing without a sensor” addresses bearing condition monitoring offering load and lubrication state determination without additional mechanical parts by integrating impedance spectroscopy (Figure 6.5).

2017: Young Enterprise: Detectors for absolute power measurement in the THz spectral range (SLT Sensor- und Lasertechnik GmbH with PTB)

2018, Young Enterprise: Efficient security for level train crossings using vibration analysis (SENVISYS GmbH)

2021: Young Enterprise: 2π SENSE – D-Band FMCW Software Defined Radar (2pi-Labs GmbH)



Figure 6.5 Sensor bearing without a sensor
(Source: HCP Sense GmbH)

2022: Young Enterprise: Sensor bearing without a sensor – measure rolling bearing forces within the existing installation space (HCP Sense GmbH, Figure 6.5)



Figure 6.6 FUSE - Capture femto to microamperes quickly and with low noise
(Source: Ackision GmbH)

2022: Young Enterprise: FUSE – Capture femto to microamperes quickly and with low noise (Ackision GmbH with Leibniz University Hannover, Figure 6.6)

6.4 Manufacturing Technologies

The Innovation Award winner 2024 (Figure 6.7) is a prime example for heterogenous integration. The photonic integrated FMCW single chip LiDAR by Scantinel Photonics opens new application fields for the well-known LiDAR principle for ambient sensing by integrating the necessary optical and electronic components on one single chip. This offers advanced miniaturization and greatly reduced costs to open up new applications for LiDAR beyond autonomous driv-

ing, i.e., in robotics and household appliances for autonomous lawnmowers or vacuum cleaners.

2024: Photonic integrated FMCW single chip LiDAR (Scantinel Photonics GmbH)



Figure 6.7 AMA Innovation Award 2024. From left to right: Prof. Dr. Andreas Schütze (Jury Chairman), Jin Wang, Dr. Michael Richter (both Scantinel Photonics GmbH), Peter Krause (AMA Chairman of the Board)
(Source: AMA)

This brief overview can only show a few of the exciting innovations in the field of sensors and measurement science. Many more can be found in the complete list of nominations and applications for each year's AMA Innovation Award. Also, the level of innovation cannot be described in the few lines here, which can only highlight the main focus of each innovation. When looking more closely, many innovations could also be assigned to other categories because physical and (bio-)chemical measurands require significant improvements of electronics, system integration and/or data analysis to achieve their full performance. All of the innovations, however, demonstrate the interdisciplinary nature of sensing and measurement, spanning the spectrum from physical and chemical basics and principles over material science and systems engineering to metrology and data analysis. And all of these innovations provide valuable solutions for improving science and technology and, ultimately, our society.

References Chapter 6

AMA Association for Sensors and Measurement, AMA Innovation Award

<https://www.ama-sensorik.de/en/science/ama-innovation-award> (accessed on: March 11th 2025)

Annex

Table A1: Comparison of different assembly and connection technologies for high-temperature use

Technology	Maximum operation temperature $T_{\max}$	Advantage	Disadvantage
Anodic Bonding	>400 °C [BRI-2004]	Extremely high shear strength	High voltage [BRI-2004]]
Eutectic Bonding Au/Si	~350 °C [LI-2017]	Low bonding temperature	Oxide layer removal required
TLP-Bonding (FlipChip) Au/Sn	400 °C [AAS-2010]	higher resulting melting temperature	Comparatively low shear strength
TLP-Bonding (FlipChip) Cu/Sn	675 °C [LIU-2011] 415 °C [CHE-1994]	Higher resulting melting temperature	Comparatively low shear strength
TLP-Bonding (FlipChip) Au/In	400 °C [WEL-2010] 454 °C [LEE-1993]	Higher resulting melting temperature	Comparatively low shear strength [OTT19]
TLP-Bonding (FlipChip) Ag/In	500 °C [CHU-2002]	Higher resulting melting temperature	Comparatively low shear strength
Reactive multi-layer foil	515 °C [OTT-2023] 1000 °C [IND-2021]	Flexible foil activation	Not automated yet
Silver sintering	900 °C [KRA-2013] 960 °C [HAD-2023]	High thermal and electrical conductivity	Expensive
Ceramic adhesives (ZrO ₂)	2200 °C [FIN-2021]	Extremely high temperature range	Low high temperature adhesive strength
High-temperature epoxies	260 °C [FIN-2023]	Inexpensive	Outgassing possible
Wire bonding Al/Al (pad/wire)	200 - 300 °C [GRY-1994, JOH-2008]	Inexpensive, high adhesion	Corrosion, electromigration
Wire bonding Al/Au (pad/wire)	125 °C [HEI-2013]	Reliable, frequently used	Pore growth, intermetallic phases
Wire bonding Al/Cu (pad/wire)	250 °C [BIS-1984]	Halide avoidance influences corrosion	Hard, galvanic corrosion
Wire bonding Al/Pd (pad/wire)	200 °C [TIJ-1999]	No Kirkendall voids	Interdiffusion zone at high temperature possible
Wire bonding Cu/Al (pad/wire)	150 °C [HO-2023]	More stable in a vacuum	Oxygen content influences strength
Wire bonding Cu/Au (pad/wire)	250 °C [HAR-2010]	pad microstructure determines strength	Strength-reducing ductile phase

Technology	Maximum operation temperature $T_{\max}$	Advantage	Disadvantage
Wire bonding Cu/Cu (pad/wire)	150 °C [HEI-2013]	No inter-metallic phases	Oxidation at high temperature
Wire bonding Au/Al (pad/wire)	250 °C [JOH-2008]	$T_{\max}$ higher than Al/Au; for pad thickness > 1 µm	From 5 µm: Au pad degradation
Wire bonding Au/Au (pad/wire)	500 °C [SAL-1998] 515 °C [OTT-2023]	Very corrosion-resistant, diffusion advantageous	Expensive
Wire bonding Au/Pt (pad/wire)	350 °C [HEI-2013]	Tensile strength equal to Au/Au	Expensive, high contact pressure
Wire bonding Au/Pd (pad/wire)	(250...350) °C [HEI-2013]	No brittle intermetal phases, fast process	High hardness
Soft soldering	< 450 °C [DIN-2023]	Widely used	Susceptible to oxide surfaces
Hard soldering	450 °C < $T_{\max}$ < 900 °C [DAV-2021]	More stable than soft soldering	High thermal load
High temperature soldering	> 900 °C [DIN-2023]	More stable than hard soldering	High thermal load
Glass soldering	(350...700) °C [MÜL-2022]	Gas-tight, chemically resistant	Primarily limited to glass materials
Welding	515 °C [OTT-2023]	Suitable for a variety of materials, automatable	Conductivity, hardness defines strength

References Annex

[BRI-2004] Danick Briand, Patrick Weber, Nicolaas F. de Rooij, Bonding properties of metals anodically bonded to glass, *Sensors and Actuators A: Physical*, Volume 114, Issues 2–3, 2004, Pages 543–549, ISSN 0924-4247, <https://doi.org/10.1016/j.sna.2003.10.070>.

[LI17] Li D, Shang Z, She Y, Wen Z. Investigation of Au/Si Eutectic Wafer Bonding for MEMS Accelerometers. *Micromachines* (Basel). 2017 May 15;8(5):158. doi: 10.3390/mi8050158.

[AAS-2010] Aasmundtveit, K.E.; Luu, T.T.; Nguyen, H.V.; Johannessen, R.; Hoivik, N.; Wang, K.: Au-Sn fluxless SLID bonding: Effect of bonding temperature for stability at high temperature, above 400 °C. In: 3rd Electronic System-Integration Technology Conference (ESTC) IEEE, 2010, S. 1-6

[LIU-2011] Liu, H.; Salomonsen, G.; Wang, K.; Aasmundtveit, K.E.; Hoivik, N.: Wafer-Level Cu/Sn to Cu/Sn SLID-Bonded Interconnects with Increased Strength. In: *IEEE Transactions on Components, Packaging and Manufacturing Technology 1* (2011), Nr. 9, S. 1350–1358

[CHE-1994] Chen, Y.C.; Lee, S.J.; Lee, C.C.: High temperature Cu-Sn joints manufactured by a 250 °C fluxless bonding process. In: *Multi-Chip Module Conference (MCMC) IEEE*, 1994, S. 206–211

[WEL-2010] Welch, W.C.; Najafi, K.: Gold-indium Transient Liquid Phase (TLP) wafer bonding for MEMS vacuum packaging. In: *21st International Conference on Micro Electro Mechanical Systems IEEE*, 2008, S. 806–809

[LEE93] C.C. Lee, C.Y. Wang, G. Matijasevic, "Au-In bonding below the eutectic temperature," in *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, vol. 16, no. 3, pp. 311–316, May 1993, doi: 10.1109/33.232058.

[OTT19] R. Ottermann, R. Knöpke, M.C. Wurz: Elektrische Kontaktierung bauteilinhärenter Dehnungsmessensorik mithilfe des Transient Liquid Phase (TLP) Bonding, *MikroSystemTechnik Kongress*, Berlin, 2019

[CHU-2002] Chuang, R.W.; Lee, C.C.: Silver-indium joints produced at low temperature for high temperature devices. In: *IEEE Transactions on Components and Packaging Technologies 25* (2002), Nr. 3, S. 453–458

[[OTT-2023]] Direct-Deposited Thin-film Strain Gauges for High-temperature Applications, R. Ottermann, N. Kyoushi, M.C. Wurz., *MikroSystemTechnik Kongress*, Dresden, 2023

[IND21] Indium Corporation, Product Data Sheet NanoFoil, Form No. 98569 R4, 2021, <https://documents.indium.com/qdynaemo/download.php?docid=4811> (accessed on: March 11th 2025)

[KRA-2013] S. Kraft, S. Zischler, N. Tham, A. Schletz: Properties of a novel silver sintering die attach material for high temperature - high lifetime applications, in *Proceedings AMA SENSOR 2013*, DOI: 10.5162/sensor2013/B3.3

[HAD23] S. Haderler, Y. Long, R. Ottermann, F. Dencker, J. Twiefel and M. C. Wurz, "Influence of Microscale Tin Particles on Mechanical Properties of Silver Sintering Joints with Reduced Processing Parameters," 2023 IEEE 73rd Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 2023, pp. 676–681, doi: 10.1109/ECTC51909.2023.00118.

[FIN-2021] Final Advanced Materials, Technical Data Sheet Zirconium Oxide-Based Adhesives, France, https://www.final-materials.com/gb/index.php?controller=attachment&id_attachment=244 (accessed on: March 11th 2025)

[FIN-2023] Final Advanced Materials, Technical Data Sheet Epoxy Adhesives, France, https://www.final-materials.com/gb/index.php?controller=attachment&id_attachment=13 (accessed on: March 11th 2025)

[GRY-1994] Gryzbowski, R.R.; Kerwin, D.B.: High Temperature Reliability of Al/Au and Au/Au Wire Bonds. In: *2nd High Temperature Electronics Conference*, 1994, S. 9–14

[JOH-2008] Johannessen, R.; Oldervoll, F.; Strisland, F.: High temperature reliability of aluminium wire-bonds to thin film, thick film and low

temperature co-fired ceramic (LTCC) substrate metallization. In: Microelectronics Reliability 48 (2008), Nr. 10, S. 1711–1719

[HEI-2013] W. Heiermann: Entwicklung mikroelektronischer Kontaktierungsmethoden für Hochtemperatur-Anwendungen über 250 °C, Dissertation, Duisburg-Essen, 2013

[BIS-1984] Bischoff, A.; Aldinger, F.: Reliability criteria of new low-cost materials for bonding wires and substrates. In: 34th Electronic Components Conference, 1984, S. 411–417

[TIJ-1999] Tijssen, E.: Ball bonding of palladium wire on aluminium bond pads. In: International Symposium on Microelectronics, 1999, S. 734–739

[HO-2003] Ho, H.M.; Lam, W.; Stoukatch, S.; Ratchev, P.; Vath III, C.J.; Beyne, E.: Direct gold and copper wires bonding on copper. In: Microelectronics Reliability 43 (2003), Nr. 6, S. 913–923

[HAR-2010] Harman, G.: Wire Bonding in Microelectronics. McGraw-Hill Professional, 2010

[SAL-1998] Salmon, J.S.; Johnson, R.W.; Palmer, M.: Thick film hybrid packaging techniques for 500 °C operation. In: 4th International High Temperature Electronics Conference (HITEC) IEEE, 1998, S. 103–108

[DIN-2023] Schweißtechnik: 5: Hart- und Weichlöten, ISBN 9783410316046, Deutsches Institut für Normung, Beuth Verlag 2023

[DAV-2021] Welding technology, J. Paulo Davim, ISBN 9783030639853, Springer, 2021

[MÜL-2022] Untersuchung von Grenzflächenreaktionen von kristallisierenden Glasloten bei der Fügung von Hochtemperaturbrennstoffzellen, 2022, Melanie Müller, Würzburg, 2022, Dissertation, urn:nbn:de:bvb:20-opus-296871

Team of authors

Lead authors

Professor Dr. Klaus Stefan Drese

Hochschule Coburg, (ISAT)

Dr. Julia Osten

Fraunhofer-Institut f. Photonische Mikrosysteme IPMS

Dr. Tilman Sauerwald

Fraunhofer IVV

Professor Dr. Andreas Schütze

Universität des Saarlandes

Professor Dr. Marc Christopher Wurz

Leibniz Universität Hannover

Professor Dr. Stefan Zimmermann

Leibniz Universität Hannover

Co-authors

Dr. Johannes Barth

Siemens AG

Dr. Sebastian Bengsch

Ensinger GmbH

Ole Behrmann

Fraunhofer-Institute for Silicon Technology ISIT

Dr. Maik Bertke

LPKF Laser & Electronics AG

Björn Betz

Fraunhofer Institute for Photonic Microsystems
IPMS

Professor Dr. Kai Bongs

Deutsches Zentrum Luft- und Raumfahrt

Silke Bramlage

Baker Hughes

Dr. Helmut Budzier

TU Dresden

Professor Dr. Heinz Burtscher

Fachhochschule Nordwestschweiz

Sascha Dessel

VDI/VDE Gesellschaft Mess- und Automatisierungstechnik

Kevin Diex

Fraunhofer-Institute for Electronic Nanosystems
ENAS

Niklas Droese

Leibniz Universität Hannover

Dr. Wolfgang Drahm

Endress+Hauser Flowtec AG

Dr. Vikas Dubey

Fraunhofer-Institute for Electronic Nanosystems
ENAS

Dr. Wolfgang Eberhardt

Hahn Schickard

M. Ebermann

Institut/Firma fehlt noch

Gilbert Erdler

Siemens AG

Dr. Magnus Fischer

Kistler Instrumente AG

Dr. Sven Fleck

obsurver UG

Dr. Jörg Gebhardt

ABB AG

Professor Dr. Gerlach Gerald

TU Dresden

Dr. Bjoern Gojdka

Fraunhofer-Institute for Silicon Technology ISIT

Torsten Hampel

TU Dresden

Dr. Olaf Hild

Fraunhofer IPMS

Rüdiger Hild

Baker Hughes

Dr. Dominik Hoheisel

Baker Hughes

Ireneusz Jablonski

Fraunhofer IPMS

Dr. Ulrich Kaiser

Endress + Hauser

Alexander Kassner

Leibniz Universität Hannover

Dr. Daniel Klaas

Leibniz Universität Hannover

Dr. Ansgar Kirk

Ackision GmbH

Peter Klöfer

Endress+Hauser Level+Pressure

Jannik Koch

Leibniz Universität Hannover

Dr. Steffen Kurth

Fraunhofer Institut for Electronic Nano Systems
ENAS

Dr. Thomas Lehmann

TU Chemnitz

Professor Dr. Volker Lohweg

Technische Hochschule Ostwestfalen-Lippe

Dr. Lukas Lorenz

Fraunhofer IPMS

Dr. Christian Meyer

Renesas Electronics Germany GmbH

Jan Müller

Baker Hughes

Marco Neubert

in.hub GmbH

Dr. Benjamin Nuß

Karlsruher Institut für Technologie (KIT)

Dr. Dragana Popovic Renella

SENIS AG

Tim Prangemeier

Heimann Sensor GmbH

Maren Prediger

Leibniz Universität Hannover

Dr. Tino Pügner

Fraunhofer Institute for Photonic Microsystems
IPMS

Tobias Reichenstein

FAU Erlangen-Nürnberg

Dr. Nooshin Saeidi

Fraunhofer-Institute for Electronic Nanosystems
ENAS

Dr. André Schäfer

hottinger brüel & kjaer gmbh

Dr. Michael Scholles

Fraunhofer Institute for Photonic Microsystems
IPMS

Dr. Marion Simon

Heimann Sensor GmbH

Dr. C. Thomas Simmons

AMA Verband für Sensorik und Messtechnik
e.V.

Sasa Spasic

SENIS AG

Antje Steller

Baker Hughes

Dr. Chris Stöckel

Fraunhofer-Institut ENAS

Jürgen Uebbing

NCTE AG

Fiete Stoll

Fraunhofer-Institute for Electronic Nanosystems
ENAS

Sebastian Wöckel

ifak Institut für Automation und Kommunikation
e.V.

Dr. Fabian Stoppel

Fraunhofer-Institute for Silicon Technology
ISIT

Professor Dr. Jürgen Wöllestein

Universität Freiburg (IMTEK)

Pascale Taube

AMA Verband für Sensorik und Messtechnik
e.V.

Henri Zeller

Fraunhofer-Institute for Silicon Technology
ISIT

Ansgar Thilmann

HCP Sense GmbH

Professor Dr. André Zimmermann

Hahn-Schickard-Gesellschaft für angewandte
Forschung

Professor Dr. Henning Trsek

Technische Hochschule Ostwestfalen-Lippe

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VDI Verein Deutscher Ingenieure e.V.
VDI/VDE-Gesellschaft
Mess- und Automatisierungstechnik
Sascha Dessel
Tel. +49 211 6214-678
dessel@vdi.de
www.vdi.de