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Sensor Trends 2014

Trends in Future-Oriented Sensor Technologies

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Editorial Team

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1 Introduction, Objectives, Limitations

1.1 Introduction and Objectives

This study is a supplier-neutral overview from the AMA Association for Sensor Technology of the expected short-term to medium-term technological developments in electromechanics and gas-sensor technology. Its orientation is strictly technological and as such is not a marketing study.

The aim of the study is to provide support to anyone who wants to obtain a quick overview of the main technological developments behind the physical and gas-sensor technology, especially in view of feasible development strategies. The target groups comprise decision makers in high-technology fields, such as sensor suppliers and governmental agencies for funding programmes.

In practically all branches of industry and modern life, such as in mechanical and plant engineering, the automotive and aerospace industries, entertainment and consumer industries, medical technology and life sciences, as well as in safety and security technology, sensors and measuring devices have become indispensible. In fact, there is hardly any industrial area that can do without measuring, testing, monitoring, or automation. The value chain extends from detection of process parameters in process technology to the analysis of product characteristics in the entire productive industry. Sensors are to be found in ever growing numbers even in everyday households. With the help of sensor technology, the ability to manufacture products with unique features, but without significantly increasing production costs is more and more successful.

In this high-tech area, Europe – and particularly Germany – are in the top position worldwide, not only in regard to the technological standard, but also in view of global market shares. As for turnover, a comparison between commercial studies regarding the demand (see (1) or (2) for example) and the results of the polls carried out by the AMA Association (3) regarding the supplier market, shows that European suppliers cover about 35% of the worldwide demand on sensor products (4).

The number of manufacturers of industrial sensors and measuring systems in Europe alone is estimated by the AMA Association for Sensor Technology to comprise almost 1,000 enterprises. Overall there are approximately 3,000 companies from makers to retailers, from engineering consultants to specialized service providers that are active in European sensor tech-

nology. The figure for jobs directly in measuring technology, not counting peripheral equipment or peripheral activities, is estimated at 290,000 employees in Germany alone. With sales and sensor-specific services they generate 30 to 40 billion euros. At an average yearly rate of 9% (not including the years 2008 and 2009), the growth of European sensor technology is about four times as fast as the EU economy as a whole. Even in the crisis year 2009, the German export quota of sensor and measuring technology achieved 47%. If we include the additional indirect exports of machines, plant equipment, and other products, in which sensor and measuring systems are integrated, it can be surmised that approximately 80% of the German sensor and measuring equipment is exported.

The biggest sensor trade fair is the annual SENSOR+TEST in Nuremberg, an event organized under the auspices of the European AMA Association. All in all, Europe is thus among the worldwide top sensor suppliers, not only in regard to turnover, but also in view of the capability of technological innovation.

The market for sensor technology is very inhomogeneous and very hard to segment even for those involved. These, however, are experiencing a noticeable shift from the market for capital goods to the market for consumer goods with an increasing importance of end products. Therefore, the market for sensors in consumer end products is generally growing at a faster rate than for those in process measuring and control technology. New applications with considerable growth rates are found in household appliances, safety and security technology, medical equipment for diagnosis and therapy, biosensorics, and automotive engineering. The greatest growth rates, however, are to be found in image sensors, acceleration sensors, pressure sensors, position and proximity sensors as well as in biochemical sensors. All in all, prices can be said to be falling, while quantities are rising.

1.2 Purpose of the Analysis

Using selected areas of application as examples, this study bundles the experience of the authors from the research facilities organized within the AMA Association Science Board.

The focus is not on completeness, but rather on the elaboration of some major trends. The paper considers development trends in sensor technology for measuring mechanical, calorific, and chemical parameters, such as pressure, flow, temperature, distance, speed, acceleration, force, torque, ph-value, concentration and composition of gases and liquids.

The focal points are:

- → Principles for measuring physical, chemical, and biological parameters
- → Electronic assembly and packaging
- → Functions and methods of signal processing
- → Sensor-signal interfaces and transfer, including wireless transmission with autonomous energy management, bidirectional communication, and networks
- → System integration: sensor systems and directly coupled sensor-actuator systems
- → Interference tolerance of sensors and sensor systems: automated fault detection, diagnosis, and correction (AFDDC)
- → Testing and calibration technology

Due to the extremely broad application spectrum of sensor technology in all branches of industry and fields of application – from R&D and automated production to control and monitoring of product characteristics – the study is limited to the following areas of application, which are to serve as examples:

- → Process, energy, and environmental engineering
- → Mechanical engineering
- → Automotive engineering
- → Medical technology / life sciences
- → Consumer goods

The Terms "Sensor" and "Measuring Principle"

The term "sensor" is variously interpreted. In this study, it is used as a superordinate term describing any component that generates a usable electrical signal from a measured physical parameter, as illustrated in **Fig. 1.1**. In its simplest form, a sensor consists merely of a naked sensor element, for instance an unhoused pressure sensor element made of silicon, mounted on a substrate, no more than a few millimetres exterior dimension.

The term "measuring principle" (also referred to as the "active principle") is understood to mean the principle of physical or chemical conversion resulting in a usable electrical signal.

Further terms used in this study are defined in the Glossary, Chapter 7.

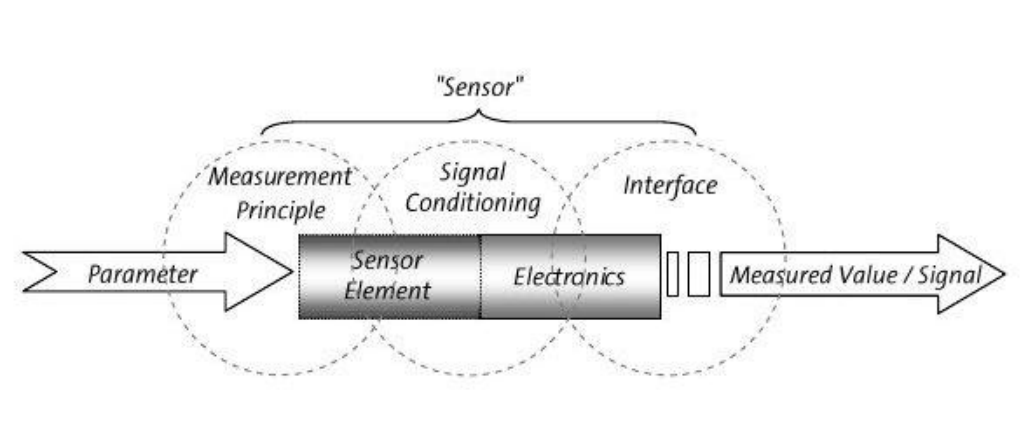


Fig. 1.1: Classification of the term “sensor”: A measuring parameter is converted into an internal signal by means of the physical measuring principle of the sensor element. After possible signal conditioning, a measured value is available at the output as a usable or electrical signal – for example, luminous intensity as an analogue voltage.

1.3 Typical Areas of Application and Requirements

The deduced development trends are to be evaluated for concrete areas of application. This evaluation is based on different sensor requirements in the respective areas of application. (see **Table 1.1** and **Table 1.2**).

Table 1.1: The Selected Areas of Application

Sensor Type	**Area of Application Under Examination**
Process sensors	Process, energy, and environmental technology
Industrial sensors	Mechanical engineering and plant automation
High-reliability mass sensors	Automotive engineering (cars and commercial vehicles)
Specialized sensors, extracorporeal and intra-corporeal	Medical technology / life sciences
Mass sensors	Consumer goods

Table 1.2: Typical Sensor Characteristics for the Selected Areas of Application

Characteristic	Process, Energy, and Environment Technology	Mechanical Engineering	Automotive Engineering	Medical Technology / Life Sciences
Quantities*	5 - 100 T	20 - 200 T	> 1 Million	1 - 100 T
Price	50 – 1,000 €	20 - 200 €	1 - 10 €	50 - 100 €
Measurement uncertainty	0.1 – 0.5%	0.5 - 1%	1 - 5%	1 - 5%
Installed size**	< 20x20x20 cm^3	< 5x5x5 cm^3	< 2x2x2 cm^3	< 5x5x5 cm^3
Energy consumption	< 0.1 W	< 0.1 W	< 0.01 W***	< 0.01 W
Analogue output	4 - 20 mA	0 - 10 V	0.5 – 4.5 V	Voltage
Digital output	Profibus, FF-Bus, HART	ASI, CAN, Interbus	CAN, wireless technologies	-

* Typical annual production figures of a sensor supplier
** Depending on site and type of housing
*** In the exhaust tract > 5 W

Moreover, sensor technology is gaining in importance in safety and security technologies (**Table 1.3**).

Table 1.3: Selected Sensor Tasks in Safety and Security Technologies

Application	Sensor Type
Analysis of drinking water	Chemical sensors
Air analysis	Chemical sensors
Warnings of natural catastrophes (storms, inundation, tsunamis, earthquakes, volcanic eruptions)	Physical sensors
Detection of liquid and solid explosives	Chemical and physical sensors, radiation sensors, image processing

Autonomous sensor networks are gaining in significance. The areas targeted for application range from environmental monitoring to health-care monitoring and elder-care management as well as for household assistance (“ubiquitous computing”, “smart home”, “ambient web”). Greatly increasing production quantities are expected in these areas, but at present figures are still difficult to ascertain.

1.4 Requirements in Selected Areas of Application

Basic user requirements and wishes in regard to sensors are (5):

- → Attainment of minimal measuring uncertainty
- → Constant availability of physical and chemical data from all systems and processes
- → Measurements are to be performed with minimal impact on the processes involved
- → Measuring values are to be available in real time
- → Sensors should function without maintenance, calibration, or adjustment
- → Sensor should work with minimal interference and a minimum of care
- → Sensor and sensor-system costs should be as low as possible
- → Sensors are to be equipped with integrated “on-board” diagnostics

In this context we are able to perceive that some of the requirements are contradictory, e.g. minimal measuring uncertainty vs. cost. Typical requirements and their evaluation as to quality according to selected fields of application are listed in **Table 1.4**.

Table 1.4: Qualitative Evaluation of Typical Requirements According to Selected Fields of Application

Requirement	Vehicle	Mechanical Engineering	Household	Process Technology	Medical Technology
Price	+++	++	+++	+	++
Measuring uncertainty	O	+	O	+++	O
Installed size	+++	+	++	+	+++
Energy consumption	+++	O	++	O	+++
Real-time	++	+	+	+++	+
Minimal impact on measured parameter	O	+	O	+++	+++
Availability	+++	++	+++	+++	O (unique)
Ex-protection	O	+	O	+++	O
Maintenance costs	O	+++	O	+++	O
Standardized interfaces	++	++	++	+++	O
Long-term stability	++	++	+	+++	+
Self-diagnosis	++	++	+	+++	+
Reliability	+++	++	++	+++	+

+++ very important, ++ important, + desirable, O not important

Beyond these qualitative characteristics, each area of application also has special characteristics.

Example: sensors in process technology

The requirements for process sensor technology is at present subject to fundamental changes (5):

- → Application not only for new equipment investments, but increasingly for further optimization of existing equipment
- → Besides the detection of process data, the detection of intermediate and trend data is gaining in importance
- → For specific applications there is a demand for reduced measuring uncertainty of process parameters
- → The desire for data on the spatial distribution of process data is increasing

2 Development Trends – Electromechanical Measuring Principles

Abstract

In the area of sensors based on electromechanical measuring principles, resistive and capacitive methods are still prevalent.

Here is an overview of the major trends:

- → Continued miniaturization
- → Increasing use of MEMS beginning use of NEMS (micro or nano electromechanical systems)
- → Increasing use of silicon measuring elements – also for calorific and chemical parameters
- → Multi-sensors for mass application
- → Increasing use of direct sensor-actuator coupling
- → More robust process coupling
- → Lower measuring uncertainty
- → Increased long-term stability

The active principles of gas sensors are at present still very diverse. Electrochemical and resistive principles dominate the field. The following trends can be discerned:

- → For concentration measurements, physical measuring methods are prevailing
- → For selective gas detection, potential measurements are increasingly prevalent in cost-critical applications; in areas in which the price is acceptable, optical methods prevail
- → Increasing application of silicon MEMS
- → Increasing integration of numerous sensor into a sensor array, e.g. on a hot-plate in conjunction with pattern recognition
- → Increasing miniaturization and integration
- → Increasing production of sensor elements at foundries; this in turn makes the manufacture of complete sensors increasingly lucrative for SMBs (Small and Medium Businesses)

2.1 General

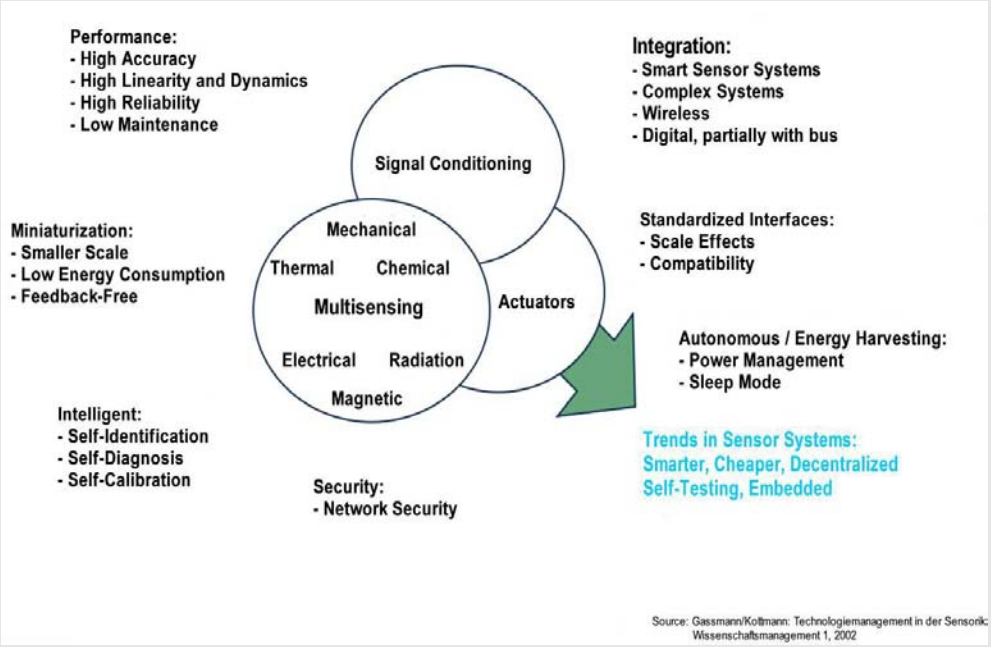


Fig. 2.1: Function integration and trends in sensor technology (6)

Irrespective of the manifold applications and sensor types, some general trends can be discerned (**Fig. 2.1**), the acceptance of which is to be expected despite increasing cost pressure:

1. Increasing proximity of sensors to the measured parameter as well as decreasing impact of the sensors on the parameter through:
   - → Miniaturization
   - → Contactless measuring principles
2. Introduction of novel measuring processes, e.g. for detection of spatially distributed measuring data, such as:
   - → Tomography for industrial application
   - → Impedance spectroscopy
3. Increasing application of energy-autonomous sensors and sensors with wireless communication:
   - → Activation only on demand
   - → Application of various micro-generator principles for autarkic energy generation: piezoelectric, thermoelectric, electromagnetic, capacitive (bio-)chemical (fuel cell), photovoltaic (solar cell)

- → Networked miniaturized measuring sites for collective detection of measuring values and transmission

4. Increasing system integration for mechatronic applications:
   - → Transition to directly coupled sensor-actuator systems for detection and control of local process parameters
5. Increasing holistic sensor design:
   - → Utilization of novel 3D design tools, FEM (finite elements method) computation, Matlab/Simulink, use of comprehensive and exact material data
6. Increasing functional integration based on highly integrated components in sensor electronics and safeguarding of the expanded functionality:
   - → Pattern detection, additional data acquisition
   - → Self-monitoring
   - → Interference detection and diagnosis
   - → Self-calibration (self-adjustment) and reconfiguration
   - → Derivation of data for preventive maintenance
   - → Integrated communication interface
     (TEDS, IEEE 1451)
   - → Plug and play
   - → Localization (positioning)
7. Utilization of highly integrated components for real-time signal conditioning and processing:
   - → High resolution and fast A/D conversion
   - → Single-chip microprocessors
     µC, FPGA, DSSP (digital sensor-signal processor)
   - → Programmable logic devices (PLDs)
   - → Semiconductor memories
   - → Coupling modules for electrical interfaces (wired, wireless)
8. Coupling of physical, chemical, and biological sensors on a single sensor element, e.g. for pressure measurement, pH-value measurement (animal husbandry), lab on a chip, lab on a disc
9. Increasing production of sensor elements by specialized suppliers (foundries); thus making production of complete sensors increasingly lucrative for SMBs

2.2 Selected Measuring Principles

2.2.1 Sensors for Physical Measuring Parameters

For the application fields in this study (**Table 1.1**), the subarea of sensors based on electro-mechanical measuring principles, resistive, land capacitive methods prevail. In the middle term, the measuring principles listed in **Table 2.1** will dominate.
Here an overview of the major trends:

- → Miniaturization
- → Increasing MEMS and beginning NEMS
  (micro or nano electro-mechanical systems)
- → Increasing silicon measuring elements, also for calorific and chemical parameters
- → Multisensors for mass application
- → Increasing direct sensor-actuator coupling
- → More robust process coupling
- → Decreasing measuring uncertainty
- → Increasing long-term stability

Table 2.1 Measuring Principles Dominating in the Middle Term

Measuring Principle	**Comments**
Resistive and piezoresis-tive	Film, thick-film, thin-film strain gauges, crystalline effects in silicon
Capacitive	Ceramic or silicon with thin-film electrodes
Magnetic	Hall and magnetoresistive elements (AMR, GMR, TMR), on semiconductor or thin-film basis
Piezoelectric	Quartz, Ceramic, lithium-niobate, langasite with thick-film and thin-film electrodes
Ultrasound and microwave sensors	Runtime and Doppler measuring processes
Resonant	BAW and SAW structures on quartz or silicon basis
Optic	Reflection processes, interferometers, fibre Bragg gratings, principles using semicon-ductor and solid-state lasers, LWL, photodiode cells

The following trends can be discerned in physical measuring principles:

1. Among the sensors for mechanical parameters, resistive and capacitive methods maintain their present prevalence
2. Decreasing measuring uncertainty for selected applications by optimizing packaging technology and retroactive impact on the measuring value
3. Increasing application of silicon as a substance for measuring elements for various physical parameters, besides pressure and acceleration, also force, humidity, and temperature
4. Utilization of silicon allows further reduction of sensor-element size by application of micromechanics
5. Use of electromechanical converters, such as Si-pressure plates or Si-cantilevers for detecting calorific (humidity, temperature) and chemical parameters, e.g. with piezoresistive measuring elements and sensitive polymer coating
6. Increasing utilization of silicon multi-sensors for mass applications
7. Detection of multiple measuring values with a single sensor element
8. Detection of spatial distribution measuring parameters by means of sensor arrays
9. Increasing directly coupled sensor-actuator systems, e.g. optical scanner systems (DVD), control valves (pressure, flow, settings parameters, ...), micro-positioning systems, (smart) orthotic and prosthetic, haptic displays, etc.
10. Great increase in application of micro and lately also of nano electromechanical systems (MEMS and NEMS)

Here an itemized list of prevalent development trends:

2.2.1.1 Resistive Sensors

This includes stain gauges, thick-film, thin-film on metallic deformation elements or ceramics. The relative proportion of these principles will remain nearly stable.

- → Foil strain gauges (k-factor approx. 2):
  Pressure sensors (1 to 5.000 bar), force and torque
  - → Miniaturized foil gauges < 2 x 2 mm²
  - → Novel substrate and conductor materials
  - → Continued development of deformation elements, novel materials
  - → Integration in machine components (adaptronics) and textiles, e.g. in carbon fibres

- → Thick-film resistors on ceramic substrates:
  Pressure sensors (1 to 100 bar)
  - → Pastes with high k-factor > 10
  - → Deformation elements with LTTC ceramics (flexible forming, also for low production quantities, capability of establishing electric contacts)
- → Thin-film resistors (k-factor 2 to 3) with isolating layers on metallic deformation elements:
  - → Pressure (0.1 to 1,000 bar), force and torque sensors
  - → Optimization of substrates and passivation layers

2.2.1.2 Piezoresistive and Capacitive Silicon Sensors

- → Continued miniaturization, e.g. pressure sensor elements with a surface area < 0.5 x 0.5 mm²
- → Integration into sensor systems with low energy consumption
- → Application of the capacitive principle in precision sensors as differential capacitors with defined dielectric
- → Direct allocation of primary electronics as a single-chip or two-chip solution

2.2.1.3 Ultrasound and Microwave Sensors

- → Ultrasound silicon miniature sensors with an area of < 1 x 1 mm²
- → Configuration into an ultrasound sensor array with directional radio effect
- → Tomography with ultrasound and/or microwave methods

2.2.1.4 Resonance Sensors

- → Miniaturized quartz or silicon bulk acoustic wave (BAW) sensors
- → Surface acoustic wave (SAW) sensors
- → Use of new materials, such as lithium-niobate, langasite, etc. (greater temperature ranges)

2.2.1.5 Integrated Optical Sensors

- → Bragg fibre grating arrays for strain gauges and temperature measurement
- → Miniaturized optical solid-state resonators on semiconductor basis, e.g. neodymium YAG (yttrium-aluminium-garnet) crystals
- → Miniaturized spectrometers, fully adjustable semiconductor lasers

Special Significance of Silicon as a Measuring Element Material

Based on its excellent elastic characteristics as well as its very good selectivity in regard to electrical and chemical attributes, silicon will continue to gain significance as a substance for sensor elements. The following trends are expected especially for these sensors and their associated measuring principles:

- → Increasing significance for measurement of various physical parameters, such as pressure, acceleration, and force, but also of humidity and temperature
- → Continued increase in the importance of electromechanical transducers, such as Si pressure plates or Si cantilevers for determining various parameters (piezoresistive measuring element + sensitive coatings)
- → Wide-spread application thanks to minimal dimensions of sensor arrays for determining local distribution of a given parameter (applications: automotive engineering, medical technology, household appliances, safety and security technology, medical care, etc.)
- → Integration of sensor electronic components / primary electronics into the silicon element itself
- → Greater use of silicon multisensors for determining various physical parameters simultaneously, e.g. differential pressure, static pressure and media temperature
    - → For mass applications with multiple measuring parameters on a single sensor element
    - → For bundling physical, chemical, and biological sensors on a single sensor element, e.g. pressure + pH-value measurement (animal husbandry), lab on a chip, lab on disc, etc.

- → Special development trends, such as:
    - → Further miniaturization, e.g. on surface areas < 0.5 x 0.5 mm² (medical technology)
    - → Increased stability of monocrystalline and polycrystalline structures
    - → Application of porous silicon layers for the production of deformation elements, e.g. pressure plates
    - → Extended temperature ranges of up to 350 °C (SOI deposition)
    - → Transition from volume micromechanics to surface micromechanics
    - → Extended pressure ranges of up to 5,000 bar
    - → Piezoresistive miniature force sensors

- → Piezoresistive full-bridge strain gauges on steel elements with integrated primary electronics
- → Determination of moisture and pH-value (through the swelling of polymer coatings)

2.2.2 Gas sensors

Sensor Elements

The active principles of gas sensors are at present still very diverse. As yet there is no single technological approach, such as e.g. silicon micromechanics for physical sensors. Usually, the technology involved is adapted to the specific application and to the available in-house technology at the sensor supplier. Nevertheless, some technological trends can be discerned and described with the keywords miniaturization and integration. Electrochemical and resistive principles dominate the field:

- → For concentration measurements, physical measuring methods are taking hold
- → For selective gas detection, potential measurements hold sway in case of cost-critical applications; when prices are acceptable or if demanded by the application, optical methods are used
- → Increasing use of silicon MEMS (hot plates)
- → Increasing integration of multiple sensors on a single hot plate (sensor arrays), also used for pattern detection
- → Increasing miniaturization and integration

Two general development trends in sensor elements for chemical parameters are:

1. Thanks to improved reproducibility and long-term stability of available sensors, the chemical parameters gas concentration and liquid concentration can be measured by means of physical methods. The signal conditioning involved is often expensive, but is getting cheaper.
2. New measuring tasks and requirements are constantly arising, the solution of which are at present being realized by contending principles. Usually, the most inexpensive system is used – after a holistic selection taking the cost aspect into account.

Just as for physical sensors, transducers are being increasingly produced in silicon micromechanics (hot plates). Since foundries are now able to supply silicon micromechanics, this

technology is increasingly suited for MSBs. The transition to silicon micromechanics is not only due to the availability of inexpensive mass production, but also due to the inherent advantages offered by silicon micromechanics, such as a reduced energy consumption, which in turn enables battery powered operation, or the ability for thermal cycling, which allows an increase in selectivity. Based on the same principle, thermal conductivity sensors can be made for H_2 detection.

In research, even higher application temperatures are being used, e.g. by high-temperature Si hotplates. SiC micro-hotplates, or low-temperature co-fired ceramic (LTCC) hotplates.

The trend is towards the integration of multiple sensors on a single hotplate (sensor arrays). Thanks to pattern recognition, new applications can be opened in such areas as:

- → Safe and early fire detection
- → Medical technology
- → Food selection
- → Quality assurance in the life-sciences industry

Depending on the specific application, these may be in combination with 3D-MID or microfluidic elements.

In the near future the following tendencies will compliment rather than replace the present sensor principles:

- → Potential instead of resistive measurements
  Novel workfunction based sensors for selective gas detection at ambient temperatures are already being developed; direct and indirect thermoelectric gas sensors for detection of VOCs are being developed.

- → Optical methods
  Promising are attempts to apply optical principles for selective sensors. Examples are NH_3 or O_2 detection with the aid of laser diodes, or CO_2 sensors based on miniaturized NDIR systems priced for consumer goods. Whether the laser-diode technology will hold sway depends to a certain degree on the price tendency of laser diodes, but also on the attained degree of system miniaturization. For the measurement of minute concentrations, the long optical path may lose out to cost-effective miniaturization.

→ Methods for selectivity increase
For increasing selectivity, attempts are being made to apply catalytic filters and/or absorption filters; work on micro-gas chromatographs (µ-GC) were also successful. Thermal cycling of the sensor temperature can also increase selectivity if evaluated accordingly. These processes can also be combined with the use of sensor arrays.

The same applies for chemical sensor systems as for physical sensors. A/D conversion and sensors are being brought closer together. Analogue signal conditioning is increasingly being replaced by digital signal processing in a very early state. Whenever cost-effective, sensors and signal processing are being integrated in a single housing. In a way, the µC is thus becoming a part of the sensor component. By such means, characteristics, such as bus capability, self-monitoring, or even self-calibration can be realized.

In automotive engineering, the two-wire principle (CAN bus) with a current signal will in part prevail.

3 Development Trends – Sensor Electronics and Semiconductor Technologies

Abstract

In general it can be observed that the relatively simple sensors of the past are turning into increasingly integrated and intelligent sensor systems boasting hardware with ever greater capabilities. Depending on the application, signal conditioning is analogue, digital, or provided as a mixed signal. The trend is towards early digitalization and digital signal processing. The functionality of the sensor is increasing. Sensors are increasingly able to perform correction computations, compensate cross-sensitivity, provide application-specific algorithms, carry out self-monitoring, and contain their own communication interface. This greater capability also includes:

→ Faster signal processing with a lower noise level and higher resolution
→ Lower energy consumption
→ Greater maximum ambient temperatures
→ More compact dimensions
→ Increasingly reports on error states or threshold values instead of the mere transmission of measured values

In the majority of applications after electronic conversion of the measuring parameter this is also processed. Improvements and innovations in sensors are thus being attained more and more not only by further development of the measuring element itself, but through parallel development of the primary electronics and sensor-specific signal processing. By effectively optimizing the primary sensor, signal conditioning, and signal processing, a greater efficiency can be achieved than would be possible by only optimizing the measuring element itself.

3.1 Design

In regard to the design of sensor electronics, the following trends may be observed:

1. System design, architectural design, and circuit design increasingly mesh and are becoming more complex. The development of sensor systems is tending towards:
   - → Ever higher resolution
   - → Increasing complexity, e.g. due to local performance of data reduction, more efficient interfaces, etc.
   - → Greater sophistication of compensation, linearization, calibration, and signal processing
2. Sensor-system design is generally top down (**Fig. 3.1**):
   - → Specifications and verification as early as possible at various levels of abstraction
   - → Step-by-step system simulation
3. In order to design complex systems more effectively, IPs (digital function blocks and analogue macrocells) are used. These must be represented at different abstraction levels to enable corresponding simulations.

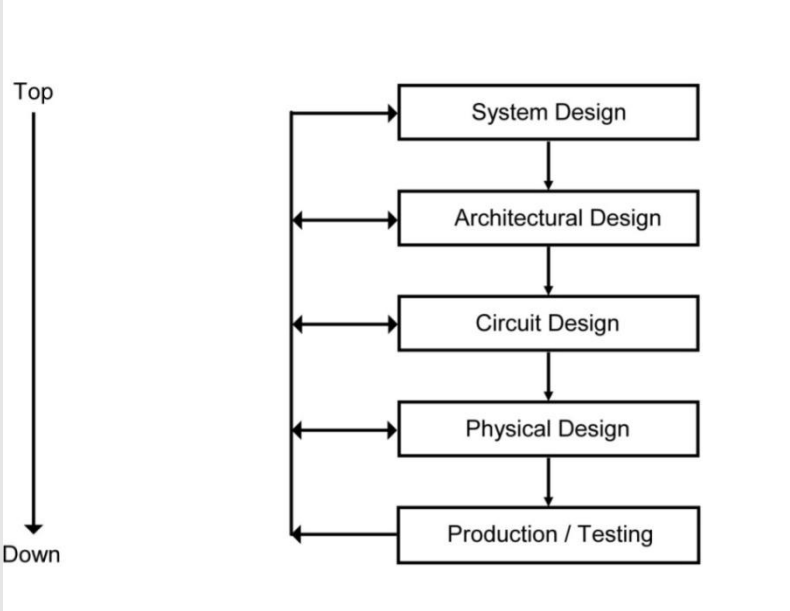


Fig. 3.1: Design methodology for sensor systems

3.2 Functionality of Sensor Electronics

In many applications, mainly where decentralized sensor nodes are being used, for instance in automotive engineering and in automation technology, but also in environmental monitoring or in ambient intelligence, sensor electronics are increasingly assuming not only the task of signal conditioning, but also of evaluating the measured value, self-monitoring, and communication. Increasingly, communication with super-ordinate control levels entails not measurement values, but rather threshold or interference values. Thus, instead of continuously sending current temperature values, an intelligent sensor will only transmit a report when a critical set temperature is exceeded. This not only reduces the bandwidth for networked sensor nodes, but also the required processing performance of the superordinate level.

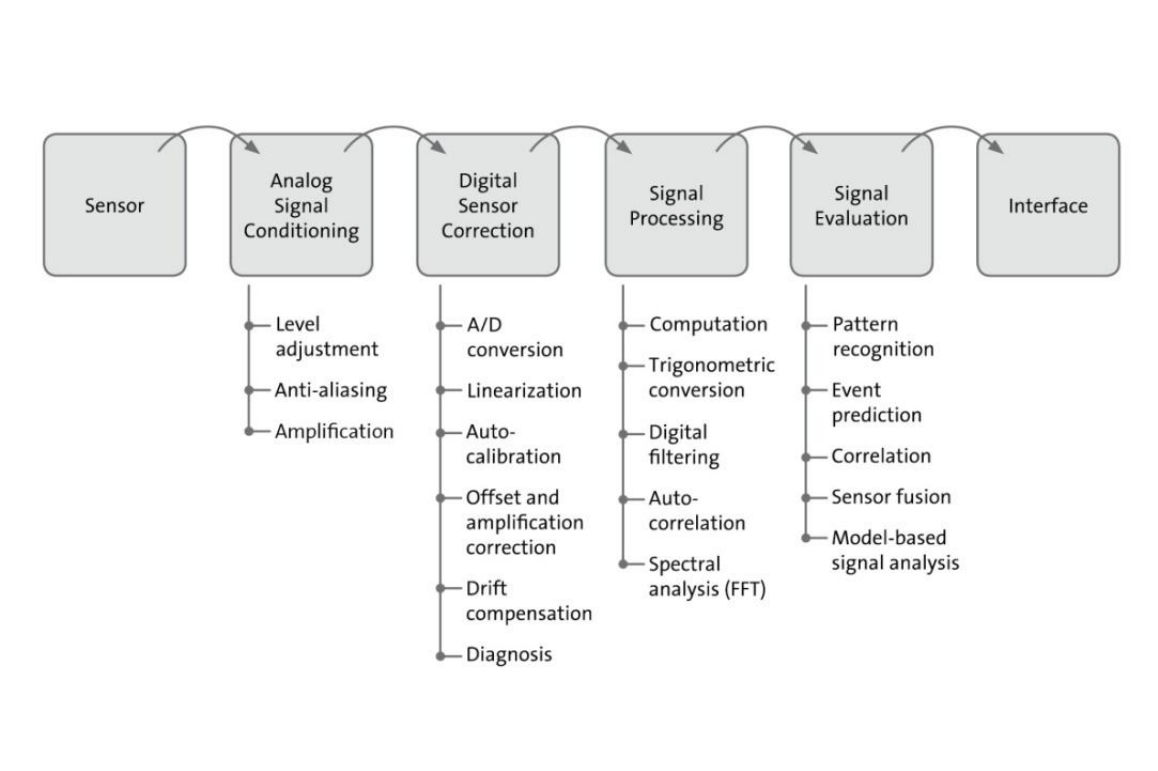


Fig. 3.2:Function blocks of sensor electronics for intelligent sensors

Analogue Signal Conditioning

Analogue signal conditioning is the first step towards a sensor system, preparing the sensor signal for A/D conversion. Since the output signals of the sensor often have a low level, noise reduction is an important consideration. If necessary, the signal bandwidth is reduced by an analogue low-pass filter to prevent aliasing in subsequent processing steps. Level adaptation and amplification adjust the dynamic range of the output signal to fit the control range of the A/D converter. Frequently, amplification is carried out by an instrumentation amplifier or a programmable gain amplifier.

By means of a sensor correction computation, systematic errors are compensated as necessary and possible. This correction often includes linearization or autocalibration. If required, compensation for offset and amplification errors or a correction of the temperature range can be implemented. Especially for safety and security applications, diagnostics or self-monitoring functions can be provided.

Digital Signal Processing

The purpose of digital signal processing is to further improve the measuring signal (e.g. by improve the signal-to-noise ratio, add digital filtering, or autocorrelation computation) or it is used to derive secondary parameters from the raw data of the transducer. Examples can be found for position sensors in which the computation of an angle is derived from the magnetic field values or by the determination of typical frequency spectrums through FFT computation.

Intelligent sensors often not only transmit measurement values, but rather asses this value and pass on the value of this assessment, in simple cases as an indication that an upper or lower threshold was exceeded. By this means the bandwidth for complex systems as well as the required processing capability of the superordinate levels can be reduced. A comparison of the processed measuring signal with respective threshold values, complex patterns, or model-based signatures follows. If necessary, the signals of further sensors are included at this level for complex evaluations or confirmation of the results by plausibility checks.

Sensor interfaces often contain a serial digital bus interface, such as CAN, LIN, I2C, HART, or SPI, or increasingly a wireless interface, such as ZigBee.

The demand of many users for improved maintainability of sensor systems is increasingly being satisfied by storing sensor-specific correction data in a non-volatile memory. This allows replacing individual sensors without recalibration. A standard data format is provided by IEEE1451.

3.3 Implementation of Sensor-Signal Processing

Along with the further development of simple sensors into highly integrated sensor systems, the following trends can be observed in the implementation of sensor-signal processing:

Reduced analogue signal conditioning, increased digital processing

As opposed to the classic analogue signal conditioning, digital signal processing offers considerable advantages:

- → Greater stability, reliability, and reproducibility
- → Greater flexibility, easier implementation of variants, modifications, or extensions, as well as adaptive evaluations

→ Better cost degression

The importance of analogue signal conditioning is thus increasingly reduced to adapting the output signal of the transducer to the input voltage range of the analogue-digital converter. The requirements for resolution and speed of A/D converters is on the rise – signal processing is in the digital domain. An example of signal filtering clearly shows the advantages: While the implementation of small-band or adaptive analogue filters demands a considerable effort for circuits and space requirements as well as compromises in the stability of the filter characteristics, digital implementation is comparatively simple.

Use of Highly Integrated Components

Despite increasing functionality, component size, dissipation loss, and costs are nevertheless required to remain low. Microcontrollers offer high functional density at low cost as well as a high degree of flexibility. Highly integrated analogue or mixed-signal interface components are also becoming increasingly available.

CMOS Analogue Circuits Instead of Bipolar Analogue Circuits

Better noise characteristics, lower power consumption for fast circuits and low offset values are the basic upsides of bipolar technologies of high-grade analogue circuits. Nevertheless, there is an obvious tendency towards CMOS-based sensor interface components. Thanks to their advanced circuitry and technology performance, downsides can be compensated and higher integration density utilized.

3.3.1 Components for Analogue Signal Conditioning

The data sheets of modern, powerful operational amplifiers reflect the advances made in analogue CMOS circuit technology: high bandwidths, low noise, low supply voltage, low power consumption, low space requirements thanks to small housing dimensions, and low cost characterize many of the components found on today's market. Based on special process options for analogue performance, noise ratios with CMOS transistors attained 2.7 nV/⊕Hz at 10 kHz and an extremely low power consumption of 1 µA.
Operational amplifiers today work with supply voltages of only 1.8 V, tending towards even further reduction. Together with low power consumption, solutions for network independent applications have become feasible.

Parallel to this development, the functionality of sensor interface components is being extended. The ZMD21013, for instance, supports multiple sensors and is especially characterized by its low power consumption. During normal operation, the ZMD21013 only requires 25 to 30 µW. In standby mode, this value drops down to 1 µW. The MUSic family is optimized for battery-operated mobile devices that operate with multiple sensors, controlled by microcontroller.

3.3.2 Analogue-Digital Converters

The requirements for analogue-digital converters (ADCs) for sensor signal conditioning are continuously being increased. A few years ago, resolutions of 8 or 10 bit were sufficient for most applications; today, however, 12 to 14 bit and more are required.

In the area of sensor signal conditioning, successive approximation converters and increasingly sigma-delta converters are being applied today.

These architectures are well suited for implementation in CMOS technology because they have comparatively few analogue components. Thus they profit from technology scaling regarding reduced area, increased speed, and lower supply. Moreover, these architectures allow the increased operating speeds of modern CMOS technologies for an increased sampling rate, and increased resolution, i.e. accuracy.

Continued development of the technology and circuitry will enable a further increase in resolution or accuracy of ADCs in sensor signal conditioning.

3.3.3 Microcontroller Units (MCUs) and Digital Signal Controllers (DSCs)

Many embedded sensor applications of today use microcontrollers for signal conditioning. They are available in performance classes of up to 32 bits. For computation-intensive applications, DSCs can be used that provide fast real-time as well as computation-intensive processing for digital signal processing. MCUs and DSCs can be obtained with various numbers of analogue inputs and ADCs. The resolution of the A/D converters is usually 10 or 12 bits, often as successive approximation converters. Single MCUs, e.g. from Analog Devices, have a 14-bit pipeline ADC e.g. TIs sigma-delta ADCs with resolutions of up to 24 bits. For network-independent applications, practically all suppliers offer variants with low dissipation loss. Moreover, MCUs and DSCs are available with a variety of bus interfaces (CAN, SPI I2C, LIN, and increasingly wireless interfaces).

This trend in MCUs and DSCs towards greater functionality and higher performance of the analogue interfaces is expected to continue. Thus, they will continue to be an attractive alternative for intelligent sensors with comparatively low development effort and greater flexibility at comparatively low cost. Due to the increasing availability of battery-operated or energy-autonomous applications, reduced power dissipation per processing unit is still one of the development objectives of many suppliers.

3.3.4 Field Programmable Gate Arrays (FPGAs)

FPGAs are a good alternative for processing digital sensor signals where the performance of MCUs or DSCs is not sufficient or where only small quantities are required and subsequent transition to an ASIC is planned. Based on a hardware description language (HDL), which is also the basis for subsequent ASIC implementation, signal processing algorithms can be verified and if necessary corrected (rapid prototyping).

Since FPGAs are usually produced in state-of-the-art semiconductor technologies, their functional density and costs will continue to profit directly from the further development of semiconductor technologies (**Fig. 3.3**).

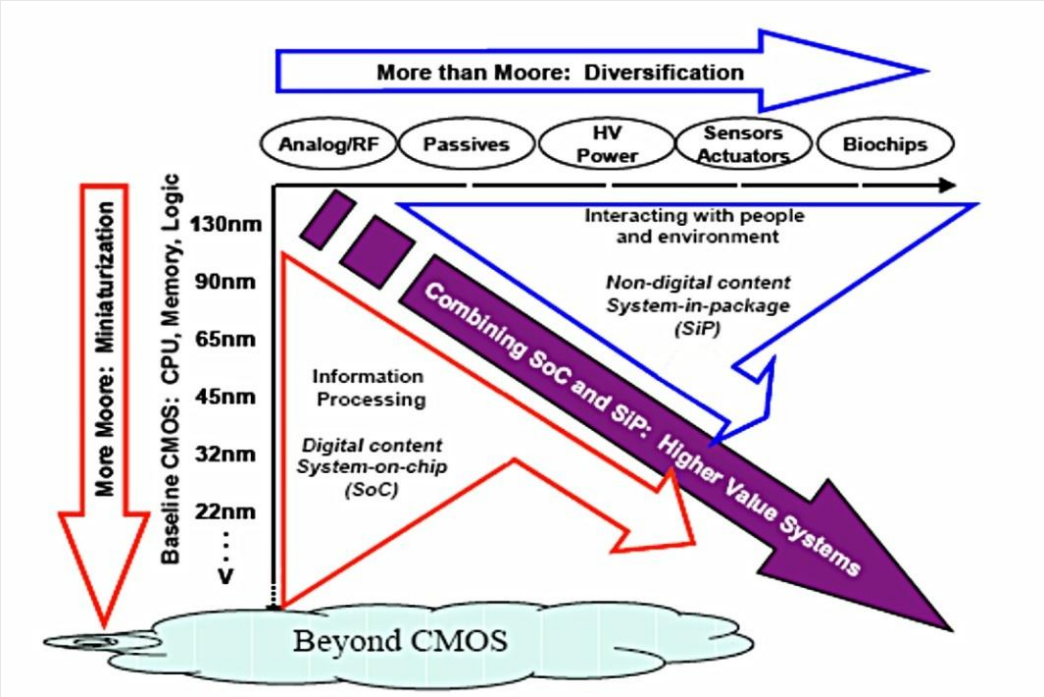


Fig. 3.3: “More than Moore” as a relevant R&D trend in sensor technology (7)

3.3.5 Application-Specific ICs (ASICs)

The development of ASICs is and will continue to be an alternative, whenever a sensor in great quantities is concerned and/or low power dissipation, minimal form factors, and higher copy protection are essential criteria in the choice of signal-conditioning implementation.

Modern ASIC technologies offer the capability to integrate analogue signal conditioning, high-resolution A/D conversion, complex digital signal processing, sequence control, memory, and interface circuits in a single IC of very small dimensions and very low power dissipation. Inputs and outputs can be matched for performance and adjusted to the system specifications. Embedded MCUs, DSCs, or standard bus interfaces can be integrated in the design as verified IPs.

The processing power can by far exceed that of MCUs and is adapted to the requirements. In conjunction with appropriate power management, power dissipation can be minimized.

The integration density of modern semiconductor technologies, enables integration of multiple ICs in to a single ASIC. By this means driver power can be reduced and space requirements, costs, and complexity of the circuitry can be minimized. The reliability is thus increased, since the circuitry requires fewer connections.

The number of ASIC developments for sensor signal conditioning will drop in the next years, because of increasing development costs due to increasing complexity on the one hand, and on the other hand because of increasing performance and decreasing cost of microcontrollers and FPGAs. Nevertheless, ASICs will remain viable wherever high quantities, high processing performance, and low dissipation losses at a low form factor are major requirements, for instance in the area of embedded systems or in ambient intelligence.

3.4 Semiconductor Technology for IC Sensors

The greater part of all digital and mixed-signal ICs is produced today using CMOS techniques. According to all predictions, the predominance of CMOS technology will continue for at least the next ten years.

The roadmap for CMOS technology reflects the well-known Moore's law since over 40 years. Accordingly, the structure size in CMOS technologies is reduced every three years by a factor of ½. The development of high-volume standard products is also being carried out at pre-

sent with 65-nm technology. According to iSuppli marketing research, in 2011 more than 60% of the silicon-based ICs produced worldwide will be manufactured with structure sizes under 130 nm (7). The major reason for this is that with every technology step, the integration density (number of gates / mm²) for digital circuits doubles, thus reducing the cost per function accordingly. The main characteristics of the technology steps, nominal supply voltage, number of metal layers for wiring, package density for logic and mask costs, are listed in **Table 3.1**.

The technological foundation for mixed-signal ICs with a significant analogue portion, such as is typical in the area of sensor signal conditioning, has followed this technological trend in the past with some delay, also for ASICs and ASSPs. In the meantime a trend can be made out in which certain technology steps have a longer service life for new designs as well as for production. There are both technical and economic reasons for this:

- → Based on scaling rules, the maximum permissible supply voltage is also reduced. By this means the usual topologies can no longer be applied in analogue circuitry. It must be assumed that essential characteristics, such as dynamic range or noise will degrade for sensor applications.
- → With small structural sizes, parameter fluctuations significantly increase for adjacent components as well. This also adversely affects the quality of analogue circuitry.
- → For analogue circuits, the size of components (transistors, resistors, capacitors) is not automatically scaled with minimal structure dimensions, it is determined rather by the required circuit parameters (e.g. noise, amplification, bandwidth). Thus the required area for analogue circuits is not automatically scaled by the reduced structure dimensions.
- → As structure dimensions decrease, leakage currents increase exponentially when transistors are turned off.
- → The immense increase in mask costs and the increasing process complexity for the most minute structure dimensions make these technology steps uneconomical for the usual quantities required by sensor applications in many branches of industry (e.g. in automation or automotive engineering).

This development is especially apparent in the mixed-signal area of the well-positioned European ASIC suppliers: 350 nm or 180 nm technologies provide a good compromise in regard to performance (e.g. gate density, switching speed, dissipation loss, supply voltage) and costs (masks and wafers). These are therefore the basis technology for process exten-

sions, such as high-voltage or RF options, non-volatile memories, special devices, which make them interesting for sensor applications.

Table 3.1: Characteristics of CMOS Technology Nodes

Process (µm)	VDD [V]	Metal	Gates per mm²	Mask Set Cost [US $]
0.065	1.0	9	400k	3,000,000
0.09	1.0	9	200k	1,500,000
0.13	1.2	7	100k	750,000
0.18	1.8	5	40k	250,000
0.25	2.5	5	24k	150,000
0.35	3.3	3	12k	40,000
0.5	3.3	3	5k	20,000
0.6	5.0	2	4k	18,000

Notes:
Process (µm): Process nodes as per ITRS roadmap
VDD: Standard supply voltage
Metal: Maximal number of circuit layers
Gate/mm²: Benchmark for number of gates per mm²
Mask Set Cost: Reference value for the cost of a mask set in US$

This trend is also reflected by future exploratory research in the field of micro and nano-electronics in Germany and Europe in general: A major objective of the R&D activities is the expansion of existing digital semiconductor technologies towards platforms for the development of heterogeneous systems (**Fig. 3.3**).

3.5 High Temperature Electronics

Especially in automotive engineering, the requirements for the reliability of sensors and silicon-based sensor signal conditioning are increasing. Ten years ago, sensors/actuators and control devices in vehicles were still spatially separated. Even for applications in the engine, a maximum ambient temperature of 150 °C was thus sufficient for signal conditioning. The spatial bundling of sensor/actuator technology leads to today's requirement of a maximum ambient temperature of 175 °C. The trend towards system integration of electronics and sensors/actuators also leads to further increases of the required ambient temperature. In a few years, the requirement will be at 210 °C. Semiconductor suppliers are increasingly accom-

modating this trend: More and more manufacturers are qualifying their silicon processes and libraries according to the requirements of automobile makers. There are already a number of makers, who are specifying a maximum ambient temperature of 150 °C or even 170 °C with a temperature profile, specifying 1,000 hours for instance at the maximum temperature (8).

3.6 Self-Monitoring and Reconfiguration

The more “intelligence” integrated in a sensor in form of sophisticated signal processing algorithms, the greater the possibilities of self-monitoring and reconfiguration. Self-monitoring of sensors refers to fault (disturbance) detection and interference (noise) diagnosis (9), (10). With the aid of such monitoring processes, sensor reliability, i.e. knowledge of their operating status, increases (**Fig. 3.4**).

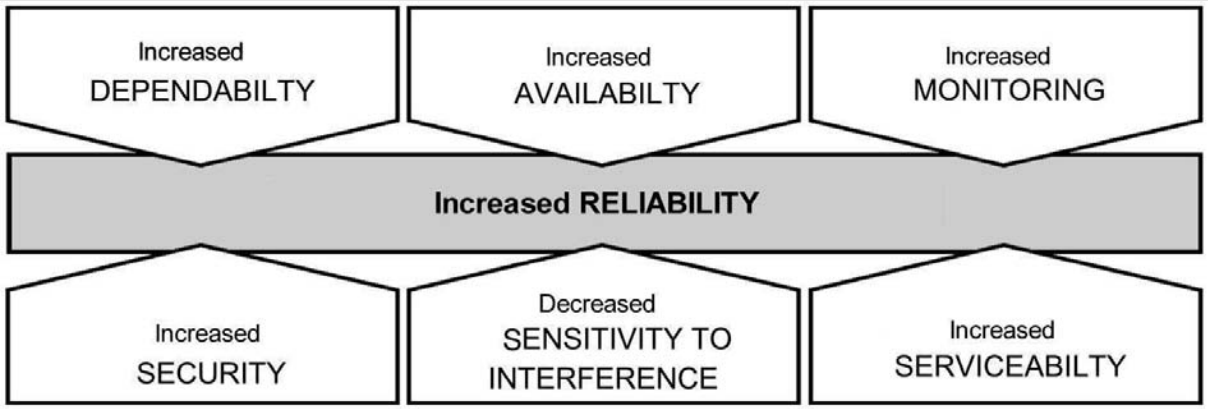


Fig. 3.4: Parameters affecting the increase of reliability as the main objective of sensor self-monitoring (12)

On the other hand, the additional processes for self-monitoring, which also have a limited reliability, effectively reduce the overall reliability of autonomous sensors. Therefore, one of the future aims is to compensate this reduced reliability by adding redundancies in the sensor (10).

As opposed to model-based error detection and error diagnosis of complex mechatronic systems or process plants (10), self-monitoring and sensor configuration is based entirely on information coming from within the sensor. The sensor is thus considered to be an autonomous system (**Fig. 3.5**). This approach is absolutely necessary for sensor suppliers, in order to enable as application-neutral a sensor as possible.

In contrast to error detection and error diagnosis in mechatronic systems, sensor technology refers to disturbances, since the term “error” has, since Gauss, a different meaning: In measuring technology every sensor has permissible errors – uncertainties of measurement.

The method of process coupling requires external data for self-monitoring that do not originate from the sensor itself. In its more basic form this might rely on data exchange between nearby sensors and actuators with subsequent comparison and plausibility checks. More advanced forms of process coupling incorporate computations based on process models. By means of available parameters in the model, such as the measuring signal or actuating variables, the output parameters to be monitored can be computed. Of course these methods require comprehensive knowledge of the process behaviour.

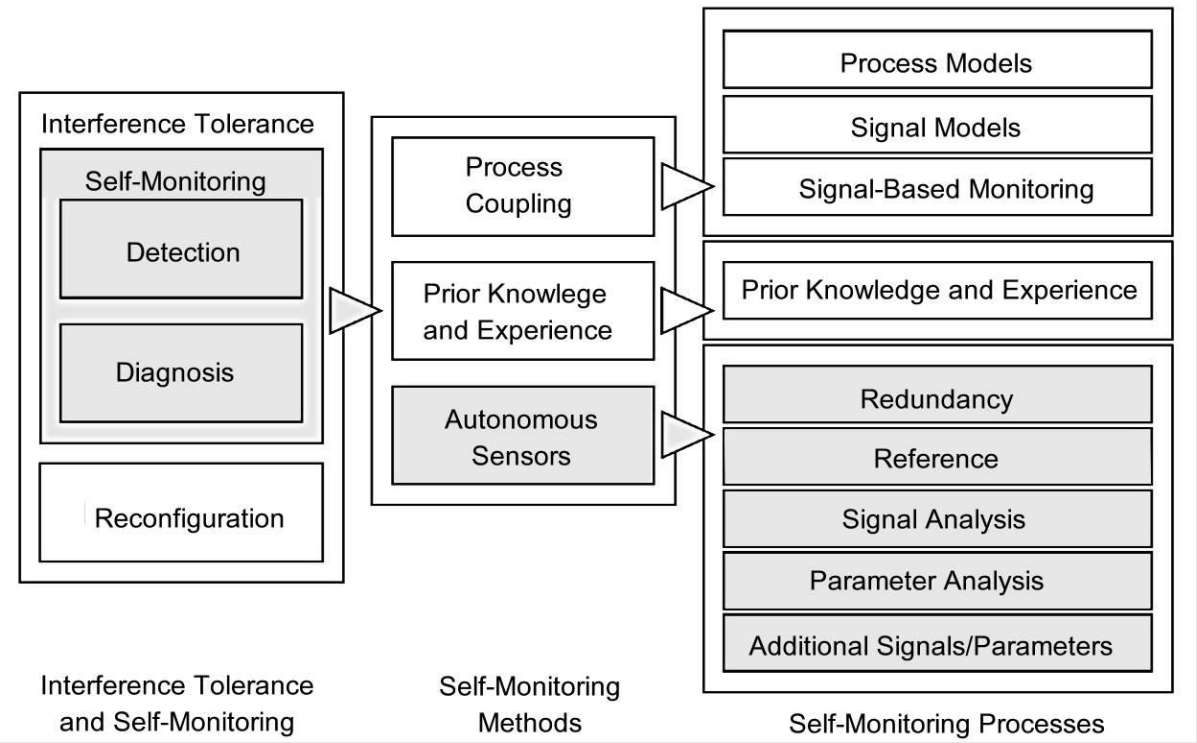


Fig. 3.5: Classification of sensor self-monitoring methods and processes (12)

Only the user has knowledge about the process involved and only he can thus subsequently implement the monitoring algorithm. Model-based processes are at the focus of error detection and diagnosis of mechatronic systems (10). The high development costs required here are borne by the quantities of the systems, e.g. in automotive engineering.

Sensor suppliers, however, want to provide autonomous devices that can be used in a broad range of applications. **Fig. 3.5** shows five self-monitoring processes for autonomous sensors (11) and (12):

- → Application of redundancy
- → Generation of a reference value
- → Analysis of the measuring signal
- → Analysis of the impact of a fault variable
- → Analysis of supplementary signals in the measuring chain

This division is supported by a comprehensive analysis of industrial process sensors equipped with self-monitoring functions (13). Within the 25 different self monitoring process sensors which the study found, the applied methods were distributed as: redundancy 25%, analysis of the measuring signal 20%, analysis of a fault parameter 5%, analysis of supplementary signals 20%.

An intermediate position utilizes pre-knowledge and experience characteristics about the signal. This includes simple threshold monitoring and plausibility tests. Self-monitoring is performed autonomously, but previous knowledge about the process must be available. With available experience-knowledge, this method is easy to implement, e.g. in form of qualitative plausibility tests, and is considered to be very effective (12).

All three of the discussed methods can be integrated in the sensor by applying special algorithms – although for process coupling with some restrictions. In accordance with objectives of the sensor developer, the explanations in **Fig. 3.5** refer to the five monitoring methods mentioned for autonomous sensors

The redundancy method uses redundant signals generated by similar (homogenous) or diversified sources. This can apply to the entire measuring chain or to certain parts. If the signal deviates from a set tolerance, a disturbance has occurred. In the cause of simple redundancy, merely in the fact that a disturbance hat taken place is registered. In case of three or more redundant units, a majority redundancy decision leads to reconfiguration by turning off the deviating unit.

By means of comparison with a reference, the sensor can monitor itself and, if this reference can be applied as input, can recalibrate itself. Intermediate electrical values in the sensor

measuring chain can also be referenced. In this case, monitoring is restricted to the subsequent signal processing blocks.

To analyze the measuring signal, sensor-specific threshold values and trends are monitored. These values are derived from the specific operating conditions of the respective sensor group. A further monitoring possibility is offered by additional information contained in the measuring signal, e.g. higher frequency components in semi-static measurements.

Analysis of disturbance requires evaluating how the undesired, but known effect of the sensitivity to disturbance (cross-sensitivity) affects the various transfer blocks of the measuring chain. This is achieved by detecting the disturbance parameter in a separate measuring channel. Subsequent comparison with the intermediate signals of the disturbed measuring chain, allows identifying, diagnosing and possibly compensating the disturbance.

Supplementary sensor-internal signals or supplementary parameters can be used to determine the actual state of a sensor. This involves signals and parameters that are not transmitted along with the measuring signal, e.g. the supply voltage of measuring bridges, and their resistance parameters. These methods are primarily applied to monitor the sensor electronics (self-testing) and are concentrated on especially vulnerable assemblies and components.

An evaluation of the monitoring methods in (12) and (14) results in the advantages and disadvantages listed in **Table 3.2**.

Progress in sensor self-monitoring is especially being made in the area of complex signal processing in autonomous sensors. Main focus is methods that analyze the measuring signal and the cross-sensitivities to disturbances. However, combinations of various methods and the implementation of known characteristics of the main application areas also seems promising.

The possibilities of sensor reconfiguration are being increasingly explored. A major contribution in this area could come from micro-electromechanical silicon sensors (MEMS sensors) that can be implemented in low-cost arrays to provide the required redundancy. Other approaches are automatic recalibration or specific reduction of sensor functionality and accuracy, i.e. degradation strategies.

Table 3.2: Evaluation of Methods for Self-Monitoring of Autarkic Sensors

Method	**Advantages**	**Disadvantages**
Redundancy	Excellent disturbance detection through diversified redundancy; three or more redundant sensors provide capability to automatically reconfigure, if redundancy diversified, additional capability through signal analysis, reduced measurement uncertainty, achievable through averaging	Redundancy involves considerable effort, there is a risk of superimposing negative sensor characteristics and thus worsening of the entire sensor
Reference	At sufficient reference accuracy, reconfiguration through recalibration is possible, this can be easily implemented by generating an intermediate electrical reference, individual components in the measuring chain are monitored directly	Generating a reference parameter involves great effort, there is a risk of adverse effects on the measurements from operating interruptions
Analysis of measuring signal	Relatively low effort involved to implement the algorithm, utilization of supplementary data, available in the measuring signal can be used to complement other methods	Dependent in part on the process or the specific application, since process characteristics are used
Analysis of disturbance parameters	The output of an additional process parameter is possible, the effect of the disturbance on the output signal of the sensor can be directly corrected, the disturbance parameter can be used for amplification of cross-sensitivity	Setup of a secondary measuring chain for the detection of the disturbance, often insufficient cross-sensitivity
Analysis of supplementary signals and supplementary parameters	This method is applied very selectively, monitoring electronic assemblies and components involves relatively low effort, exact diagnosis of the disturbance cause is selectively possible	Non-electrical assemblies require a greater monitoring effort than electrical ones, monitoring is only for a limited area of the measuring chain

4 Development Trends – Communication and System Integration

Abstract

Driven by increasing quantities and increasing price pressure, many sensor suppliers are moving their creation of value more and more to signal processing, energy management, self-monitoring, and miniaturization. Overall, the cost of ownership is diminishing. The major trends are:

- → Digital interfaces
- → More wireless sensor technology
- → Processing of measurement values
- → Parallel detection of multiple measuring values
- → Autonomous sensor systems
- → Miniaturized sensor networks (smart dust)
- → Self-diagnosis and auto-calibration

A major challenge for sensor technology lies in continuously reducing of constructive efforts required from the application. Besides standardized connectors, this leads to increasingly miniaturized designs, more decentralized signal processing and asynchronous transmission of threshold and disturbance values, instead of the continuous transmission of measured data. Energy management and self-monitoring are also becoming increasingly sophisticated.

Sensors are thereby increasingly being hierarchically networked in hierarchies and the complexity of sensor applications continues to increase along with the technical capacities.

4.1 Wire-Bound Interfaces

Digital interfaces are prevailing more and more, although application-specific interfaces continue to have their place (**Fig. 4.2**). At present, the significant interfaces are:

- → Digital: CAN automotive, EIB/LON, field bus, Profibus, Ethernet, AS interface, FlexRay, I/O Link
- → Analogue: two-wire, 4-20 mA

4.2 Wireless Sensor Technology

Wireless sensing is a new, very promising field in sensor technology. Wireless transmission of measuring data is by no means a novelty, but its potential has only recently become apparent for the industry, commerce, and end-user sectors. A significant number of market participants and applications fragments these sectors. The alluring benefits however bring with them a number of challenges, so that its implementation has progressed slowly up to now.

In the meantime though, continuous developments in this area have overcome many of the disadvantages posed by this new technology, such as a lack of reliability. It is expected that wireless sensing will be accepted by the end users. Through this route it will also find its way into other areas, proving its ability to solve real application problems that by conventional means cannot be solved at all or only with great difficulty. Some sensor companies have already started working in these areas. Thus, wireless sensor technology will open new opportunities (16).

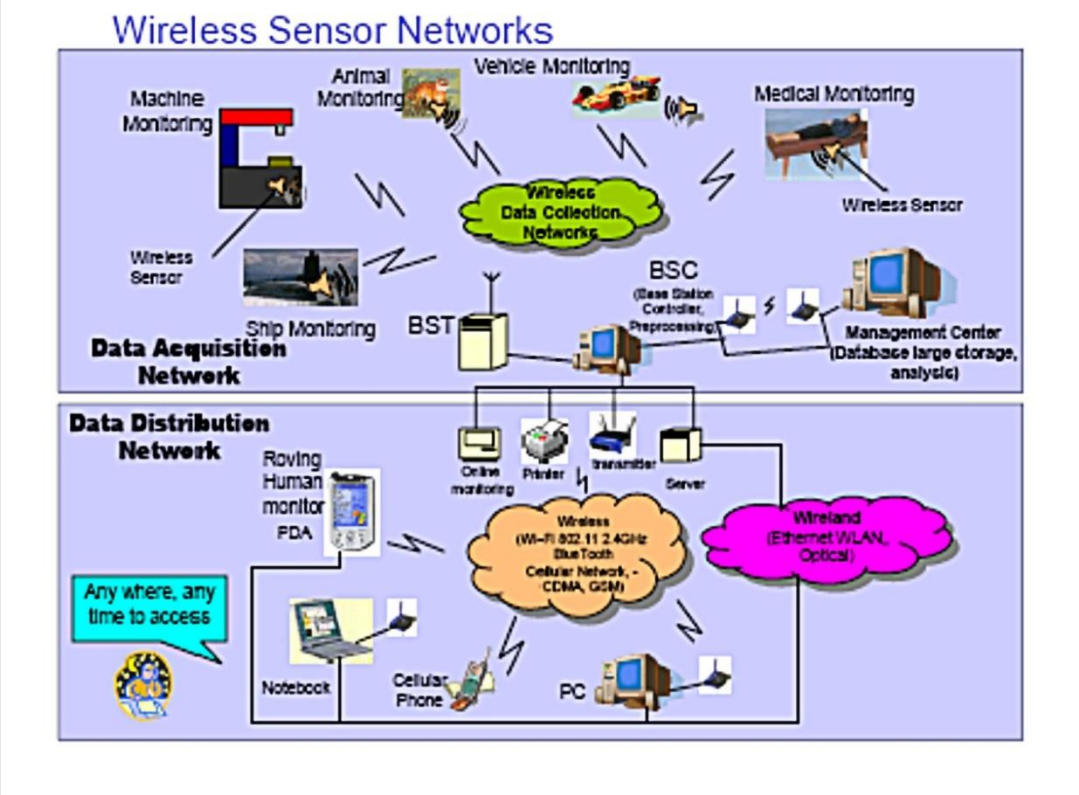


Fig. 4.1: Wireless Sensor Networks (17)

Table 4.1 shows the present standards in wireless sensing.

The frequency ranges of ISM bands used for wireless sensor networks are 433 MHz (radio thermometers, remote controls, meter readers), 868 MHz (alarm systems, remote controls), 2.4 GHz (WLAN, Bluetooth, ZigBee, video transmission, microwaves), 5.6 GHz (not much used yet).

Although the standard products for Bluetooth, ZigBee, and WLAN are available at low cost, they have disadvantages in their capabilities, i.e. high real-time capability (quality of service) usually comes at the expense of high dissipation loss and complexity (guaranteed delay). Proprietary solutions on the other hand offer technical advantages.

Table 4.1: Standard Wireless Networks

Technology	**Wi-Fi**	**ZigBee**	**Bluetooth**
Standard	IEEE802.11b/g/a	IEEE802.15.4	IEEE802.15.1
Data rate	11(b) to 54 (a,g) Mbps	10 ... 115 kbps	721 kbps
RF band	2.4 and 5 GHz	915 MHz; 2.4 GHz 868 MHz in Europe	2.4 GHz
Number of nodes	100+	65.000	8
Range	100 m	10 ... 75 m	8 m (class II, III) to 100 m(class I)
Modulation	DSSS and OFDM	DSSS	FHSS
Topology	Star	Mesh network	Peer-to-peer
Power (typ.)	350 mA	30 mA	65 ... 179 mA (class I)
Battery life	1 ... 3 h	Years (low utilization)	4 ... 8 hours (streaming audio)
Applications	Internet access, computer networks, warehouses, peripheral computer equipment, wireless networks	Wireless sensors, industrial controls, wireless switches, HVAC, meter readings	Streaming audio, mobile phones, peripheral computer equipment, printers, multimedia

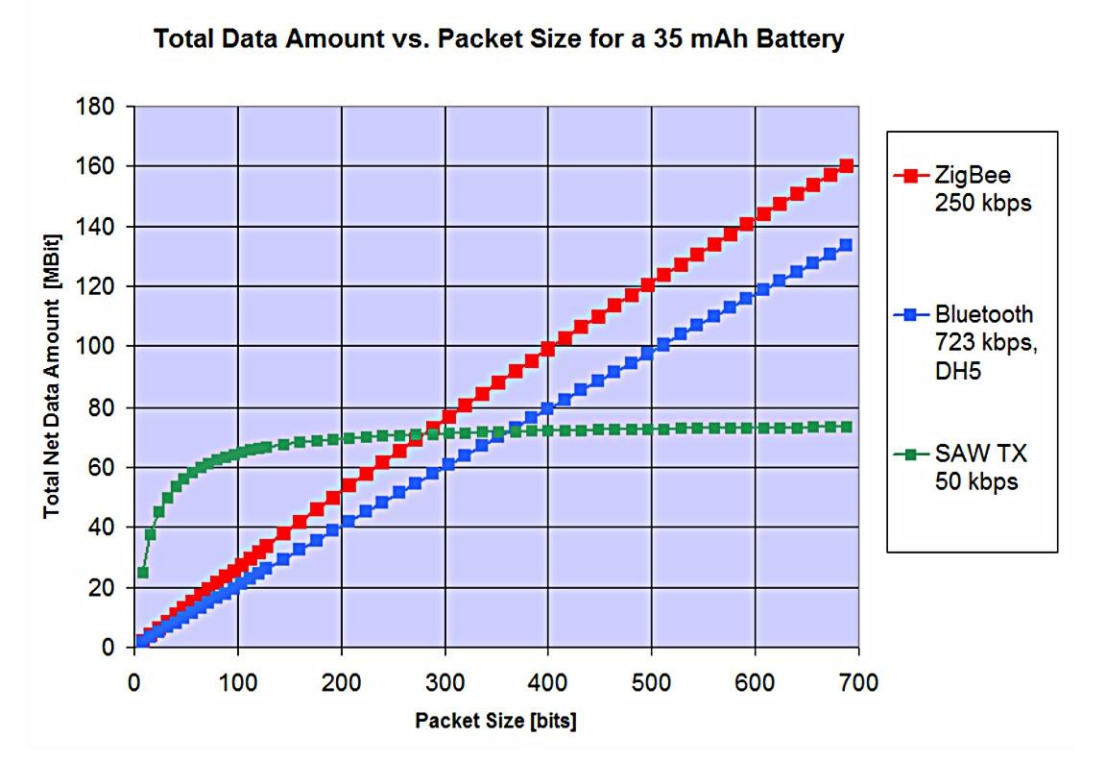


Fig. 4.2: Comparison of transmitted data quantity and packet sizes for various wireless technologies

For instance, beyond a computed data quantity SAW-TX offers a lower protocol overhead compared to standards and thus also has a lower power consumption. Transferring a 32-net-bit data packet every 10 min, for example, the maximum service life of a battery-operated device is:

For SAW-TX	< 28 years
For ZigBee	<< 4 years
For Bluetooth	<< 3 years

In standard applications ZigBee is mostly used for wireless switches, industrial controls, and sensor applications. Further technological developments and standardization efforts support wireless networking such as

- → Ultra-wide-band systems (UWB)
- → Near-field communication (NFC)
- → Wireless USB
- → Wireless Industrial Network Alliance

Embedding sensor networks in available communication networks, gives added significance to the categories space and time which thus need to be addressed accordingly. Often it is of interest where and when a physical event has taken place. Also, the complex interplay between the data from different sensor nodes requires a spatial and temporal reference system. Therefore suitable mechanisms for localizing and synchronizing the nodes in a sensor network have become necessary. Additionally, integration of sensor networks into existing infrastructures and connecting to the Internet are often needed, for instance to allow worldwide access to a sensor network or to enable sensor networks to make use of Internet-based services and resources. Protocols, such as IEEE 802.15.4 or 6LowPAN (IPv6 over low-power wireless personal area networks) function as bridges to low-cost links to the Internet.

4.3 Motes and Smart Dust

The term “mote” is derived from the word “remote” and is applied to miniaturized (multi) sensors with wireless transceivers that collectively detect and transmit measuring values in arrays of hundreds or thousands of nodes. Such arrays are also known as “smart dust”. Thanks to their networkability they enable mapping of remote events. Besides their use in military applications, they are also useful for climate control in buildings, monitoring hazardous environments, medical applications, and for traffic management systems. Their functionality includes energy management, communications, self-monitoring, and the system interface.

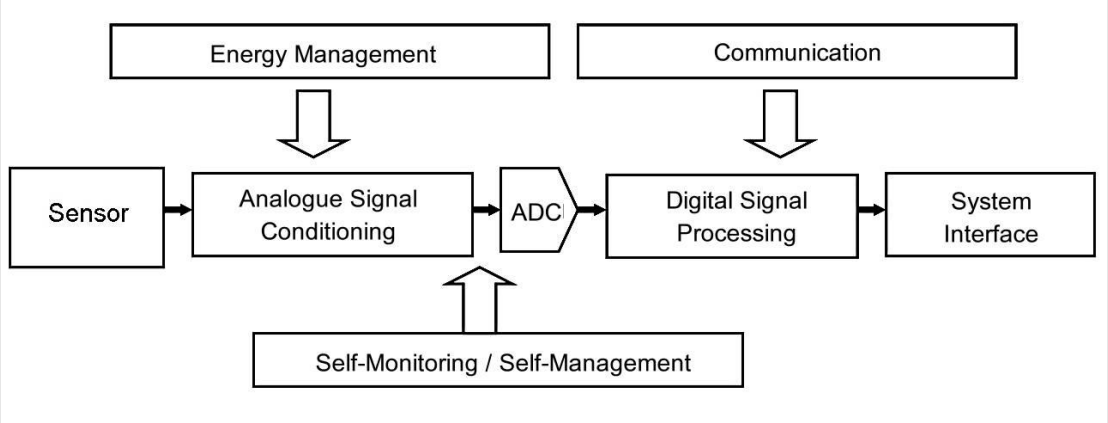


Fig. 4.3: Functionality of smart-dust mote

4.4 Autonomous Sensor Systems

Recent years have seen smart dust and mote concepts become an actual trend towards autonomous, miniaturized sensor systems.

These systems have the functionality of smart dust, but are still considerably larger and designed as heterogeneous microsystems. **Fig. 4.4** shows the size roadmap for heterogeneous, autonomous microsensor systems. Their volume share for energy supply is increasingly determining the dimensions of the overall systems.

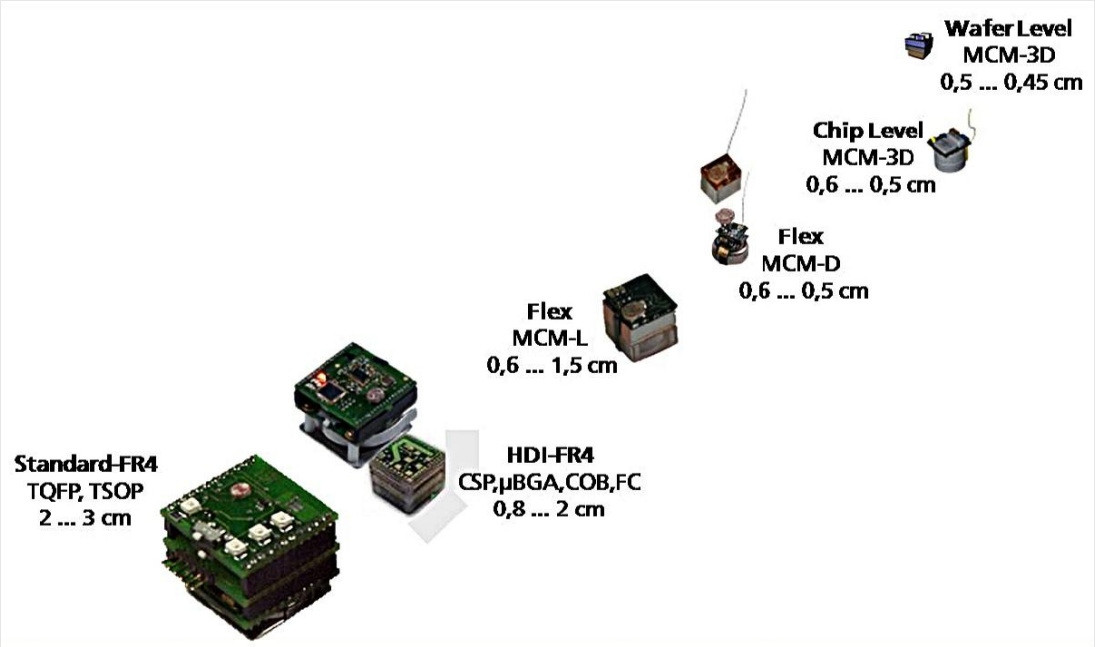


Fig. 4.4: General roadmap for autonomous microsensor systems (image: FhG-IZM)

Autonomous sensor systems are characterized by independent energy supplies and generally by wireless communications. Wire-bound systems use power supply and data-communication provided by conventional two-wire principles.

The major functional groups of autonomous sensor systems are: sensor element(s), signal amplifiers or transducers, microcontrollers, data memories, RF transceivers, antennas, energy supplies, and application-specific multifunctional housings.

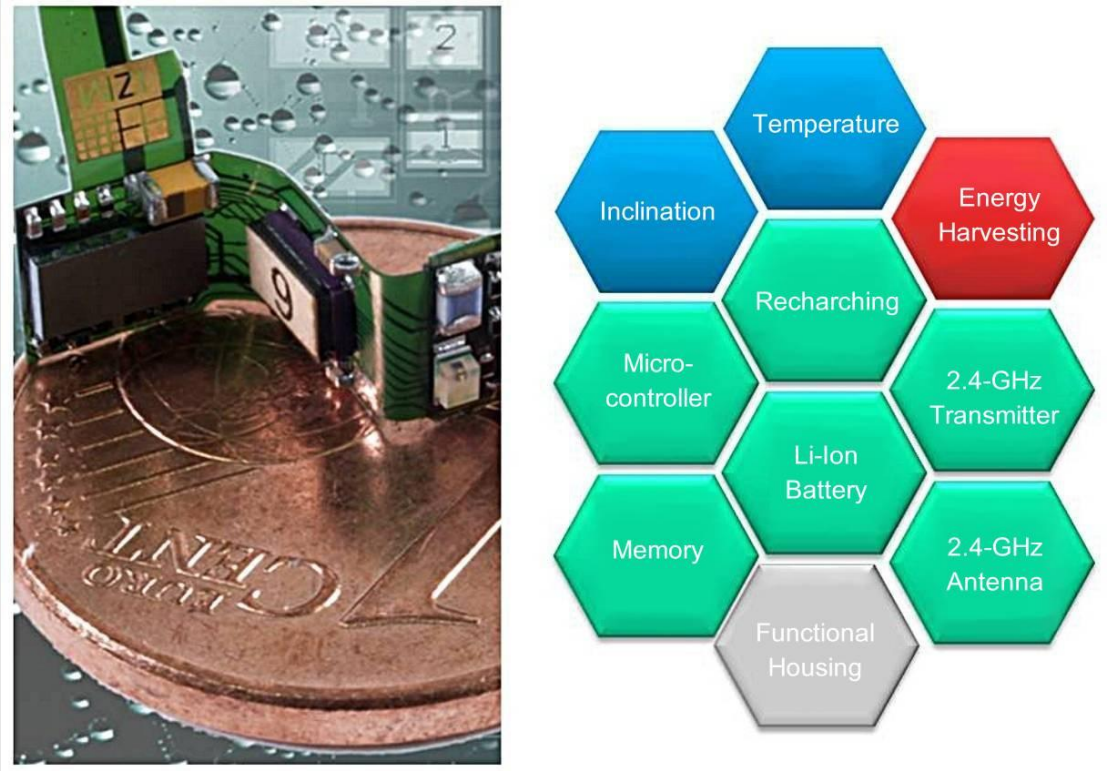


Fig. 4.5: Function groups of autonomous sensor systems and a miniaturized example (image: FHG-IZM)

The trend in individual components for functional groups has already been described in Chapter 3. Nevertheless, especially for autonomous sensor systems, it must be stated that in selecting components, lowest energy consumption is a crucial criterion. From a system point of view, energy saving starts with the choice of measuring or sensor principle and continues with the selection of the microcontroller (or SPC) through to a chosen wireless communication.

In use for energy storage are conventional micro batteries and rechargeable batteries. Special storage media such as capacitor storage (e.g. goldcaps) are being increasingly deployed, especially for buffering MEMS energy harvesters.

Operation and control of autonomous sensor systems is generally accomplished with the help of special software platforms. Particularly important elements of such platforms are sleep functions for individual components such as microcontrollers and transceivers.

The multifunctional housing of an autonomous sensor system assumes the usual mechanical, chemical, and thermal functions as well as optimized coupling of the sensor element to

the environment. It is often equipped with a visual function display and microswitches or interfaces for reset and programming functions.

Autonomous sensor systems make use of established production technologies and are subject to their trends. Nevertheless, 3D structure technologies, such as stacking and folding of flex substrates is applied, as illustrated in the example in Fig. 4.5.

Some autonomous sensor systems are equipped with software that enable autonomous sensor network generation. Besides proprietary programs, open-source software can already be found on the Internet. The market leaders in automation technology now offer receiving devices with which sensor data from autonomous sensors can be read into conventional communication structures.

Some Applications

In logistics there is a trend to include sensor functions (e.g. temperature, acceleration, GPS) on tags. Such autonomous sensor systems are often referred to as active transponders.

In the food industry, tracking and documentation systems are being developed or designed based on autonomous sensor systems – electronic labels with sensor functions.

In the field of animal protection (livestock, fish, birds) or animal food production, first autonomous sensor systems are starting to be implemented commercially, to identify animal behaviour. The trend here is to use such sensor systems to monitor the health of the livestock and thus to prevent diseases and contagion at an early stage.

Discussions are being held on the implementation of autonomous sensor systems for condition monitoring in the investment goods industry. First example applications that complement existing systems in process technology are known to be implemented.

It is estimated generally that the application of autonomous sensor systems in consumer goods (e.g. radio weather stations) has started and that other fields and areas of application will be identified and developed.

In the power industry, first applications in overhead line monitoring with autonomous sensor systems are in the trial phase.

5 Development Trends – Packaging

Abstract

Packaging costs are a major factor in sensor production. Therefore, besides improvement of robustness, the focus is on cost reduction.

In the context of greater application-specific products, the following trends can be observed in packaging:

- → Increase of stacked ICs
- → Increasing flip-chip assembly
- → Hermetic housings
- → Integrated functions in carriers and substrates
- → 3D packages with integrated function elements
- → More effective mechanical decoupling of sensor elements and housings
- → Novel integration concepts (textile, lab-on-chip, lab-on-disk, passivated medical in-vivo systems, etc.)

Generally, in the area of housing and packaging there is a trend towards specialization corresponding to the technical requirements. Sensor suppliers are working to reduce the effects of mechanical stress on measurements, because this plays an increasingly important role in reducing measuring uncertainty, due to its non-reproducibility. Existing assembly and housing materials are being improved and new ones are being developed. In medical technology a tremendous R&D effort has been started for new sensor-actuator systems for in-vivo applications, both temporary and permanent. The effort to develop “smart” clothes is also being increased considerably.

Packaging in the sensor industry is divided into various hierarchical levels. There is 1st level packaging for the sensor element, 2nd level packaging, which integrates components and substrates in an assembly, and then the overall system level, i.e. of the device or a mechatronic unit (**Fig. 5.1**).

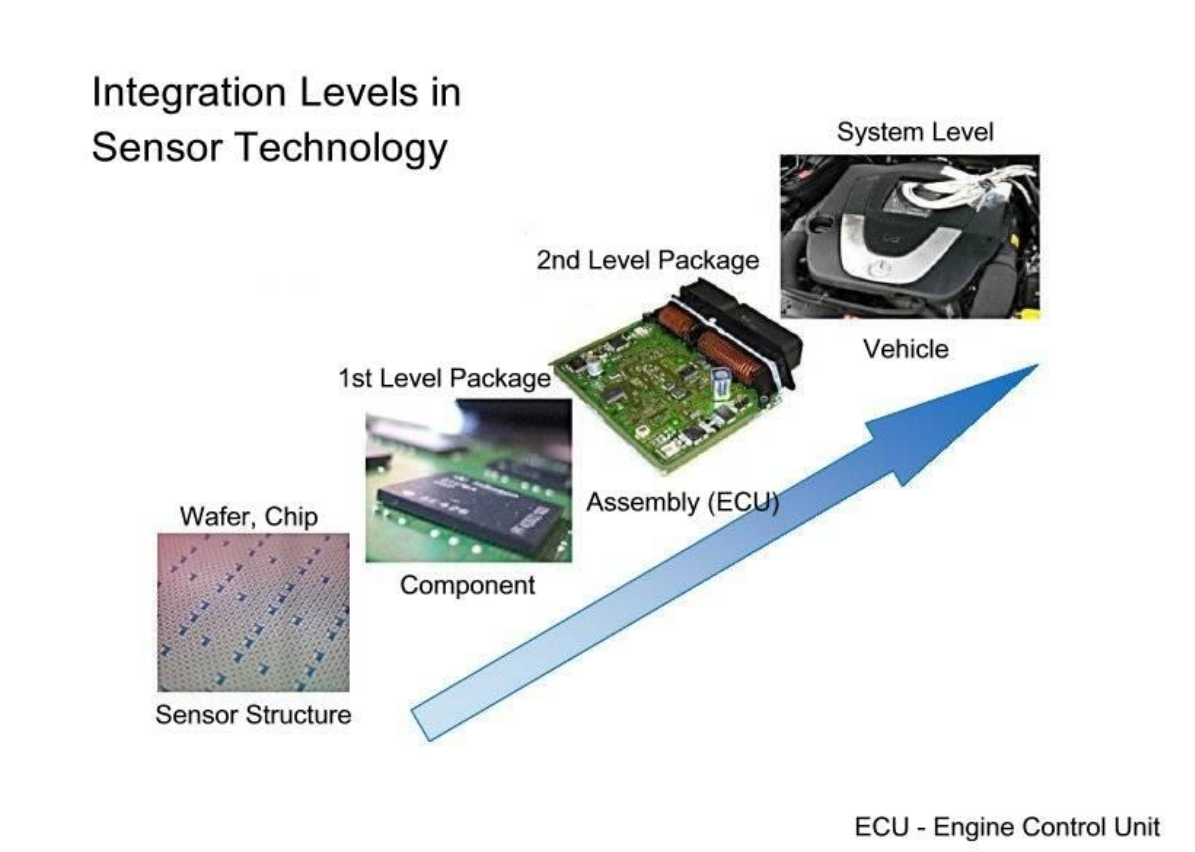


Fig. 5.1: Integration levels of packaging in sensor technology

Although the boundaries between the integration levels are increasingly blurred or shifted due to direct sensor applications in mechanical structures, an illustration of the corresponding conventional packaging is deemed advantageous. Therefore, the division into housing methods, substrates, assembly and contacting methods, and new integration concepts follow. Thus it is assumed that every branch of industry and every area of application requires its own specific packaging, because the design and reliability requirements are very application specific. For these reasons, the trend is towards specialization based on technical specifications.

5.1 Housing Technologies, Encapsulation, Wafer-Level Packaging (31, 32)

Hermetical housings are an established technology that enables packaging of sensors with low leakage rates and a minimum of moisture, as specified by MIL STD 883, Method 1014. Both, metallic and ceramic housing designs are applied. For metal housings, low-cost standard designs as well as expensive customized components are used. Suitable hermetic housings can be used at temperatures of 200 °C, in some cases even up to 250 °C (18). Ceramic housings are generally produced in standard dimensions, but according to customer

specifications. For standard multi-pin designs in both materials, housing costs of about 10 US¢ per pin can be assumed. Especially metal housings are very advantageous for optical components, since they enable hermetic sealing of fluid and pneumatic connections or optical elements (e.g. windows) (**Fig. 5.2**). Therefore it can be expected that hermetic housings will find market segments, wherever cavitation, hermetic sealing, or high-temperatures are required and cost is not the primary selection criterion.

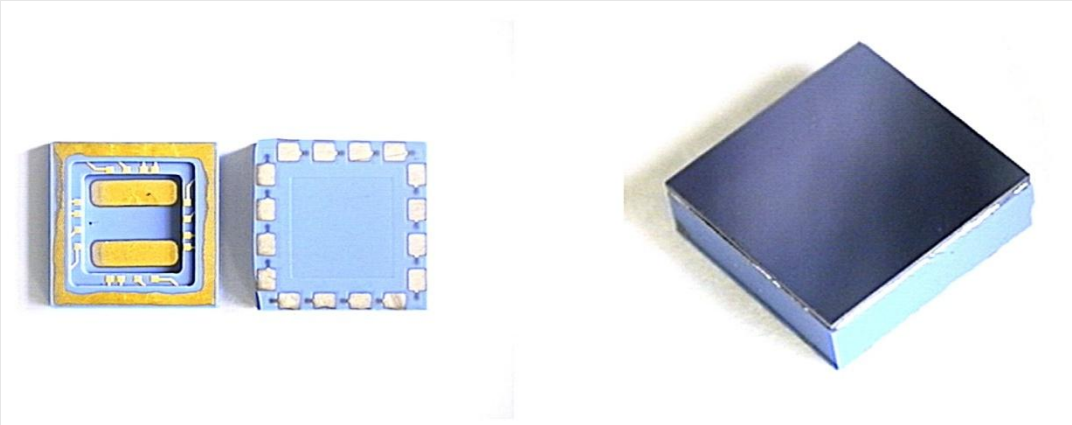


Fig. 5.2: Hermetic housing in LTCC technology for IR sensors. Left: empty housing; right: hermetically sealed housing with an IR transparent silicon cover (images: IFW Jena and Micro-Hybrid Electronic GmbH)

For cost reasons, plastic packaging prevails also for sensors – especially in mass sensor technology. For high-quantity integrated circuits (e.g. Hall sensors) the standard housing technology continues to dominate the field. It is based on transfer moulding with epoxides. These designs have costs of approx. 1 US¢ per pin.

The moulding compounds for the components have seen significant improvement in recent years. Thanks to the development of super-low-stress compounds with a low expansion coefficient, thermomechanical problems were reduced. This allows for encapsulation even for stress-sensitive sensors specified for temperatures of up to 170 °C. Epoxide-based materials for packaging are long-term stable below 200 °C. Due to its direct casing, moulding technology is limited to those sensor chips that permit contact with the moulding compound or for which sensor structures are located inside a wafer or chip cavity. This can be achieved by wafer-level capping. As a material for moulding there are now “green” moulding compounds available, that have a high flame resistance and provide good processing and usability characteristics without the need for brominated resins.

Due to miniaturization, conventional SMD designs are increasingly being complemented by chip-scale packages (CSPs) that are no more than 20% larger than the chip. This applies to sensors as well. Two basic technologies are usually encountered: encasement at the package level and wafer-level packaging. The former process is often implemented with the aid of mould processes based on lead frames.

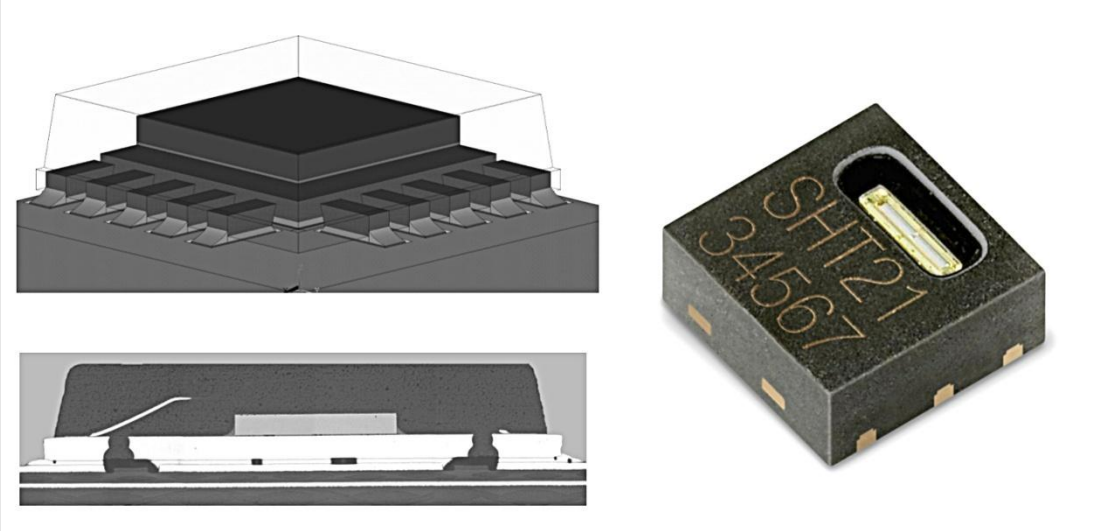


Fig. 5.3: Chip scale package for sensor ICs. Left: QFN (quad-flat no-lead) cross-section; above: finite elements model of a QFN (IMTEK); right: QFN housing of a monolithic integrated moisture sensor (images: Sensirion AG)

Fig. 5.3 shows two such CSPs in QFN design. Due to the relatively direct coupling of the semiconductor to the base material, these designs require good thermomechanical system adaptation for higher application temperatures. The grid dimensions of the CSP connections are at present approx. 0.5 mm, in some cases 0.3 mm. The main application of these surface-mounted models are monolithic sensors, produced in very great quantities with standard processes (CMOS), for automotive applications, for instance. There is also a trend to provide extremely versatile microsystems by stacking various circuits, e.g. for integration of the sensors in analogue and digital circuits (processors). These approaches are known as system-in-package or system-on-package (SiP, SoP) (**Fig. 5.4**). For manufacturers with limited quantities it is important to note that these technologies are also available as job-order productions from packaging service providers.

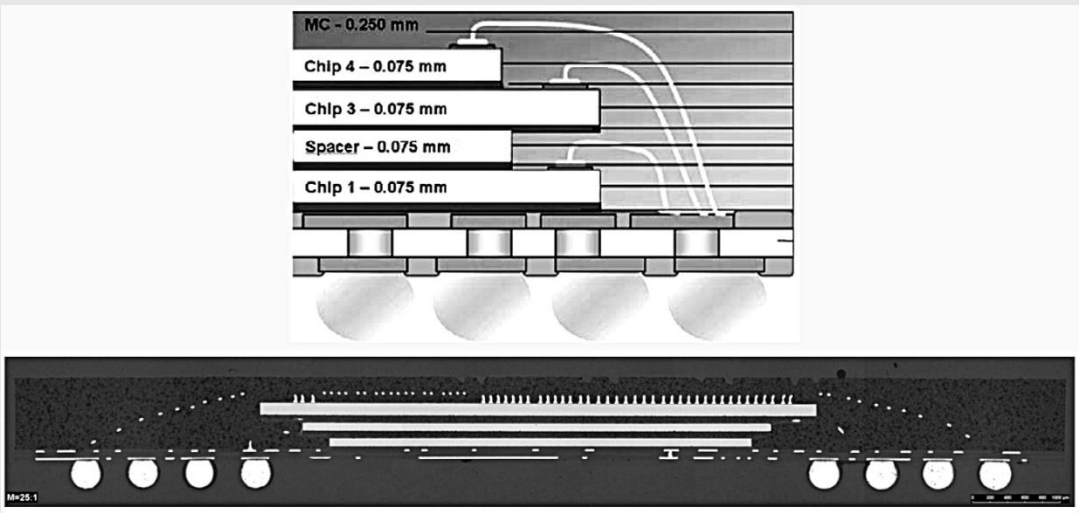


Fig. 5.4: Stacked chip housing for SiP (system-in-package). Used e.g. for integrated hybrid sensor systems. Above: principle of chip stacking and pin out; below: metallographic cross-section polish. (images: Infineon AG)

Many sensor applications require a cavity in which the sensor element is mounted, for instance for pressure sensors, mass sensors, or optical sensors. This requirement can be met with ceramic or metal housings, although their high cost is a great disadvantage. Premoulded package designs usually consist of metal conductor frames that are moulded with thermoplastics (**Fig. 5.5**). Two development trends can be identified here: designs for sensor elements that generally correspond to SMD standard models and multifunctional system housings. Standard designs made of thermoplastics are just now gaining acceptance on the German market, although they feature the cavity needed for sensors. The materials are generally temperature stable and usually more environmentally compatible than moulding compounds. These kinds of packages do not usually exceed the technical characteristics of hermetical housings in regard to ambient temperature or sealing, but are often less expensive thanks to mass production using injection moulding.

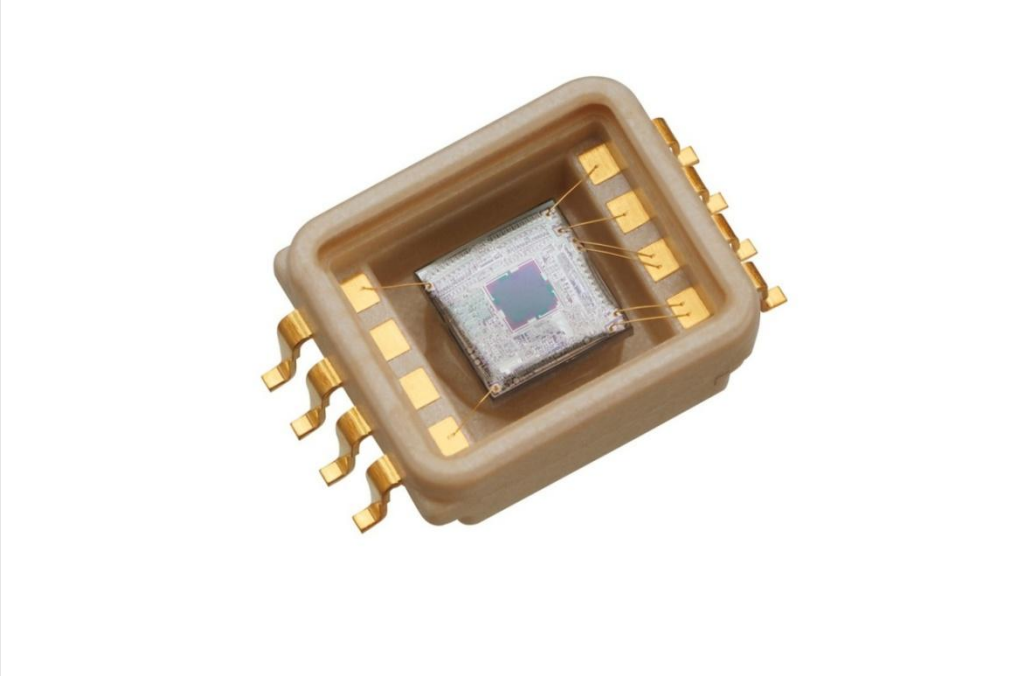


Fig. 5.5: Premoulded standard housing for sensors (image: Bosch)

The premoulded packaging technology especially dominates applications in automotive electronics with customized housings for sensors and mechatronics. There are a number of reasons for this: Tooling costs for stamped lead frames and moulding for large series production no longer play the major role. More important is the degree of freedom that can be achieved with premoulded packages. For microsystem and sensor technology these designs were developed into multifunctional packages. It is characteristic that besides the housings, other functional elements have also become feasible. This includes connectors, sockets, integrated mechanical elements, actuators, heat-sinks, as well as fluidic interfaces for gases and liquids (**Fig. 5.6**). New models have inputs for optical elements, such as lenses, lasers, and glass fibres or for coils and antenna structures for wireless sensors. This technology requires not only good electronics protection, but also very stringent production tolerances of the moulded parts – in some cases only a few micrometres.

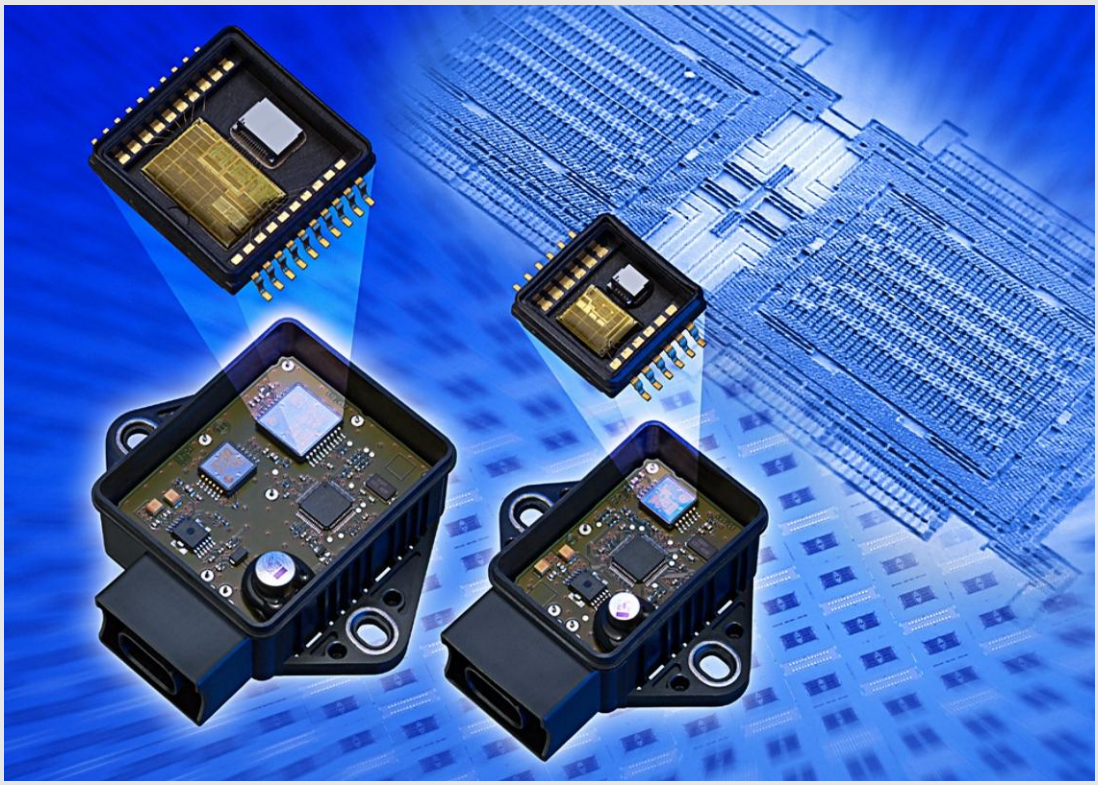


Fig. 5.6: Multifunctional premoulded packages for sensor modules (below) and premoulded standard housing for sensor elements (above) (image: Bosch)

The main material for multifunctional premoulded packages is PBT, a 30% inorganic filled polyester, suited for applications of up to 125 °C. For even higher temperatures, high-grade polymers such as PA6 (polyamide), PPS (polyphenylene-sulfide) or for standard housings LCP (liquid crystal polymers), are available. Since metal polymer lead through-holes and thus the housings are usually not gas tight, additional protection by a silicon mould of the chip and its contacts becomes necessary. Sometimes micromechanical structures, e.g. membranes, are gel coated.

The advances of automation in the production technology of premoulded packages leads to a trend towards a further shift of added value. Premoulded packages are thus often equipped with similar caps or metal lids. The established processes involve bonding and mechanical capping in combination with sealing. Using ultrasonic, heat-element, and friction welding can provide tight lids, but not hermetically sealed enclosures. In recent years, welding of plastic lids with a laser has become more significant. Because of the required IR transparency, the range of available lid material is still limited.

A technology which will be relevant in the future, to produce multifunctional packages is MID (moulded interconnect devices). Characteristic is the simultaneous multifunctional utility of the three-dimensional injection-moulded substrate as a structure element, interconnect device, and housing. The leads in MIDs are made through laser structuring or by laminating printed circuit foils. There are still a number of variants, such as additive, subtractive, or two-shot injection moulding in the development stage. It can be expected that multifunctional housings and MIDs will gain importance in the future because of the high tooling costs involved, especially for mass applications. Laser-supported structuring enables limiting the tooling to injection moulding. Besides materials such as PBT, PPS, and LCP, other high-grade thermally and chemically stable materials, such as PEEK (polyether-ether-ketone) are used. At present, sufficiently fine conductors can already be provided on MIDs, for mounting ICs or sensor chips on the MID connectors – even using flip-chip technology (19).

The MID technology excellently combines traditional housing and substrate functions. Three-dimensionality results in extensive freedom of design and the ability to integrate mechanical or fluidic functionality. Thus, for multi-axis sensors exact positioning of individual elements can be specified by integrated “stops” (**Fig. 5.7**). Based on the commonality of essential technological steps, it can be expected that techniques in premoulded packages and MIDs will converge. These new technologies are illustrated below.

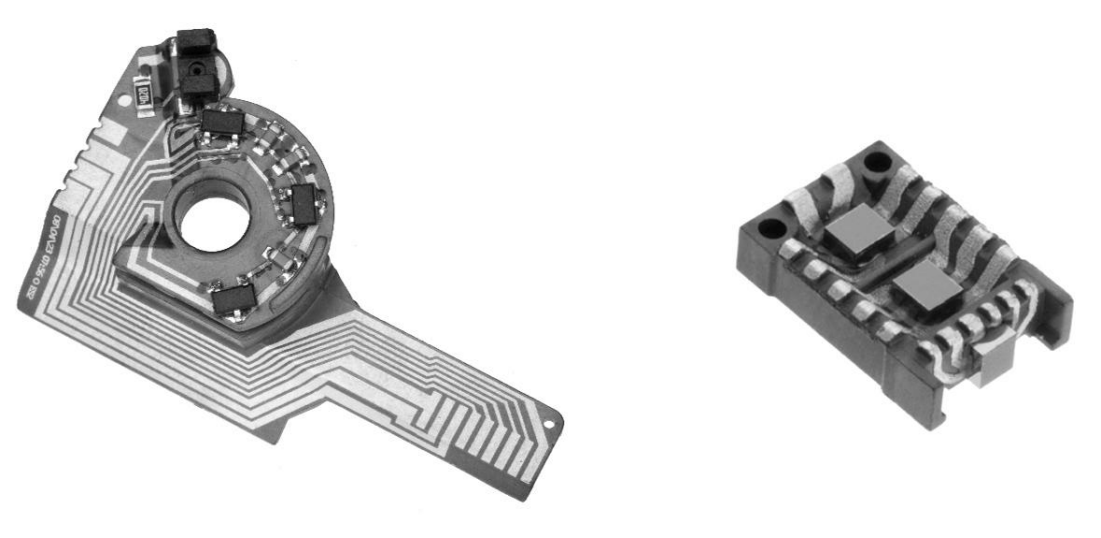


Fig. 5.7: Moulded interconnect devices:
Left: MID for an angular position sensor (image: Continental AG/Harting Mitronics AG);
right: MID for a 3D magnetic sensor (image: Harting Mitronics AG)

One of a number of new possibilities of directly fabricating multifunctional three-dimensional polymer components is by means of stereo-lithography. The plastic is polymerized by local laser irradiation of a substrate. The laser writes the individual structures directly, or in parallel through exposure masks, to generate free-form surfaces, cavities, or metal-polymer bonding. The process is suited for different batch sizes, from prototyping to series.

An alternative process that is currently being researched worldwide is ink-jet printing. This has the potential of fabricating the housing with topology features, such as MID, including conductor structures and even passive components, within the next few years. In the future, sensor ICs will also be embedded in polymers by means of printing. At present there are only scant data available on the reliability of sensor packages fabricated in stereo-lithographic or ink-jet printing technology. These attractive techniques must still prove themselves in applications. The various packaging technologies are listed in **Table 5.1** with selected characteristics for different applications.

Table 5.1: Comparison of Packaging Technologies for Sensors and Microsystems

Package type / **Characteristics**	Moulded housing	Thermoplastic injection moulding	MID(moulded interconnect device)	Hermetical housing
Application	Single and multiple IC packages	Sensor chips sensor modules multifunctional components	3D multifunctional components	Single-chip components
Produceability	++	+	-	O
Prototyping	O	+ * -- **	-	O
Design freedom	-	+	++	O
Cavitation	-	++	+	++
Multi-functionality	-	+	++	+
Costs	++	+	+	-
Thermal stability	+	+	o	++
Hermeticity	- *** ++ ****	-- *** ++ ****	-- *** ++ ****	++
Reliability	+	+	o/+	++
Ecology	O	+	+	o

* standard types / ** application-specific / *** standard chip / **** wafer-bonded chip (++ very good / + good / o satisfactory / - poor)

A paradigm shift is taking place for applications requiring hermetical encapsulation of the sensor structures in a cavity.

In the past such applications were implemented by hermetical packaging, so as to meet stringent reliability and ambient-condition requirements. In the future, however, hermeticity will be achieved at wafer level by bonding with glass or silicon lids. Besides the conventional anodic and hydrophobic bonding processes, bonding of thin glass or metal layers is also available. By this means, electrical through holes in the cavity can be attained that are hermetically sealed. Wafer bonding processes on the other hand do not provide long-term stable gas sealing. Wafer-level packaging also enables integration of getter materials for vacuum sensors and optical as well as fluidic through holes for multifunctional components. Sensor elements packaged in wafer fabrication will prevail in the future, as they enable integration in all polymer packaging technologies as well as direct mounting on substrates and MIDs. Thus, small series as well as large-scale production can be realized economically and reliably, while also providing hermeticity (**Fig. 5.8**).

5.2 Interconnect Devices and Substrates

For substrates, on which sensor components are mounted, PCBs will continue to be mainstream. The main reasons for this are high availability, low costs, rapid prototyping, and – in recent years – high reliability even for rough ambient conditions or high temperatures. Continued development and specialization have made printed circuit boards available featuring a high circuit density, suitability for chip-and-wire or flip-chip design, high temperature stability, as well as passive components.

Other trends in interconnect devices include flexible substrates. Especially for sensors, stable substrate systems of polyimide or now LCP have become relevant. For low-cost applications, including smart cards or smart labels, polyester substrates are being used; the integration of sensors, however, is just starting. Flexible substrates are robust; small dimensions and the capability of integration in complex enclosures are enabled through folding designs.

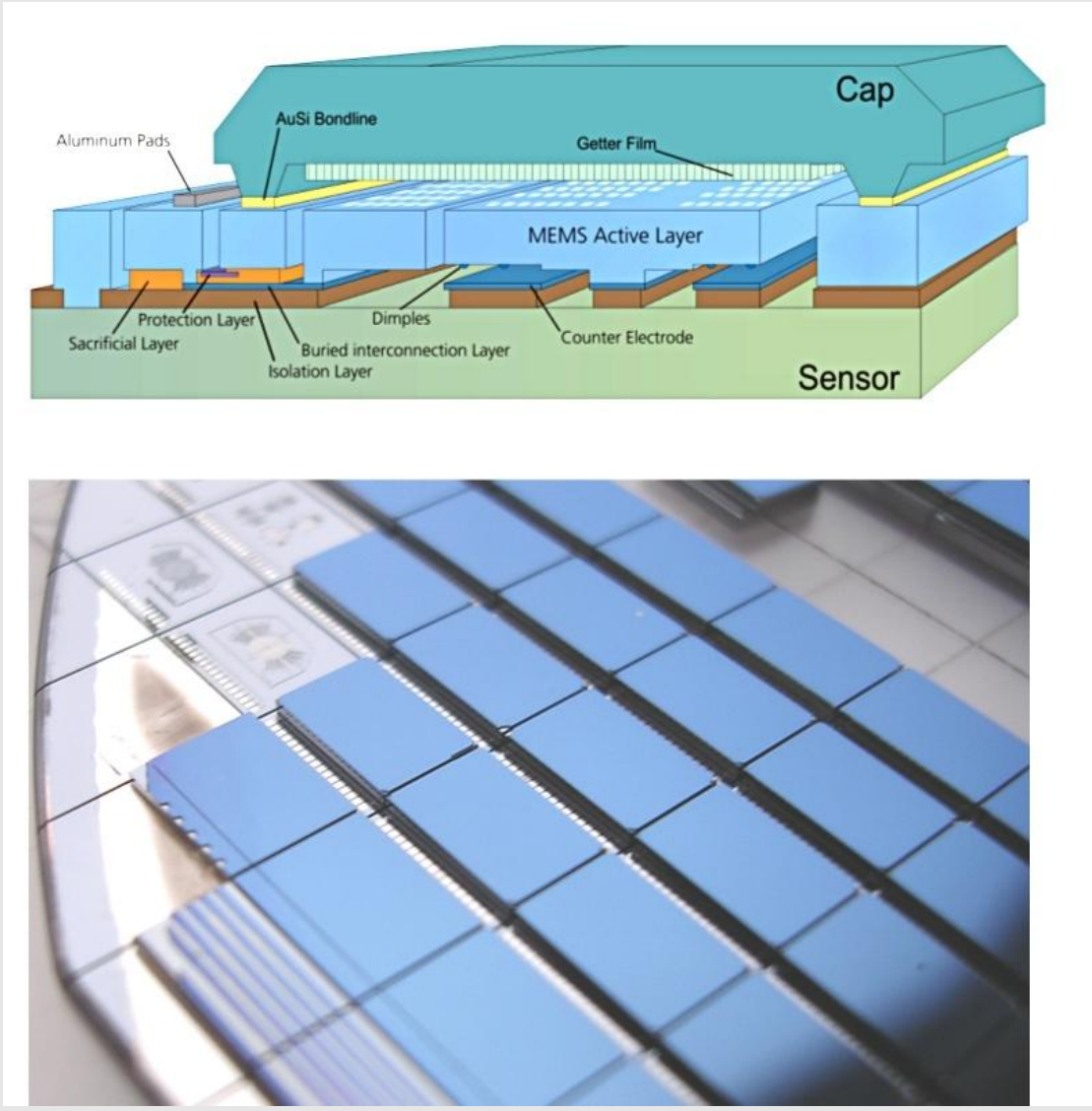


Fig. 5.8: Above: Principle of wafer-level packaging for hermetically packaged sensors; below: example of wafer-level packaging of sensors (images: FhG ISIT)

In general, a clear trend can be observed towards integrating of additional functions and structures for implementation in all kinds of substrates. One technology that is being researched intensively and is still in incipient state of industrial implementation is that of embedded chip technologies, chip in polymer. Thinned ICs are laminated to the PCB and directly contacted. The advantages are small size and thickness (**Fig. 5.9**).

First applications of tactile sensors are being implemented with optical elements on foil substrates or active circuits in TFT technology on flexible circuits. Integrated wave guides are fabricated on substrates for optical data transmission as well as for optical measuring using a

broad range of technologies. Thanks especially to improvements in optical coupling, further applications are on the horizon. Parallel to this development, generation of fluid channels in polymer substrates has been repeatedly and successfully demonstrated.

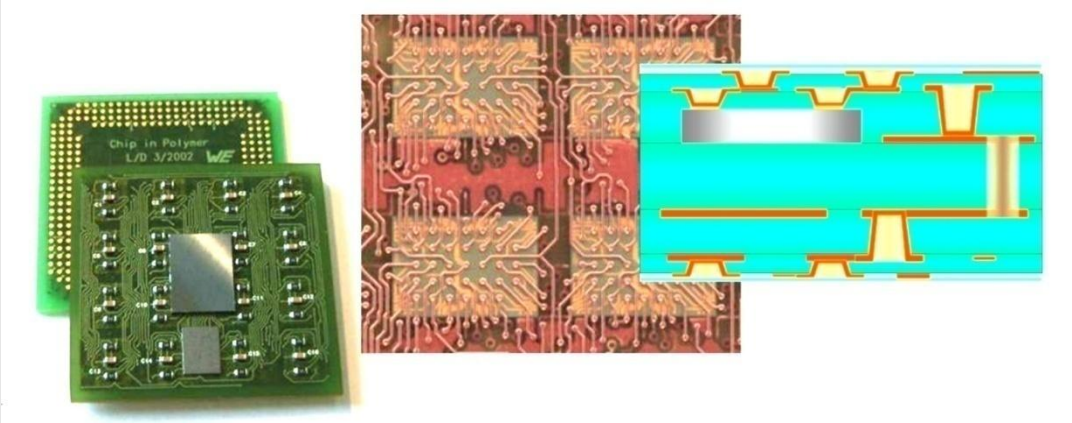


Fig. 5.9: Chip-in-polymer functional design 2000+ based on PCB technology (image: Würth Elektronik)

Ceramic substrates are essentially dominated by three technologies: The established thick-film and thin-film hybrids are predestined for stringent electrical requirements, high-temperature applications, and high reliability. Many applications have been opened in sensor technology. In the next years, gradual improvements can be expected technologically, especially in regard to the continued reduction of structure dimensions. For thick-film layers, conductor widths and gaps of approx. 20 µm are expected.

New low-temperature cofired ceramic (LTCC) technology was developed from hybrid technology. The multilayer ceramics, fired at a relatively low temperature of 850 °C, continue to have a significant growth potential thanks to characteristics such as simplified multilayer circuitry, potential three-dimensionality, formability in the green state, and the capability to generate fluidic elements, such as flow channels and electrodes for the media to be analyzed.

LTTC materials are corrosion proof and temperature stable. The example in **Fig. 5.10** is a 16-layer coil to be used as an eddy-current sensor for up to approx. 500 °C. A new concept for the assembly of media-isolated pressure sensors is based on LTCC for its circuitry elements. However, limitations result from the limited number of suppliers and because of the high costs, especially for prototyping. Thus, LTCC will show its benefits in sensor technology in high-quantity series and in high-end applications.

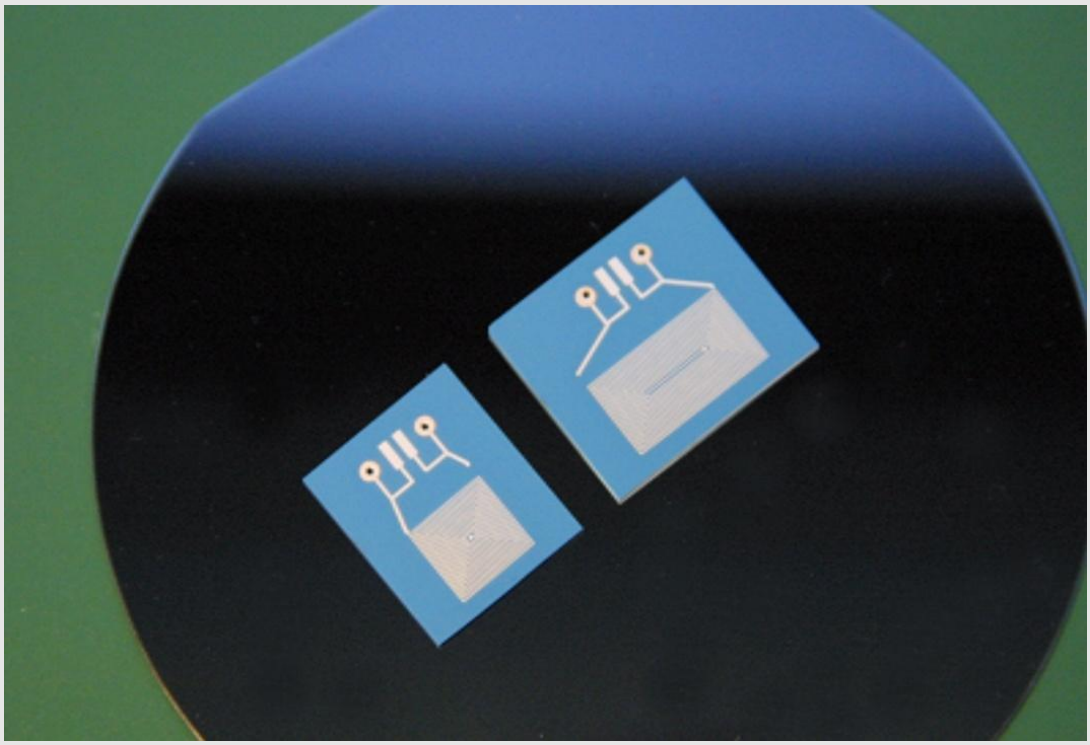


Fig. 5.10: Coils for an eddy-current sensor implemented in LTCC design (image: IMTEK; samples: TU Ilmenau)

5.3 Assembly Techniques

A mechanically stable coupling is required for mounting sensor elements. At the same time, measuring elements and housing are to be uncoupled in regard to mechanical stress. In many cases, micrometre-exact assembly is necessary. The effect of mechanical stress is becoming increasingly significant for sensor suppliers striving for minimum measuring uncertainty. The underlying reason is the sensitivity or cross-sensitivity of all mechanical sensors to mechanical disturbance stress. Among others, the effects involved are piezoresistivity, geometric effects on the resistance, or piezo-Hall effects. Generally, mechanical stress in the sensor assembly is thermally induced, as the sensor elements have a different expansion behaviour than the assembly materials (20) (21) (22). Furthermore, moisture absorption has a major effect that is often not identified (23) (33) (34). Newer work also deals with reducing the effects of large accelerations on sensitivity and cross-sensitivity, for instance in the aerospace industry (35) (36) (37).

The measures for reducing stress effects can be divided into three groups:

- → Thermomechanically compatible assembly techniques
- → Use of flexible, optimized assembly materials
- → Increased robustness of the sensor element

For each of these fields, developments and trends in recent years are described below.

1. Thermomechanically Compatible Assembly Technology

The most significant measure taken here is to reduce the thermal expansion coefficients of substrate, housing, and encapsulation materials. Because silicon is in many cases the dominating sensor material, the expansion coefficients must be compensated. Trends, deriving from this, are the use of high-grade materials, such as LTCC or other ceramics and the use of low-stress mould compounds of filled epoxides for encapsulation of large-volume sensors. In recent years, the compounds available on the market have attained a significant reduction of the thermal expansion coefficient (approx. 8 ppm/K).

Moreover, an increasing use of advanced layout methods can be observed. Since sensor designs based on the finite elements method (FEM) are often available in SMBs, complex assemblies are increasingly being mechanically optimized by the application of the FEM. Thus, it is now possible to compute stress emergence in sensors during their production as well as in their application quite exactly (up to < 15%). The effects on the sensor characteristic of Hall and pressure sensors can also be predicted (20) (21) (24).

2. Use of Flexible, Optimized Assembly Materials

The process of sensor assembly by bonding has become widely accepted. For sensor technology, the relevant materials are epoxides, silicons, and polyimides. Besides adhesion and permanent joints, the bonding process must also provide electrical contacts and in some cases thermal coupling to a heat sink. Therefore, bonding materials are often functionalized with fillers, such as Ag, Al_2O_3, SiN, or even diamonds. Depending on the application, adhesives with either a high or low glass transition temperature are used. A continued development of the materials and processes used in bonding can be observed.

3. Increased Robustness of the Sensor Element

This applies to measures taken on the sensor element to reduce the propagation of mechanical stress to a minimum. For pressure sensors, for instance, this can be the glass body that decouples the sensor structure from the substrate. Despite this good effect, development trends are more in the direction of reducing the thickness of the glass body and to optimize it by applying FEM. Some approaches aim at decoupling the sensor elements through suitable yielding structures from their substrates. For pressure sensors, for example in form of silicon bellows or silicon substrates, these have not found wide acceptance. The main obstacle besides the micromechanical complexity was the significant loss of active silicon surface area on the wafer. This is usually not tolerated. Whenever suitable suspension structures can be integrated in micromechanical sensor assemblies, these are used successfully. This applies especially to angular rate sensors (gyroscopes), for which a complex, multi-axial, statically and dynamically balanced suspension is imperative.

5.4 Bonding Techniques

The dominating bonding techniques relevant for sensors in the next few years are already largely available.

Ball-wedge wire bonding with pure gold wires is already at a high level of process stability and reliability. Thus for the bonds, minimal error rates of a few ppm are attained. Thanks to new technical devices, a trend towards wedge-wedge bonding with aluminium wire (AlSi1) was observed for non-IC applications, that will probably continue into the future. The significant advantages, such as a high degree of flexibility, low costs even for small batches, and simple prototyping, will allow both wire bonding techniques to dominate in sensor technology, especially for low quantities. Moreover, wire bonds keep their long-term stability at operating temperatures of up to 200 °C – or even higher for good metallurgical adaptation.

Both techniques now enable wire diameters of less than 20 µm. Deciding which of the two bonding techniques are to be implemented depends on such factors as topology, metallurgy, and bonding speed. For integrated sensor-actuator systems requiring currents in the ampere range, wire bonding with aluminium wire or Al-strips will find increasing acceptance. In regard to safety applications, such as in medical technology, good verifiability of wire bonds with destructive and non-destructive process is a major advantage. For wire bonding in general detail improvements at a high level can be expected and it will therefore maintain its dominant position in many applications in sensor technology.

The flip-chip technique is based on the principles of adhesion, thermo-compression bonding, or soldering. Flip-chip assembly is implemented in both, SMD processes and special FC bonding devices. The rise in these technologies is a consequence of the technical requirements that cannot be met otherwise, e.g. for RF applications. Due to the significantly lower inductivities compared to wire bonds, fast signals in flip-chip contacts will be considerably less delayed. For optical components, such as CCD chips, the high contact parallelism offers advantages for fabrication, economy, and dimensions. Thus already more than ten years ago, in singular, non-cost-critical applications (CCD IR sensors) bump pitches of less than 25 µm were industrially produced for hundreds of connections. It is to be expected that such characteristics will become available in series for a wide range of applications. In general, a continued improvement in the supplier infrastructures of flip-chip technology can be assumed for the next years. In this context, suppliers of bumped sensor ICs, service providers for wafer bumping, device manufacturers, and material suppliers (e.g. of adhesives) may be mentioned. Thus, for system developers in sensor technology, it will be easier in future to realize a variant in flip-chip technique.

At the assembly level, soldering with lead-free solder is being qualified at present. The results up to now show that on the average reliability data can be expected that is comparable to SnPb solders and that these soldering materials will have a better temperature stability of about 10 to 20 K than SnPb alloys. However, the reliability must be proven for the specific application. Overall, it can be expected that lead containing solder will be widely replaced – also in sensor technology – even if this is not required by law.

5.5 New Integration Concepts

5.5.1 Sensor Structures in Structure Components and Clothing

One of the technical possibilities and customer demand driven trends is the wide application of RFID in applications of logistics and everyday life. The tasks to be performed in such systems often exceed mere identification or labelling. On-chip integration of sensors, e.g. for temperature, moisture, vibration in RFIDs, smart tags, or smart labels is technically feasible and has been demonstrated. The technical requirements for assembly, however, are not always fulfilled. Only when specific demands have been met, for instance for low-stress assembly, thin silicon components (< 50 µm) with fragile micromechanical structures, will sophisticated sensor principles for mass applications become quasi-ubiquitous.

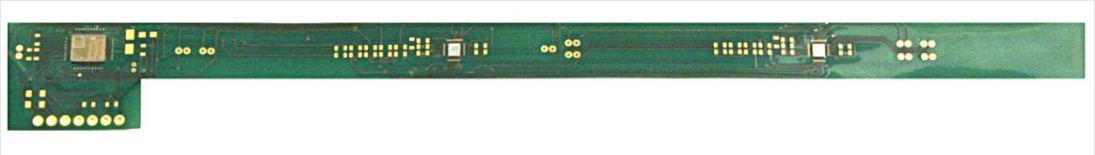


Fig. 5.11: Example of an intelligent load detection system (image: pro-micron GmbH, width 205 mm)

Sensing mechanical parameters in structure components or mechatronic systems is also an important technical task. Here, wireless systems are being realized, with which real-time torque or force on moving machine elements can be measured and transmitted wireless to a superordinate circuit (**Fig. 5.11**). Application-specific analogue-digital signal conditioning circuits for sensors can include amplification, filtering, conversion, and communication in a single monolithic integrated component. Since these kinds of systems are often fabricated in low quantities, the use of standard technologies makes sense. Very thin, flexible PCBs or flexible substrates are suited as integration carriers. The advantages of these future solutions lie in reduced sensitivity to disturbance thanks to short leads, elimination of complicated measuring amplifiers, small dimensions of the overall system, digital outputs, and data processing and reduction directly at the measuring location.

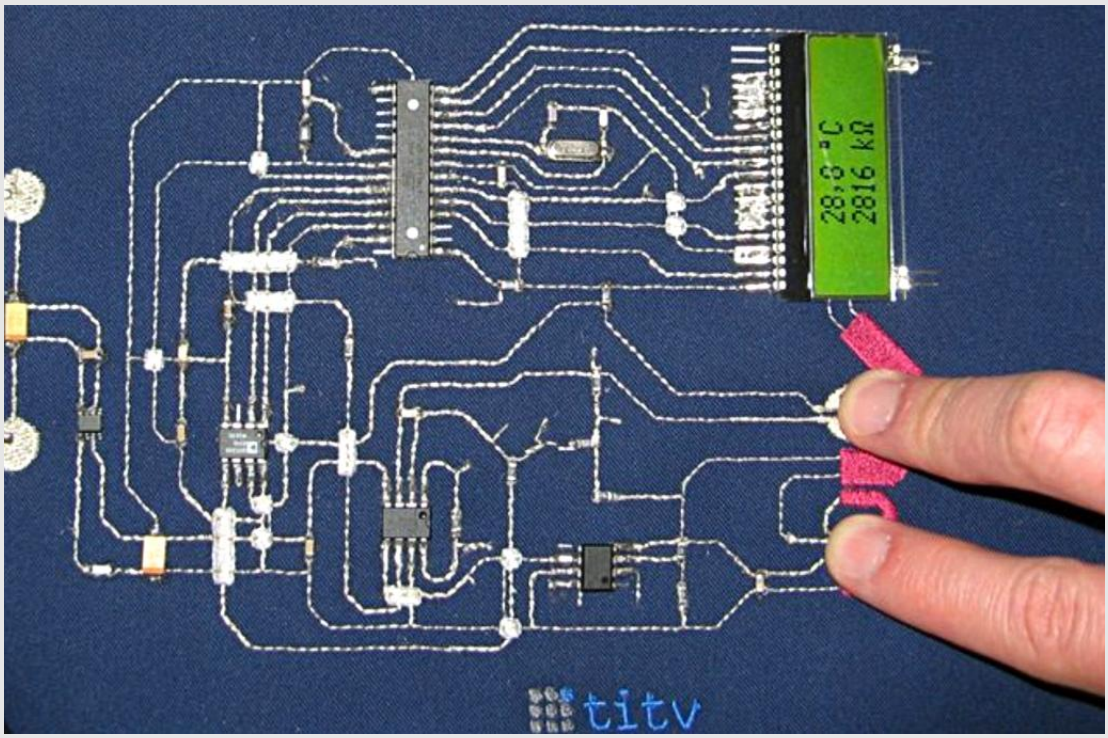


Fig. 5.12: Integrated textile moisture and temperature sensor with processing circuit (image: Textilforschungsinstitut Thüringen-Vogtland e.V.)

A similar development may be observed for “smart” clothing. Here sensors for moisture, temperature, or metabolical parameters can be integrated in the fabric as can substrates, energy supply, and an antenna. For the depicted moisture and temperature sensor in **Fig. 5.12** a complete electronic circuit was integrated on a flexible textile substrate. Commercially available components were contacted to the textile conductors without further aid. Alternative techniques, however, are flexible printed circuit board assemblies (PCBAs) or smart labels. The later offer the advantage of completely independent processes for electronic manufacture and textile production.

5.5.2 Lab-on-a-Disk and Lab-on-Chip

Sensors are often manufactured by a component manufacturer and then integrated by a system supplier. This kind of integration or cooperation concept is no longer expedient for many future microsystems. Applications which are now transitioning from the research state to production include chemical microreactors as well as lab-on-a-disk or lab-on-chip systems, as e.g. for biochemical applications.

Such microfluidic systems need to combine reservoirs, pumps, measuring cells, cuvettes, separation columns, reaction chambers, and sensors. Discrete assembly is often prohibited

due to the dimensions, dead volumes, dead times, and costs. Such fluidic systems are assembled monolithically or in hybrid assembly using as few individual components as possible. Typical sensors to be integrated detect temperature, volume and mass flow, pressure, colour, or chemical parameters. Moreover, they have integrated cavities for optical measurement of media characteristics with external analysis systems. Therefore, the developer will design and fabricate simple sensors in the future as elementary constituent system parts. In other cases it will become necessary to integrate e.g. the sensor IC as a bare chip. In such cases, the application-specific sensor knowhow resides at the system house and not at the sensor manufacturer.

Many of the sensor suppliers represented in the AMA generate added value through their application-specific knowledge to meet industry-specific specifications and standards. For monolithically integrated chemical or fluidic systems, a strategy for added value creation might be to target system leadership for such microsystems and thus develop from a sensor supplier to a microsystem supplier.

5.5.3 Medical Technology

In medical technology, a considerable R&D effort is being committed to the development of new sensor, actuator, or stimulation systems for in-vivo applications. These are made to be implanted permanently or temporarily in patients to replace essential bodily functions. With the aid of neuroprosthetics, interfaces to nerves are being created; other applications require access to the skin or body fluids. Besides the stimulation of nerves and detection of nerve signals, other in-vivo applications deal with sensing metabolical parameters or dosage of medications.

For in-vivo systems in the demonstrator state or in animal experiments, a standard packaging process has been developed, driven by biocompatibility requirements, and targeted at mass applications. In many cases, flexible substrates are used, on which integrated circuits or sensors are usually mounted as bare chips. The flexible substrate is used as a carrier for electrodes and for sheathing nerve cells.

To counteract the low resistance of silicon materials to media diffusion, additional thin protective layers are applied for passivation. Here, CVD or PVD layers of parylene, glass, oxides, nitrides, or SiC are being tested.

6 Development Trends – Testing Processes for MEMS Components

Abstract

Many new sensor types are based on MEMS technology and suppliers are expending great efforts totest conductivity, quality, and reliability. Moreover, comprehensive tests are performed for checking production steps as well as for field monitoring and self-testing of MEMS components. This chapter describes the various tests that are carried out on MEMS-based sensors. It also illustrates how these methods can be applied as part of a comprehensive quality strategy.

For testing MEMS components there is a strong tendency towards characterizing sensor functions and cross-sensitivities as early and as comprehensively as possible. On the wafer level this is achieved by wafer-level tests with physical stimulation:

- → Via a probe
- → Via a chuck

For both surface and bulk micromechanics, there is a trend to integrate built-in self-tests (BISTs). Internal structures are used to stimulate the transducer structure. There is also a trend towards sensors with self-calibration capabilities.

6.1 Fault Types

For micro-electronic systems two basic types of fault can be distinguished. The first group comprises faults that lead to complete malfunction. The second group consists of parametric faults, systematic and random faults that change the characteristic or transient behaviour (**Table 6.2**).

For constituent mechanical parts of MEMS, a total failure can be due to broken or non-separated structures (**Table 6.1**). If this has impacted functional parameters, often either mass, rigidity, or an attenuation coefficient are out of the permissible range. In such cases, static and dynamic behaviour is noticeably impaired. Thus, functional behaviour may be an indirect indication of physical defects of the micromechanical elements. The effectiveness of the various testing concepts can be determined by means of physical failure models and simulation using the finite elements method. An example of this is the effect of vacuum qual-

ity on the damping characteristics of a resonance structure and thus on the natural frequency and the quality factor of the vibration.

Table 6.1: Defects Causing Failure of CMOS-Compatible Thermal MEMS Due to Manufacturing Faults

Electronic Structure Faults	**Mechanical Microstructure Faults**
Short-circuit ▪ Polysilicon, single layer, two layers ▪ Between polysilicon and metal ▪ metal, single layer, two layers	Disruption ▪ Outside of measuring structure ▪ Within sensor structure
Conductor failures ▪ Polysilicon ▪ Metal layers ▪ Poly-metal contact	Mechanical blocking ▪ Non-separated microstructures ▪ Static friction ▪ Cavity fault ▪ Asymmetric structures ▪ Others

Table 6.2 shows possible parametric faults in microprocessed thermal MEMS. Geometry as well as structure and material characteristics are influenced primarily by the fabrication process. These factors in turn affect the parameters determining the characteristics of the electrical or mechanical element, such as rigidity, mass, performance, or resistance. In the tests, characteristics, such as resonance frequency, offset, and sensitivity can be monitored.

Table 6.2: Classification of Parametric Faults for Microprocessed Thermal MEMS, According to (18)

Mechanical	**Electrical**
▪ Structure characteristics ▪ Edge defects, width, length, thickness ▪ Cavity faults ▪ Friction and adhesion ▪ Missing structures ▪ Partial suspension or detachment of structures ▪ Vacuum quality or pressure	▪ Structure characteristics of conductors ▪ Width ▪ Length ▪ Thickness ▪ Doping profile ▪ ...
Thermomechanical material characteristics ▪ Density ▪ Elasticity modulus ▪ Thermal expansion coefficient of metal ▪ Thermal conductivity and capacity ▪ Radiation emission coefficient ▪ Convection coefficient ▪ Friction coefficient	Thermo-electrical material characteristics ▪ Specific resistance of polysilicon and metal ▪ Contact resistance ▪ Temperature coefficient of polysilicon and metal ▪ Piezoresistive coefficient of silicon ▪ Seebeck coefficient of polysilicon and metal ▪ Dielectric constant and loss factor
Variation of mechanical coefficients ▪ Rigidity, resilience ▪ Mass ▪ Attenuation factor / viscosity ▪ ...	Electrical interference components ▪ Parasitic resistances ▪ Parasitic capacities ▪ Parasitic inductivities ▪ ...
System behaviour ▪ Natural frequency ▪ Quality factor ▪ Nonlinearity	System behaviour ▪ Offset shifts ▪ Sensitivity changes ▪ Changes in characteristic impedance

Table 6.3 shows an example of a magnetic sensor with typical electrical, mechanical, and ambient faults.

Table 6.3: Electrical, Mechanical and Environment-Related Faults in a CMOS-Integrated Magnetic Sensor, Modified According to Dumas (25)

Electrical Component Fault	**Electrical Test Parameters**
Reference resistance out of permissible range	Offset
Piezoresistive coefficients out of permissible range	Sensitivity
Electrical resistance out of permissible range	Sensitivity Offset
Reference resistance short-circuited or interrupted	Offset (=VDD/2)
Short-circuit in the resistance bridge	Sensitivity (Zero)
Measuring resistance short-circuited or interrupted	Sensitivity (Zero)

Faults in the Mechanical Components	**Electrical Test Parameters**
Rigidity out of tolerance range	Resonance frequency
Mass out of tolerance range	Sensitivity resonance frequency
Attenuation coefficient out of tolerance range	Sensitivity quality factor
Cavity faults	Nonlinear behaviour
Broken or non-separated structures	Sensitivity

In (26) a system was worked out, with which physical faults in the electrical or mechanical structures can be determined with relatively simple tests at the system level. Regrettably, such a concept has its limitations, because the main faults can only be determined by indirect methods and the measurement of the resonance frequency or sensitivity requires physical stimulation. For CMOS-MEMS, the electrical characteristics on the physical level are only accessible if measuring points are integrated in the design. This in turn requires a consistent test-compatible design concept.

6.2 Wafer-Level Tests

An integrated silicon microsensor generally has electrical connections for parameterization, programming, and power supply. The output typically comprises the sensor signal and often certain status information as well. To generate the measuring value, microsensors need

physical stimulation. Due to cross-sensitivities, a number of stimulation parameters are necessary in practice. The dominating fault parameter usually comes from temperature, but pressure, moisture, or mechanical stress must also be considered. In tests on assembly level, the device is already in contact with its environment (**Fig. 6.1**). Therefore, correct physical stimulation and measurements on complete devices are relatively easy to carry out.

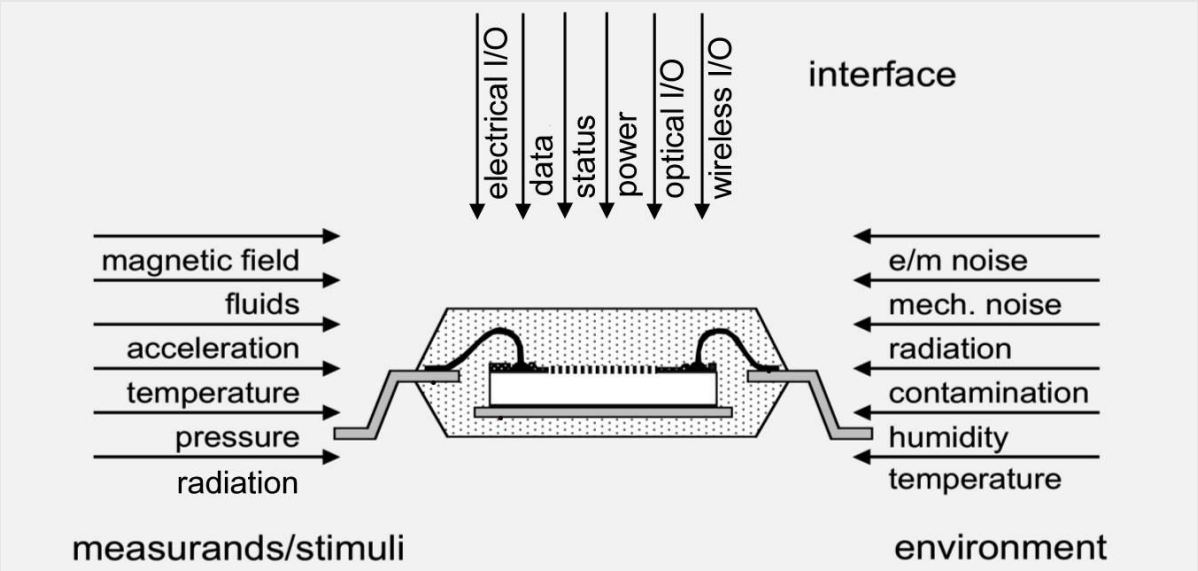


Fig. 6.1: Stimuli and fault effects during tests of microsystems on assembly level

Testing only on assembly level has, however, significant disadvantages: One of these is the delay between defect generation and fault determination due to the fabrication cycle. Another is the increased cost of a complete assembly. According to an analysis by Memunity and Süss MicroTec Test Systems GmbH (27), the costs of a MEMS assembly typically can be broken down as follows:

Cost of the sensor element:	29%
Cost of tests at wafer level:	1%
Mounting and assembly:	70%

Thirty percent of the overall fabrication costs result from the wafer fabrication process and 70% from subsequent backend technologies. Thus the economic loss for a defective 1 € sensor element amounts to 3 € per unit. If a defective MEMS chip is integrated in a device, the total loss may amount to 10 € per defective unit.

Another important aspect to consider is the time required to feed the failure information back into the production process. Fault analysis of an encapsulated unit can be tedious. The silicon chip requires artefact-free fabrication. Moreover, mounting and assembly do not take place in a clean room, but in another factory site. It can be a matter of weeks or even months before the fault data reaches the wafer factory. The data is thus not up to date and will influence wafer quality very late.

Early in-production testing of microsystems of bare chips must therefore be a major consideration in modern test strategies. For (non-MEMS) ICs it was shown that wafer-level tests are considerably more efficient than tests on individual unhoused sensor elements. Functional testing of individual sensor elements requires costly adapters and would be considerably more expensive than the 10% share of costs for testing at wafer-level. Modern testing strategy makes use of both concepts for MEMS testing at the wafer level and at the component level to optimize throughput, accuracy, reliability, and the overall acquisition of data. Therefore the costs for testing and calibration are relatively high compared to the production costs.

The following sections evaluate the available technical solutions for testing MEMS at the wafer level.

Table 6.4: Comparison between MEMS Testing at Wafer Level and at Component Level

Testing Level	**Wafer Level**	**Component Level**
Physical stimulation	Not possible for all measured variables	Simple, as all interfaces are available (electrical, mechanical, flow, optical)
Measuring equipment	▪ Physical stimulation costly ▪ Sequential testing	▪ Costs for test adapters often very high ▪ Costly automatic multichannel measuring equipment
Measureable variables	▪ Input/output variables ▪ Electrical parameters at intermediate system levels require test points	▪ Normally input/output variables only after internal signal processing ▪ Test mode optional, if available
Tested elements	▪ Specific testing of silicon elements w/o disturbance from packaging	▪ Testing of complete microsystem, including packaging effects
Purpose	▪ Measures basic functional characteristics ▪ MEMS process – measuring technology & control ▪ Elimination of defective sensor elements at reduced costs	▪ System testing ▪ Measures usable characteristics ▪ Functionality ▪ Reliability ▪ Burn-in
Test duration	▪ Fast testing ▪ Enables fast control loops for production processes	▪ Long-term testing ▪ Aimed at stability and long-term behaviour

6.3 Testing Equipment

A wafer testing system comprises four major components:

- → The test station
- → Probes or a needle-type probe card for electrical connection to the device
- → A chuck that keeps the wafer at an exactly constant temperature
- → Electronic measuring equipment

The wafer is placed in the probe station chuck manually or by an automatic transport system and held in place by vacuum. Commercially available are fully automatic systems intended to monitor mass production, semi-automatic systems for development purposes, as well as manual systems for research or less frequent use.

6.3.1 Temperature Control

Electrical parameters, such as impedance or transmission function, are usually measured in a wafer probe station. As many electrical characteristics of silicon structures are sensitive to temperature, temperature control is essential for sensor accuracy. Special thermal wafer chucks enable control wafer temperature and thus of the test item. This is achieved by electrically heating or cooling the chuck. Typical test temperatures range between - 65 °C and 200 °C and for some special devices up to 300 °C.

The use of a thermal chuck requires tuning the thermal expansion coefficient of the wafer and the wafer chuck. Moreover, thermal expansion in z-direction needs to be controlled, so as to avoid breaking the contacts or destroying the needle tips.

6.3.2 Physical Stimulation at Wafer Level

To characterize sensor functions and cross-sensitivities, additional ambient stimuli, such as temperature, pressure, gas load, or magnetic fields (**Fig. 6.2**) must be applied. Biotechnological and microfluidic components often also require additional media channels. Examples can be found in the following sections.

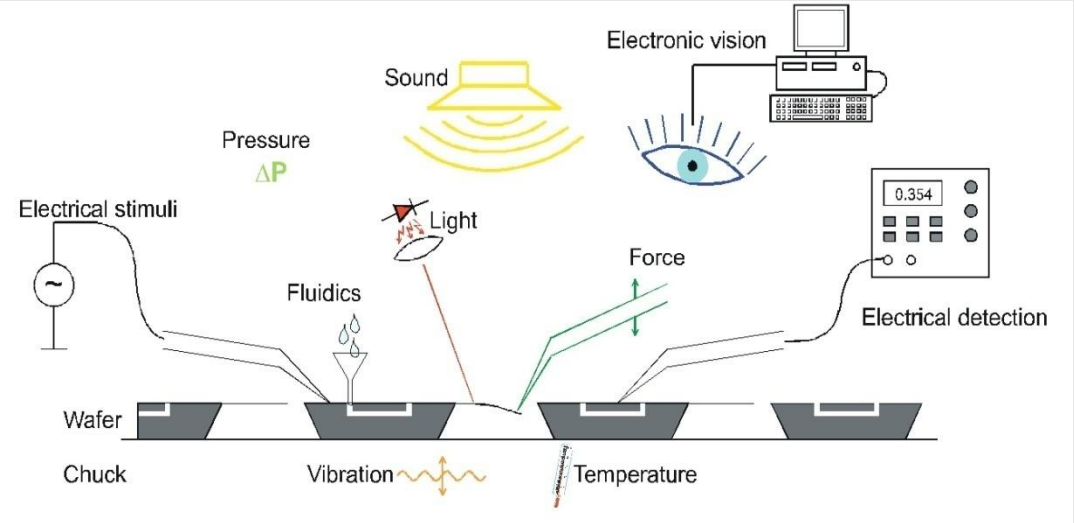


Fig. 6.2: Examples of physical stimulation for MEMS tests at wafer level (image: Suess)

There are three possible fundamental strategies for testing integrated MEMS at wafer level (**Table 6.5**). Conventional testing of analogue and digital circuits of MEMS at wafer level corresponds to testing of ICs at wafer level. The physical stimulation at wafer level is a new, very promising technology that, but also has its limitations. The third concept aims at replacing physical stimulation by electrical excitation.

Table 6.5: Comparison of Test Strategies for MEMS at Wafer Level

Method	**Advantages**	**Disadvantages**
Electrical testing of analogue/digital circuits	Standard wafer test	Only partial testing of the system
Physical stimulation	Realistic and comprehensive testing	Requires wafer stimulation equipment
Electrical stimulation of the sensor structure	Efficiency, avoids the need for stimulation equipment	Requires test-compatible designs

The rapid growth of the market for MEMS components has led to a considerable expansion of the product range by suppliers of testing equipment, such as used for physical MEMS testing at wafer level. Thus, MEMS wafer-level tests by means of physical stimulation have become state of the art in some applications.

Table 6.6: MEMS That Can be Tested for Physical Characteristics and Dominant Cross-Sensitivities

Kind of Device	Physical Characteristics	Dominant Cross-Sensitivity
Temperature sensors	Temperature	-
Pressure sensors	Pressure	Temperature, ambient pressure
Gas sensors	Gas composition Flow rate Pressure	Temperature
Microbolometers	Radiation intensity	Temperature
Acceleration sensors	Acceleration	Non-axial acceleration, mechanical load, pressure
Gyroscopes	Yaw velocity	Out-of-axis acceleration, mechanical load, pressure
Silicon microphones	Acoustic pressure	Temperature
HF-MEMS	Resonance frequency	Temperature, pressure, vibration, and acceleration
Micromirrors	Angle deflection	Vibration

Table 6.6 provides an overview of the physical characteristics of MEMS that can be tested at wafer level. For many relevant sensor types, commercial solutions have become available that enable physical stimulation. Wafer-level tests are available for micromirror drives and RF-MEMS.

The dominating cross-sensitivity for almost all components is temperature, but ambient pressure or in-component pressure can be important. Additional typical tests for mechanical structures on the wafer are possible. These tests provide information on structural characteristics, but without characterizing the complete functional behaviour. According to **Table 6.7** geometry, topology, as well as the kinematic and dynamic behaviour are tested with additional testing systems.

Table 6.7: Additional Test Equipment for MEMS Tests at Wafer Level

Analysis Type	Test Equipment
3D mechanical motion analysis, modal analysis	Laser vibrometer or interferometer
Visual inspection, identification characteristics	Camera systems with automatic image processing
Topology analysis and profiling	Optical test systems, interferometer

6.3.3 Basic Concepts of the Test Equipment

Using a pressure sensor as an example, the three basic wafer-level test concepts are described as follows: The transducer element of a pressure sensor is a silicon plate that is deflected to one side or the other by the difference in pressure. Pressure sensors can measure absolute pressure by using a reference chamber or differential pressure between two pressure feeds. Resistive expansion structures are necessary to measure the pressure exerted on the silicon plate. The pressure range of silicon sensors is in the range of a few mbars up to approx. 100 bar. For measuring the functional parameters of the sensor, such as the sensitivity, a physical stimulus is applied. Also, the mechanical structure must be placed under a certain pressure. **Table 6.8** lists the available methods for applying pressure on the wafer:

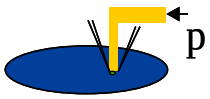
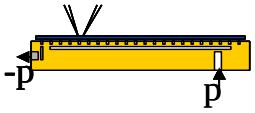
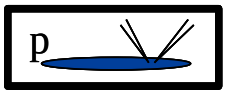
- → Application of a pressure probe on the top side of the wafer in addition to the electrical test probes
- → A chuck to exert overpressure or vacuum on the bottom of the wafer
- → Operation of the entire test station in a pressure or vacuum chamber

There are specific application cases for each of these concepts. The accuracy that can be attained, the required effort, and the test costs vary widely.

Both the pressure probe module (**Fig. 6.3**) as well as the pressure chuck have the advantage of requiring only a slight modification of the standard equipment. In regard to the pressure range and accuracy, both have limitations.

If the entire station is installed in a pressure chamber (**Fig. 6.5**), the system is very versatile and enables numerous options, e.g. additional temperature control. Pressure settings are in a range between rough vacuum and high pressure. However, such systems are expensive, as efficient operation can only be provided by motorized or fully automatic wafer probers.

Table 6.8: Methods and Characteristics of Tests on Pressure Sensors at Wafer Level – Compilation of Data According to Suess

Method of pressure application	**Pressure Test Probe**	**Pressure Chuck**	**Pressure Chamber**
Diagram			
Function	Test probe on the top wafer surface under pressure	Rear pressure	Complete setup inside a pressure chamber
Cross-sensitivity	Optional control of temperature up to 125 °C	Optional Temperature control	Optional Temperature control
Limitations	Very flexible, can be extended	Limited pressure range, vacuum tests	Very versatile, many options
Sensor types	Absolute and differential-pressure sensors	Individual chucks for every wafer pattern	Few limitations
Pressure ranges	Up to 7 bar	Rough vacuum up to light overpressure	Vacuum up to high pressure of 50 bar
Testing limitations	Useable with all test probes	Useable with all test probes	Motorized or fully automatic wafer prober
Costs	Good price / performance ratio	Inexpensive	Expensive

6.3.4 Tests at Wafer Level with Stimulation via Probe or Wafer Chuck

Using a pressure probe module (**Fig. 6.3**), gas pressure is applied to the upper surface. The typical pressure range is between atmospheric pressure and 7 bar. An option for controlling the temperature of gas up to 125 °C is important. This is needed to prevent cooling of the sensor membrane, which would lead to a significant signal disturbance. Pressure modules can be used with manual, semi-automatic, or fully automatic wafer probers.

Fig. 6.3: Test probe module, exerting pressure from the top (image: Suess)

Vehicles use acceleration sensors extensively and relevant measuring ranges start at one g and go to up to hundreds of g. For stimulation at wafer level, an acceleration chuck has been developed that generates vibrations perpendicular to the wafer surface (**Fig. 6.4**). According to the manufacturer, Suess, the acceleration at 500 Hz is in the range of 3 to 5 g, at 1 kHz 14 g, and at 2 kHz over 50 g. In this frequency range, deflections between 100 µm and 200 µm are generated that can still be tolerated by the appropriate prober points.

Fig. 6.4: Acceleration chuck for wafer level tests of acceleration sensors (image: Suess)

6.3.5 Tests at Wafer Level with Under-pressure or Overpressure

For wafer probers installed in a pressure chamber, motorized or automated systems make sense. Typical data of commercially available systems with a pressure chamber are as follows (according to Suess):

- → Pressures in the range from rough vacuum to 50 bar
- → Thermal chucks from - 65 to + 250 °C
- → Non-aggressive gases or controlled moisture possible
- → Wafer sizes up to 200 mm
- → Typical 8-probe manipulators (HF to 65 GhZ, DC) or alternatively needle-type probe cards

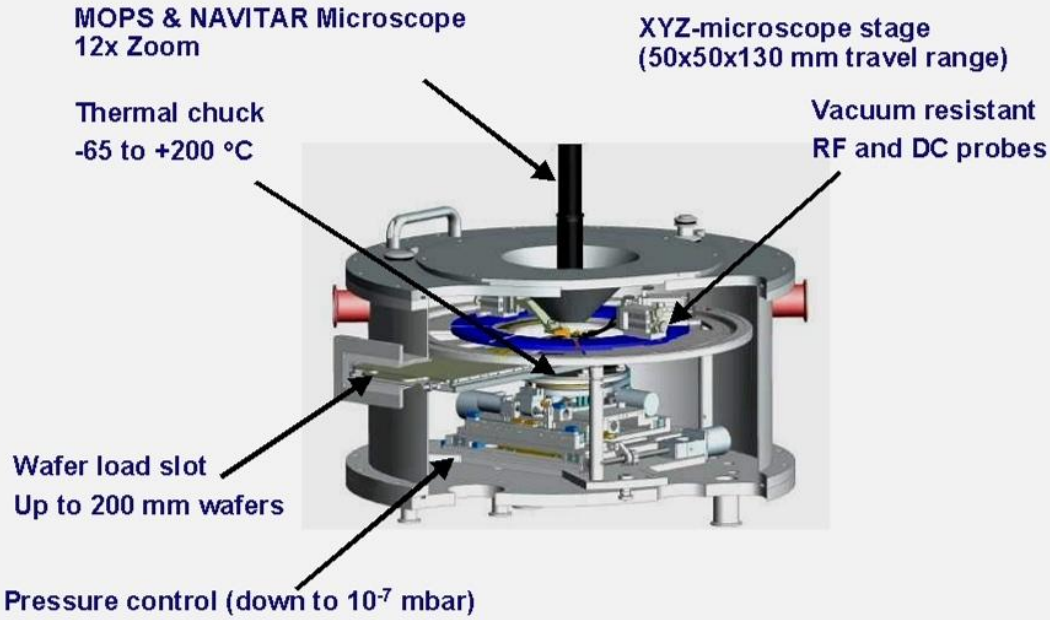


Fig. 6.5: Above: vacuum prober; below: vacuum chamber of a semi-automatic low-pressure prober (image: Suess)

Many MEMS types need to be tested in vacuum or in specially controlled atmospheres, such as RF-MEMS, micromirrors, resonators, and mass sensors. Low pressures are also needed for testing microbolometers for infrared imaging, pressure sensors, chemical sensors, and MEMS for aerospace applications. A special vacuum test station is required if tests are to be performed at wafer level. Such a station includes a complete prober with manipulators in a vacuum chamber (**Fig. 6.5**), allowing all degrees of freedom. Depending on the vacuum chamber, control of pressure from high vacuum (10^{-7} mbar) to atmospheric pressure are possible.

6.3.6 Application of Tests at Wafer Level

6.3.6.1 Gas Sensors

Based on legal requirements as well as safety and convenience features demanded by users, MEMS gas sensors are becoming increasingly important. In the application areas of automotive engineering, industry, or households, there is an increasing demand to monitor exhaust and toxic gases such as CO_X or NO_X. The use of vacuum or low-pressure chambers in conjunction with flow controls enable contactless and accurate dosing of gases down to the ppm range.

An economical alternative is to apply the gases to the sensors at the wafer level using an electrical test probe and a gas nozzle (see **Fig. 6.3**). Since this only allows measurements with limited accuracy, it should therefore be limited to application with non-toxic media.

6.3.6.2 RF-MEMS

Testing in a vacuum is absolutely necessary for MEMS that are to be operated at high frequencies. For mechanically switching elements, vacuum avoids adhesion effects, moisturization of mechanical structures, as well as the effects of air viscosity and acoustic interferences in the cavity. Recommended for such tests is a semi-automatic vacuum prober with a sufficient number of manipulators and HF test probes, if necessary up to 100 GHz. Many applications also require an additional thermal wafer chuck for temperatures of - 65 °C to 250 °C. Other characteristics of such test equipment already in use are:

- → Laser trimming facilities
- → Mechanical motion analyzers

6.3.6.3 MEMS Infrared Arrays

Microbolometers are often used to measure the temperature of objects giving off infrared radiation. For tests, such sensor components are subjected to infrared radiation with a defined wavelength. The radiation is generated by emitters installed on an aperture. Also the temperature of the wafer must be controlled and the test setup installed in vacuum to prevent heat transfer by convection. For sensor wafers, special needle-type probe cards with frontend electronics are used on the upper side and in the vicinity of the needle tips to prevent artefacts by the circuitry.

6.4 Electrical Fault Detection and Self-Tests

6.4.1 Electrical Measurements

Many fabrication faults in MEMS components lead to topological or geometric structure deviations. Defective structures can often be identified by such methods as automated microscopic testing with the aid of image-processing and pattern-recognition software. To avoid having to carry out many different tests, it is convenient to determine the faults by means of electrical measurements at wafer level. An extremely efficient strategy is fault determination by electrical stimulation. This concept was tested by Dumas et al (25) on bending beams, produced through bulk micromachining and used as magnetic Lorentz-force sensors. **Table 6.9** lists. Possible fault classes after etching and their process-based causes.

Table 6.9: Fault Classification in Deep Etching and Bending-Beam Structures (25)

Structure Faults	Cause
Completely detached	Etching is in order
Partially attached	Almost completely etched
Rigidly attached	Partially etched
Not detached	Not etched

The following questions must be posed:

- → Which physical effect is influenced by this fault?
- → How can it be electrically stimulated?
- → What reaction can be electrically determined?

To assess the effectiveness of electrically stimulated tests, physical modelling and simulations can be applied. These enables evaluation of the sensitivity to typical faults.

Regarding the magnetic sensor example, there are two phenomena that affect etching faults:

- → In case of incomplete detachment, thermal impedance is effected by changed masses and thermal conduction cross-sections – for control purposes, a heater and temperature sensor structure can be provided
- → A micromechanical beam has a characteristic resonance frequency that changes upon attachment – stimulation by a thermal pulse can also be performed here, which tests the resonance frequency with the aid of the piezoresistive structure already available for the basic functions **(Table 6.10**)

Electrical tests generally enable determination of certain faults even after complete fabrication and encapsulation. However, such a concept requires test-compatible designs and can only be used for a subset of all possible faults.

Table 6.10: Deep Etching of Bending Beam Structures – Results of Electrothermal Fault Determination by Heat Pulses and Periodic Heating (25)

Structural fault	**Time constant in ms**	**Amplitude**	**Limit frequency in Hz**	**Flat band reaction in dB**	**Thermally induced resonance peak**
Completely detached	4.2	2.6 V	19	38	Yes
Partially attached	4.2	2.6 V	19	38	No
Rigidly attached	1.5	1.1 V	57	31	No
Not detached	0.2	17 mV	600	-5	No
Test	- Pulse heating -		- Periodic heating -		

6.4.2 Built-In Self-Tests (BIST)

Depending on the parameters to be measured, such as pressure or acceleration, external physical stimulation of the microsystem might be deemed impractical, inconvenient, or too costly. Stimulation with a defined reference value can also be difficult in the application. This is why the concept of microsystems built-in self-tests was developed.

Table 6.11 Examples of Successful Applications of Built-In Self-Tests (BIST) for MEMS-SMM Surface Micromechanics, and Bulk Micromechanics (BMM) (29)

Component	**MEMS Sensor Principle**	**BIST Principle**	**Purpose**
Accelerometer	Capacitive comb structure (SMM)	Deflection by electrostatic forces	Fault detection, testing of sensitivity
Accelerometer	Seismic mass on bending beam (BMM)	Thermal bimetal deflection	Fault detection, testing of sensitivity
Infrared sensor, gas flow sensor	Thermal column array (BMM)	Built-in heater structure	Testing of function and sensitivity of all pixels

A few years ago, band-gap references were presented for autocalibration of A/D converters. The built-in self-test can be utilized not only for calibration, but also to determine whether a sensor is defective or is functioning incorrectly. For MEMS, built-in test structures are required to facilitate internal stimulation. Although built-in self-tests are currently mostly conceptual, they have already been used for industrially produced MEMS (29). One successful technique is pulse-behaviour testing in combination with pseudo-random tests (30). For built-in self-tests, it is usually necessary that a monolithic MEMS component is integrated into the test circuitry.

7 Glossary

7.1 Acronyms and Abbreviations

ADC	Analog to Digital Converter
AMR	Anomalous Magnetoresistance
ASIC	Application Specific Integrated Circuit
ASSP	Application Specific Standard Part (Product)
BAW	Bulk Acoustic Wave
BIST	Built-in Self-Tests
BMM	Bulk Micro-Machining
CMOS	Complementary Metal Oxide Semiconductor
CSP	Chip Scale Packages
DSC	Digital Signal Controller
DSSP	Digital Sensor-Signal Processor
FC	Flip-Chip
FEM	Finite Element Model
FPGA	Field Programmable Gate Array
FR4	PCB material (type FR4)
GC	Gas Chromatograph
GMR	Giant Magnetoresistance
HVAC	Heating, Ventilation, Air-Conditioning
HDI	High Density Integration (standard PCB technology for Multilayer boards)
HDL	Hardware Description Language
IP	Intellectual Property
ITRS	International Technology Roadmap for Semiconductors
LCP	Liquid Crystal Polymers
LTCC	Low Temperature Co-fired Ceramic
MEMS	Micro-Electro Mechanical System
MCU	Micro-Controller Unit
MCM	Multi-Chip Module
MID	Moulded Interconnect Devices
µC	Micro-Controller / Micro-Processor
µGC	Micro-Gas-Chromatograph
NEMS	Nano-Electro-Mechanical System
OBD	On-Board Diagnostics

PCB	Printed Circuit Board
PEEK	Polyether-Ether-Ketone
PBT	Polybutylene Terephthalate
PLD	Programmable Logic Device
PPS	Polyphenylenesulfide
RF	Radio Frequency
SAW	Surface Acoustic Wave
SIP	System in Package
SMD	Surface-Mounted Device
SMM	Surface Micro-Machining
SOC	System on Chip
SOI	Silicon on Insulator
SPC	Small Peripheral Controller
TEDS	Transducer Electronic Data Sheet
TFT	Thin-Film Transistor
TQFP	Thin Quad Flat Package
TSOP	Thin Small Outline Package
VOC	Volatile Organic Compound

7.2 Terms

7.2.1 Faults and Failure of a Sensor

- → A sensor disturbance is a reversible sensor malfunction whereby the sensor exceeds its specified tolerance band. Its causes lie in deviations within the signal processing chain. By subsequent calibration of the sensor, such faults can be corrected. If the faults are not identified, considerable costs may be incurred by the user (see Sensor Self-Monitoring).
- → A sensor failure is an irreversible sensor malfunction whereby the sensor exceeds its specified tolerance band. There is no new stationary state of the sensor. Rather, the output signal is wrong and does not react adequately to measurand stimuli. Subsequent recalibration of the sensor is impossible.
- → **Fig. 7.4** and **Fig. 7.5** show a typical fault and failure during static sensor behaviour.

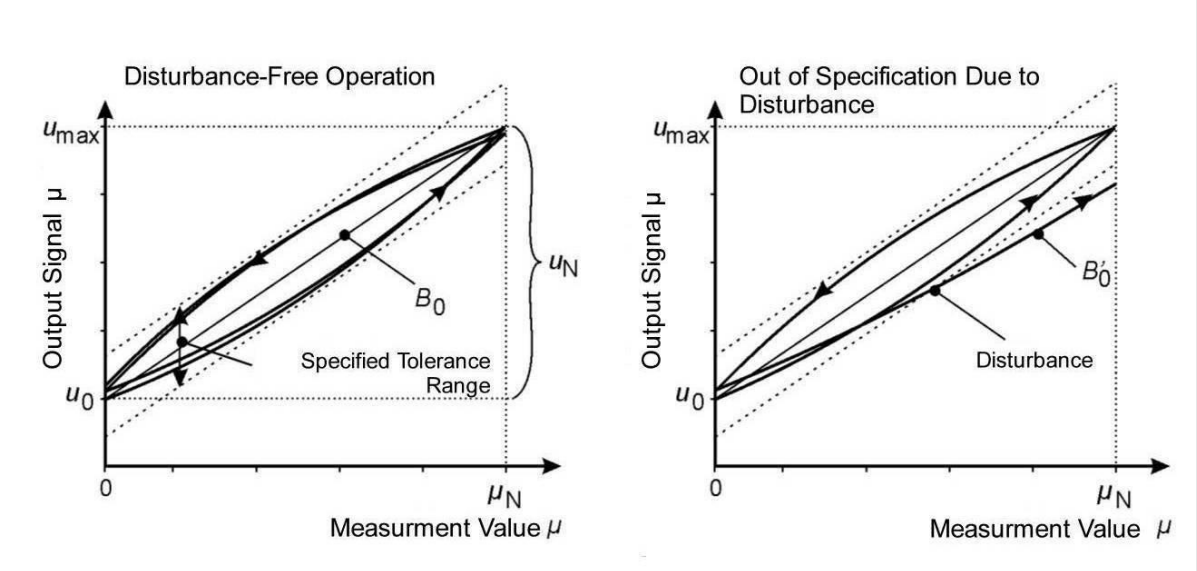


Fig. 7.4 Occurrence of a failure or fault of the static transfer behaviour in a sensor (14)

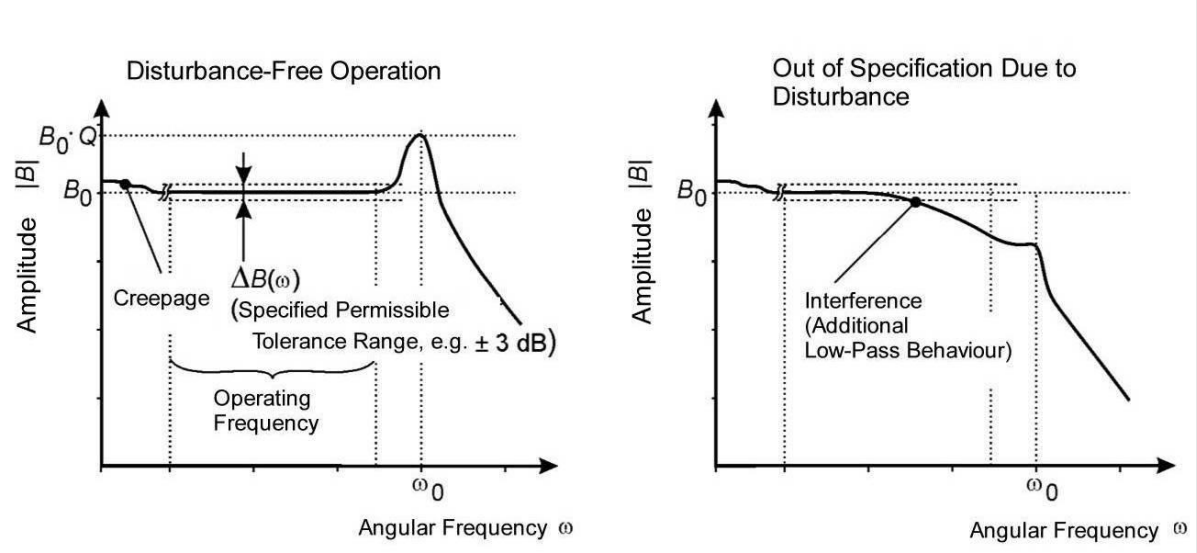


Fig. 7.5 Fault-free dynamic operation of a sensor and the occurrence of a fault (14)

7.2.2 Measurement Parameter, Value and Signal

The measurement parameter is the physical, chemical, or biological property of the measurand to be determined. Depending on its sensitivity, a sensor converts this into a measurement value, expressed numerically and with a unit of measure, e.g. a gas pressure of 5 bar as an output voltage of 5 V. The time-dependent course of the output is referred to as the measurement signal.

7.2.3 Measurement Uncertainty

Simplified: Tolerance range from superimposed systematic bias and random errors. Characterizes the range of uncertainty when correlating sensor output signal and measuring parameter. Thus it provides the overall error of a sensor under concrete application conditions (for a detailed explanation and computation instructions, see GUM, IEC/EN 16770). In the medium term, a transition is to be expected from stating errors to stating the measuring uncertainty; also see 7.2.13 → Sensor Errors.

7.2.4 Measuring Method

Two types of measuring method are basically distinguished:

1. With auxiliary power

→ Deflection methods, e.g. capacitive, resistive, piezoresistive, magnetic, optical, inductive sensor elements
→ Compensation methods, e.g. electrodynamic balances
→ Comparative methods, e.g. balances with mass pieces
→ Differential methods, e.g. thermocouples
→ Correlation methods, e.g. acoustic flowmeters

2. Without auxiliary power
→ Electrodynamic converters, e.g. speed sensor
→ Electrostatic converters, e.g. electret microphone
→ Piezoelectric converters, e.g. acceleration sensor
→ Magnetostrictive converters, e.g. torque or force sensor

7.2.5 Measuring Principle

The physical conversion principle of the sensor element, often referred to its active principle. It describes the physical functioning by which the sensing element generates its electronically usable intermediate signal, e.g. a change in resistance, capacity, resonance frequency, or charge, from the state to be measured (measuring parameter).

7.2.6 Measuring Process

Combination of conversion (measuring principle) and signal conditioning (measuring method) of a sensor element.

7.2.7 Output Signal

Electrical signal obtained from the sensor secondary electronics for further processing (Fig. 7.1). May be electrical, optical, wireless, analogue or digital, and may comply with some standard, such as 0 to 10 V, 4 to 20 mA, digital AS interference, CAN bus, Profibus etc.

7.2.8 Primary Electronics

Interface electronics for the sensor element. Invariably analogue. Describes that part of the sensor electronics which converts the intermediate signal from the sensor element to an analogue, electrical signal, including amplification, after which the signal is not as susceptible to interference, e.g. voltage, current, or frequency. Optimizes the signal for a subsequent A/D converter or a counting component of the digital processing electronics. For analogue condi-

tioning it often also realizes rough compensation of systematic errors. Increasingly merging with secondary electronics.

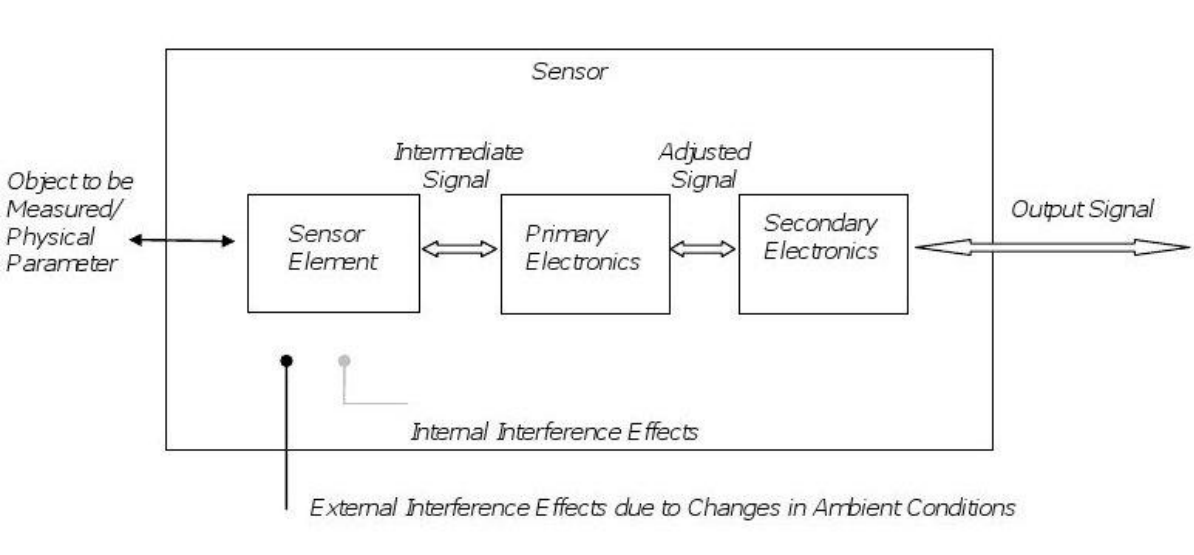


Fig. 7.2 Generalized signal-conditioning chain inside a sensor

7.2.9 Secondary Electronics

That part of the sensor electronics which processes the analogue electrical signal coming from the primary electronics, digitally or analogue to a standardized output signal. Besides correcting systematic errors and filtering random errors, it can include further functions, such as sensor self-monitoring or adaptation to an analogue or increasingly digital standard interface, e.g. a data bus. Secondary and primary electronics are increasingly being merged.

7.2.10 Sensor

A collective term for a product that generates a defined, electronically usable output signal out of a measuring parameter (**Fig. 7.2 and 7.3**). A basic version of a sensor will e.g. consist of an unhoused sensor element on a socket with electrical contacts. A more complex sensor can, for example, include housing, a standard process connection, as well as an internal microprocessor control and signal processing with a calibrated output to a wireless network link.

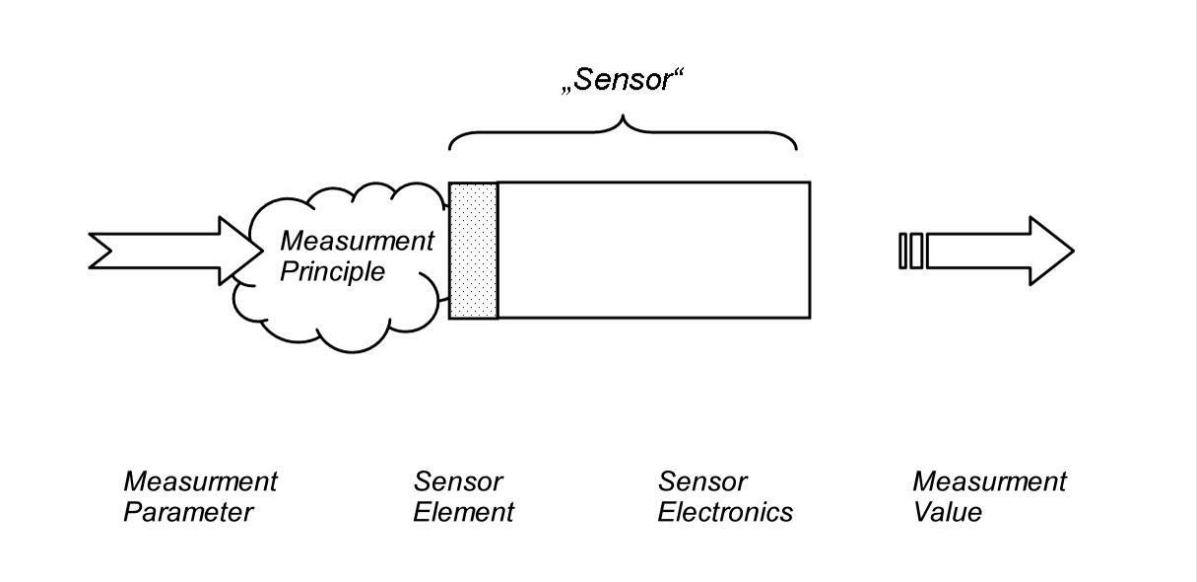


Fig. 7.3 A measuring parameter is converted by the measuring principle at the sensor element into an internal signal. After possible further processing, a measuring value is available as a signal at the output, e.g. incident light intensity as an analogue voltage value.

7.2.11 Sensor Characteristic

A characteristic value that describes the ideal and real, static and dynamic transfer behaviour of a sensor. **Table 7.1** lists some examples to illustrate this.

Table 7.1: Some Examples of Characteristics and Their Significance

Characteristic	**Significance**
Transfer factor (also: sensitivity)	Gain in static response curve (ratio of measurement value to measurement parameter)
Nominal signal	Maximum sensor input or output signal after subtracting the offset
Zero or offset of the measuring parameter	Shift of the sensor output signal at zero input parameter
Measuring uncertainty	Characteristic measure of the deviation of the real from the ideal transfer behaviour

7.2.12 Sensor Element

Also sometimes referred to as primary sensor. Basis for every sensor. It converts the measuring parameter into an analogue, electronically usable intermediate signal, e.g. into a change of an electrical resistance, a capacity, charge, frequency, etc. Often also called sen-

sor elements are minimal OEM assemblies, comprising the actual sensor element on a mounting socket with an electrical lead, possibly encapsulated, e.g. oil-filled stainless-steel pressure cells, incl. piezoresistive silicon pressure element (see measuring cell in **Fig 7.1**).

7.2.13 Sensor Error

- → Absolute, relative (to the actual value) or reduced (to a nominal value) deviation of the real sensor value from the ideal nominal value. The deviation can be systematic or random.
- → Static and dynamic errors:
  - → Static errors: The sensor is in a stationary state (transient effects have subsided), dynamic errors are neglected
  - → Dynamic errors: Static errors are neglected, the sensor is considered to be a linear transfer system
- → Sensor inherent errors: No measuring parameter is available at the sensor input, but a systematic, time-dependent output signal is measured – zero drift – or a random output signal – sensor noise.
- → Creepage: Change in the sensor output signal after input to nominal signal or nominal signal to zero (systematic dynamic error)
- → Drift: Time-dependent system change of the output signal for measuring parameter zero
- → Changing external Influences: Influence of external interference parameters, such as temperature and humidity changes; approximated linear dependence is described by influence coefficients, such as temperature coefficient of the zero point or of the transfer factor. Compare 7.2.6 → Measuring Uncertainty.

7.2.14 Sensor Network

Interconnection of multiple autonomous sensors with individual or common processing electronics.

7.2.15 Sensor Nodes

A sensor node has the task of gathering sensor signals, processing them, storing them, and transmitting them to other sensor nodes or a control station by using an agreed protocol. For these purposes, a sensor node is equipped with:

- → One or more sensor elements

- → Primary and secondary electronics
- → Data memory
- → Power supply
- → Wire-bound or wireless communication hardware
- → Necessary software

7.2.16 Sensor Reconfiguration

Sensor “repair” by which a redundantly operating sensor eliminates the deviating unit upon self-monitoring and comparison between three or more redundant sub-units.

7.2.17 Sensor System

Integration of a number of similar sensors into a sensor array or for different measurement parameters, into a single housing.

7.2.18 Sensor-Actuator System, Direct Coupling

Integration of sensors and actuators including relevant signal conditioning in a single component or device.

7.2.19 Transducers and Transmitters

These are antecedent to the generic term “sensor”. Depending on the output signal and housing, a sensor was in the past often classified as a transducer or a transmitter. The term transducer generally designated a sensor with an uncalibrated, but possibly preamplified signal. The term transmitter generally designated a housed sensor for industrial process control with a calibrated analogue or digital output signal suited for transmitting over a distance of a number of metres, e.g. 4 to 20 mA, CAN bus, Profibus.

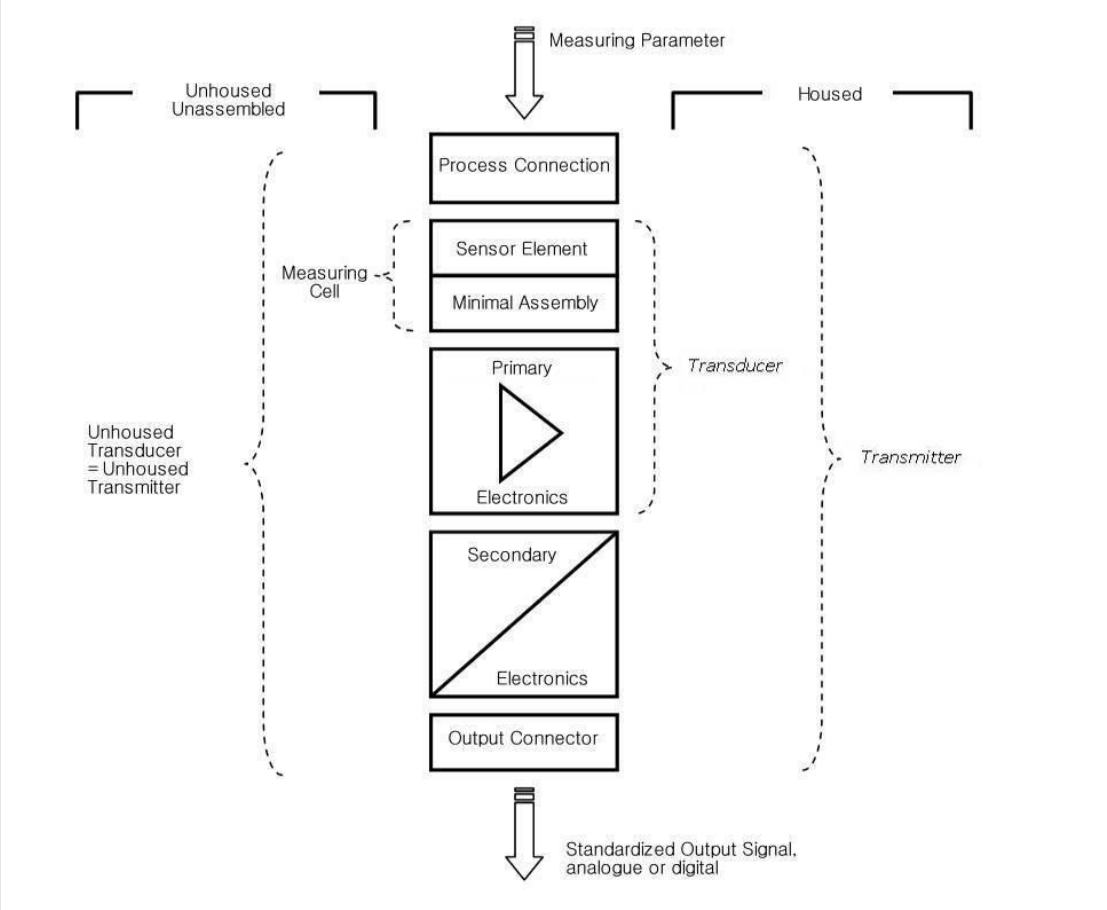


Fig. 7.1 Classification of the Superordinate Term “Sensor” and Subordinate Terms

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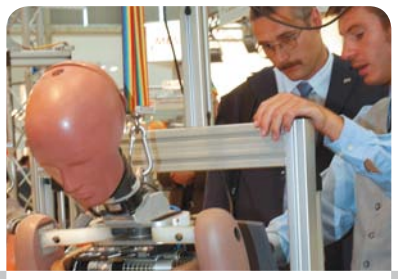
Sensors – the Sensory Organs of Technology ...

... save lives,



... provide safety,

... protect our environment,

... and improve our quality of life.

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