The history and future prospects of Azbil's MEMS technology

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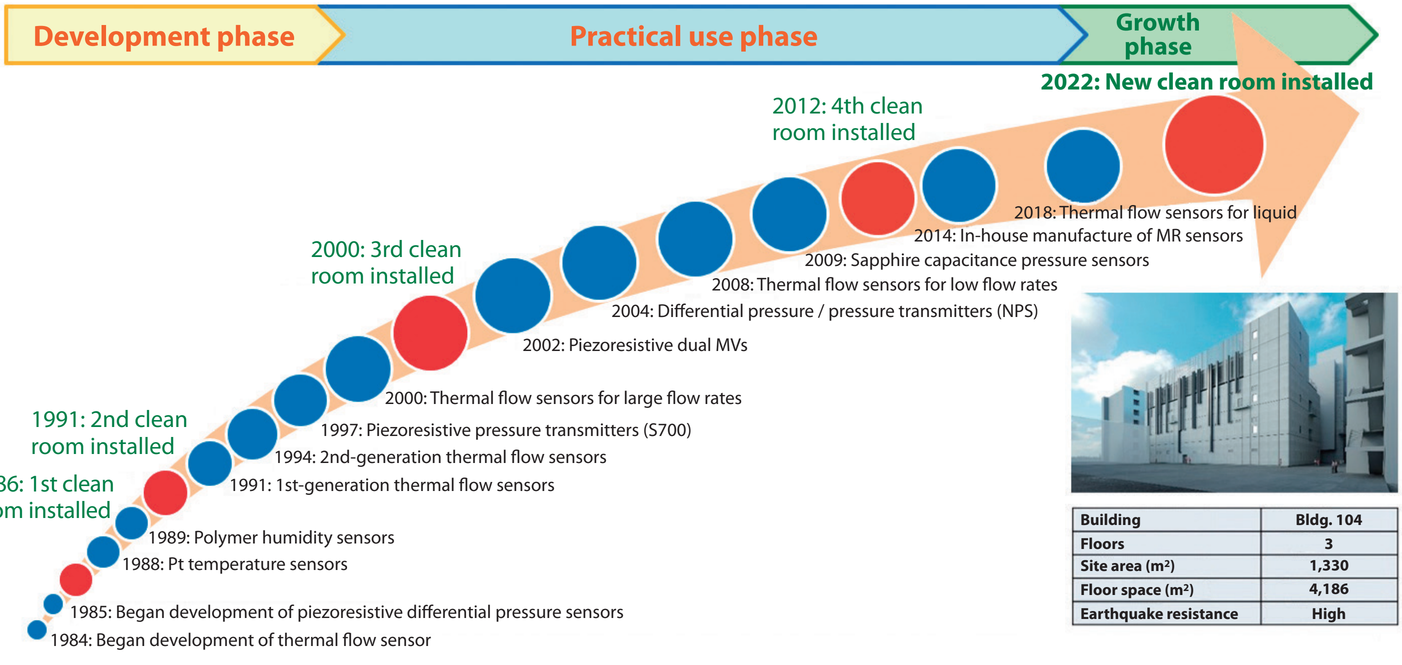
Key words

MEMS, pressure sensor, piezoresistive pressure sensor, sapphire, micro-flow sensor, MR sensor, corrosion resistance

For Azbil, in its mission to provide people with safety, comfort, and fulfillment, and to preserve the environment by utilizing measurement and control technology, and following its philosophy of "human-centered automation," sensors are a key component, and microelectromechanical systems (MEMS) are a very important core technology for realizing high-performance, high-value-added sensors. Azbil noticed this early on, and in the mid-1980s began constructing a cleanroom and developing application technology for MEMS sensors. This paper looks at the history, technology, and features of major MEMS sensors and discusses future prospects.

1. Introduction

MEMS stands for "microelectromechanical systems," which are devices that integrate not only electrical components but also mechanical components into electronic devices using microfabrication techniques. In recent years, MEMS technology is increasingly being used in sensors.



Building	Bldg. 104
Floors	3
Site area (m²)	1,330
Floor space (m²)	4,186
Earthquake resistance	High

Fig. 1. Path of MEMS development and sales launches

MEMS research began during the 1950s and 1960s. In Japan, an automobile-related company released a MEMS pressure sensor in the 1960s. While exploring electronics-related research in the mid-1980s, Azbil chose to concentrate on MEMS development, due to its relevance for Azbil's business, with its focus on small-quantity, large-variety sensor production, which differentiated Azbil from other companies. The industrial market for sensors, one of Azbil's areas of expertise, demands a variety of characteristics at a high level, which many commercial products struggle to satisfy. The required qualities include high accuracy, reliability, long life, low power consumption, and stable supply over a long period of time. Accordingly, we needed to develop customized MEMS sensors to provide significant differentiation and added value to our in-house products. Initially we had no clean room, and therefore we had to start the research process from zero. Since then, 37 years have passed, and various MEMS sensors have been developed and installed in our products. Starting with the micro-flow sensor, which first appeared on the market over thirty years ago, many of these sensors are still in production today. Each MEMS sensor is unique in terms of its materials, structure, production processes, and so on, and therefore is labor intensive and takes a long time to develop. Because MEMS sensors are difficult to manufacture and have unique characteristics, these properties along with the large size of the market make a relatively high barrier for competitors to enter this field. Once developed, many sensors have a substantial competitive advantage for a long period of time. Figure 1 shows the path of Azbil's MEMS development.

2. Main MEMS sensors

The following describes the history, technological uniqueness, and future prospects of the four types of sensors that we have developed so far with MEMS technology: the micro-flow sensor, piezoresistive differential pressure and pressure sensor, sapphire capacitance pressure sensor, and magnetoresistive (MR) sensor.

2.1 Micro-Flow Sensor

In 1984 we began research and development for a MEMS flow sensor for gases. In 1994, we began mass production of an airflow sensor to control the air-fuel ratio of water heaters. We then expanded the sensor chip lineup for high flow velocity to micro flow rates, increased applicable flow velocity and flow volume ranges, and commercialized mass flow controllers with integrated control valves. In 2017 we developed a flow sensor for micro-flow liquids [1] by applying MEMS technology gained through our experience with gas flow sensors. To date, we have sold more than 6 million flow sensors. Figure 2 shows examples of products developed by application of the micro-flow sensor.

Digital mass flow controller

Compressed air flowmeter

Panel-mount mass flow controller

Mass flow controller (micro flow rate model)

Mass flowmeter

Flow sensor for checking vacuum suction

Natural gas calorimeter

Micro flow rate liquid flowmeter

Fig. 2. Sample products incorporating the micro-flow sensor

2.1.1 Sensor structure and unique technology

The flow sensor chip consists of a 1 μm thin silicon nitride diaphragm formed on a 1.7 mm × 1.7 mm silicon substrate. In the center of the diaphragm sits a platinum film heater with temperature sensors on its upstream and downstream ends. Because there is a hollow structure made by anisotropic etching under the diaphragm, the chip has features such as extremely low heat capacity in the flow velocity detection region, high sensitivity, fast response, and low power consumption.

The properties of the silicon nitride film that serves as the diaphragm are critical to the design and production of the flow sensor. The diaphragm's thickness is only 1 μm but the diagonal length is over 1 mm, constituting an extremely high aspect ratio. Due to this structure, the internal stress on the film is too high for the diaphragm to retain its flatness. Because the deflection of the diaphragm affects fluctuation, drift, and reliability of the sensor output, an extremely low stress film is required. On the other hand, the silicon nitride film serves as protection for the thin platinum film on the heater and the temperature sensors in the flow velocity detection area. Therefore, the silicon nitride film must have good step coverage and be dense enough to withstand long anisotropic etching times. Generally, dense film has higher internal stress, but with our proprietary deposition process the silicon nitride film in this device successfully provides the desired step coverage, chemical resistance, and density while also satisfying low internal stress. The film also exhibits very low stress fluctuation under conditions such as both high and low temperatures and high humidity. This technology enabled us to create a flow sensor with extremely small drift in characteristics like the zero point and sensitivity. Figure 3 is a scanning electron microscope image of a sensor chip cut to reveal the flatness of the diaphragm.

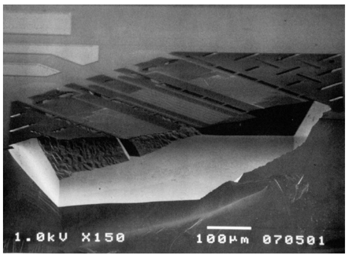
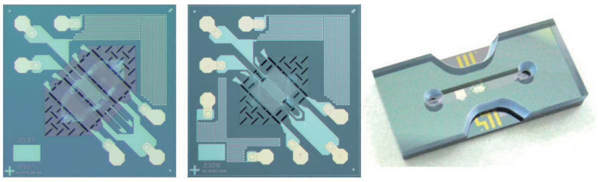


Fig. 3. Scanning electron microscope image of a sliced sensor chip

2.1.2 Flow sensor products

The first flow sensor we developed was designed for accurate measurement in the low flow velocity range based on required specifications. As we extended our product line for various flow rate ranges, the need to measure velocities up to the high flow velocity range increased. We developed a sensor chip for high flow velocities for a thermal flow sensor, with the ability to adjust flow velocity sensitivity based on the distance between the heater and the upstream and downstream temperature sensors. New needs also arose for measurement in micro flow rate ranges, but our original method of inserting the sensor into the flow channel could not be adapted for these ranges, because the large channel cross section resulted in velocities too slow for accurate measurement. Therefore, we made full use of MEMS technology to produce a micro flow channel with 1 mm width and 0.5 mm height which was attached to the surface of the sensor chip to create an integrated flow channel. With these three types of sensor chips, we cover a wide flow rate range, from a micro flow rate of 5 mL/min all the way up to 2,500 L/min. Figure 4 shows our flow sensor chip types.



Low flow velocity sensor

High flow velocity sensor

Micro flow rate sensor

Fig. 4. Types of flow sensor chip

Our development of flow sensors is not limited to those for gases, but has expanded to cover liquids as well. To take advantage of the characteristics of thermal flow sensors, and hence to focus on the micro flow rate range, we will continue to develop products with improved accuracy and response time, increased flow rate range and applicable liquid types, etc.

2.2 Piezoresistive differential pressure/pressure sensors

Piezoresistive sensors have a long history. The piezoresistive effect, in which the electrical resistance changes according to stress, was discovered in the 1950s [2]. Honeywell [3] and Toyota Central R&D Labs [4] released pressure sensors based on this effect in 1962 and 1964, respectively, and the sensors have found an expanded application range mainly among inexpensive consumer products and automobiles.

Later, in 1983, Honeywell launched a smart differential pressure and pressure transmitter for industrial applications. In 1985, Azbil, which was at that time named Yamatake-Honeywell, proposed to reduce the cost of the package, and began joint development of a differential micro pressure sensor in 1986, which marked the start of our full-scale development of pressure sensors. We installed ion implanters and oxidation/diffusion furnaces to prepare for a fully in-house development system in 1991, and first embarked on commercializing a product lineup that was not available from Honeywell. In 1995 we developed the pressure transmitter [5], and in 2002 a multi-variable pressure sensor [6] in which two sensor chips are used for measuring differential pressure and static pressure. After this, we developed and distributed various products, including the factory air management flowmeter, the steam flowmeter, and differential pressure transmitters with temperature and pressure compensation. In 2004, we developed a high-accuracy sensor that led to our main differential pressure and pressure transmitter, model GTX_ _ _, which has recently passed the one million mark of units produced (fig. 5).

Pressure sensor Steam flowmeter Air flowmeter

Differential pressure transmitter with temperature and pressure compensation

Differential pressure transmitter / gauge pressure transmitter

Differential pressure transmitter / gauge pressure transmitter Model GTX_ _ _

Fig. 5. Products incorporating a piezoresistive pressure sensor

2.2.1 Distinctive original technology of piezoresistive pressure sensors

Pressure sensors for industrial applications, in addition to requirements for accuracy and performance, must have a high level of reliability and have a long product life. Here we will describe the advanced proprietary technology that achieved the current high level of accuracy and reliability. Figure 6 shows the chip and package of the typical differential pressure and pressure transmitter.

Fig. 6. Piezoresistive pressure sensor chip and package

Temperature fluctuation and static pressure produce distortion at the interface between different materials, specifically between the Si chip, the glass seat used for electrical insulation, and the stainless steel housing. Since these are all sources of noise, we make full use of structural analysis of the joints and surrounding areas to adopt structures that prevent noise transmission to the piezoresistive element. The temperature and static pressure sensors are located separately, with noise compensation for both. To achieve high accuracy, we thoroughly investigate methods of eliminating sources of noise.

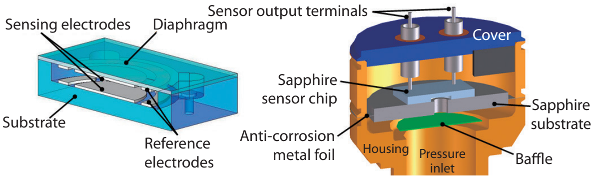
As for stability and reliability, in addition to our unique method of optimizing the concentration of impurities in the piezoresistive element, we improved the tolerance of the surface SiO_2 layer to ion impurities such as Na^+. As a result, we obtained a very high level of stability and reliability [7], with an accuracy of 0.01 % FS for over 12,000 hours at 125 °C, an extreme operating condition beyond the assured accuracy range. We wish to note that once during the testing process, the thermostatic chamber failed due to over 12,000 hours of testing under harsh experimental conditions. This forced us to stop the testing process, but the condition of the sensors was perfectly normal.

2.2.2 Future prospects

Although piezoresistive pressure sensors have already achieved a high level of maturity, they are continuing to advance. In terms of the pressure which differential pressure sensors can withstand, for example, we have reached 7 MPa for the low pressure end on the back of the chip in the 100 kPa range. This is approximately 70 times the measurement pressure. In the future, we will continue to pursue these ultra-high pressures.

2.3 Sapphire capacitance pressure sensors

Industrial pressure sensors often use silicon as a substrate, where an encapsulated oil structure with a metal barrier diaphragm is used to ensure corrosion resistance. This sealed-oil structure is a restriction, which prevents measurement at high-temperature or ultra-low vacuum. In addition, food, medical, chemical, and semiconductor manufacturers tend to avoid such sensors for fear of oil leakage. To overcome these obstacles, we turned our attention to sapphire, a material with high corrosion and heat resistance. Through research and development to use sapphire in pressure sensors, in 2009 we developed a sapphire capacitance pressure sensor that does not contain encapsulated oil [8]. Currently, this type of sensor is mainly installed in process chambers for semiconductor production. Because various corrosive gases are used in semiconductor processes, the corrosion resistance of sapphire and the reduced size of the pressure sensor itself due to MEMS technology are both significant advantages for this application area. Figure 7 shows a cross-sectional schematic of a sensor chip and package.



Sapphire sensor chip Sapphire sensor package

Fig. 7. Cross-sectional schematic of a sapphire sensor chip and package

2.3.1 Distinctive original technology of sapphire pressure sensors

For the sensor chip production process, we developed a technology to directly bond two pieces of sapphire together without an intermediate layer. Through steps such as cleaning the sapphire cavity substrate and diaphragm substrate surfaces, alignment, pressure adhesion, and heat treatment, the two pieces of sapphire are strongly bonded together, forming the pressure-sensing element of the sensor. Cross-sectional images by a transmission electron microscope (TEM) indicate that the pieces are bonded at an atomic level (fig. 8). In addition, when attaching the sensor chip to the package housing, corrosion resistance must be ensured, and mechanical and thermal stress must be reduced. To accomplish this, we reduced stress by interposing a thin anti-corrosion metal plate between the sensor chip and the housing, along with the use of diffusion bonding for the connection. As a result of these processes, the junction has the necessary strength, corrosion resistance, thermal resistance, and airtightness. The junction of sapphire at the atomic level is confirmed by cross-section TEM images in fig. 9.

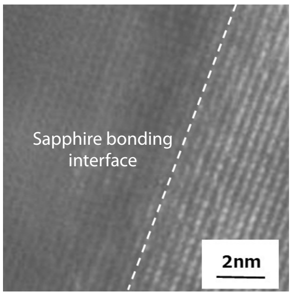


Fig. 8. Cross-section TEM image of a direct sapphire joint

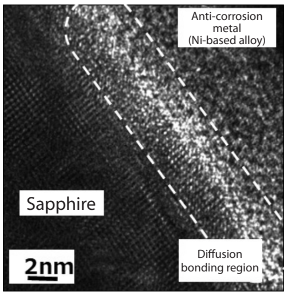


Fig. 9. Cross-section TEM image of a diffusion bond

2.3.2 Corrosion resistance of sapphire

It is a well-known fact that sapphire is highly resistant to corrosion. However, its resistance to specific corrosive gases used in semiconductor processes is mostly unclear. As a result, we are conducting joint research with Osaka University on the corrosion resistance of sapphire [9]. To overcome the problem with electrification during the evaluation of sapphire, we used a polycrystalline aluminum oxide film (Al_2O_3) in lieu of sapphire to measure etching rate in response to Ar, F, and Cl ion beam irradiation. As a result, it became clear that the etching of Al_2O_3 is slower than that of anti-corrosion metal Inconel, and that Al_2O_3 is more advantageous. Figure 10 shows a comparison of etching rate by material when exposed to various gases. We plan to conduct experiments using sapphire going forward.

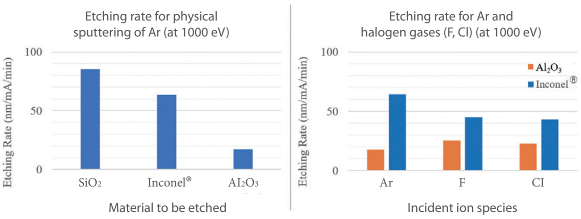


Fig. 10. Etching rate comparison by material with various gases

2.3.3 Future prospects

To meet the needs of semiconductor processes, which evolve with amazing speed, we are developing a new model with greatly improved sensor structure that is compact, highly pressure resistant, and low cost while taking advantage of the superiority of the sapphire material. In addition, we are taking a variety of measures to expand the application range of sapphire pressure sensors, such as implementing countermeasures for any drift of characteristics attributable to the accumulation of reaction products on the sensor surface, which has become a problem in semiconductor processes [10], and achieving higher operating temperatures to support the gases used in newly developed processes.

2.4 Magnetoresistive (MR) sensors

An MR sensor is integrated into our smart valve positioner 300 and 700 series as a valve position detection sensor. Previously, we procured MR sensors from an outside company, but when the supplier withdrew from business, the need for a stable long-term supply drove us to begin in-house development in 2009. We started installing our own MR sensors in products when development was completed in 2013. More than 550,000 related products have been produced, but no failures in the field that are attributable to the sensor have been reported even after more than nine years of distribution, demonstrating the sensor's high reliability.

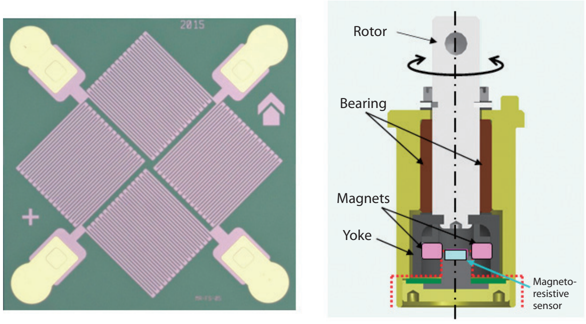
2.4.1 Sensor structure and unique technology

MR sensors use the anisotropic magnetoresistive effect (AMR effect) in ferromagnetic metal thin films. The electric resistance R changes depending on the relative angle θ between the current applied to the thin film and an externally applied magnetic field. At a constant temperature, this effect is represented by equation (1).

$$R = R_0 - \Delta R^{*} \sin 2\theta \qquad \text{Equation (1)}$$

R_0 : Electrical resistance without a magnetic field

For the sensor chip, a ferromagnetic NiFe film in a serpentine pattern across a 2 mm square glass substrate forms four resistors. Each resistor is rotated by 90° so that the whole component acts as a bridge circuit. To operate the sensor chip as an angle sensor (potentiometer), a magnetic field is applied to by sandwiching the substrate between two neodymium magnets attached to a rotor (fig. 11).



Sensor chip Potentiometer cross section

Fig. 11. Sensor structure

A valve positioner is an industrial device that requires characteristics such as high accuracy, high reliability, long life, and low power consumption. With regard to low power consumption, all components in the positioner, including the electrical circuit, must be driven by a 4–20 mA control signal. Also, the sensor was required to have a resistance of 10 kΩ. An NiFe film only 30 nm thick is used in the positioner because of its magnetic characteristics.

If any stress other than an external magnetic field is applied to the NiFe film, its resistance will fluctuate, causing measurement accuracy to deteriorate. We therefore needed a method to reduce this stress. We adopted a dense low-stress silicon nitride film that we were able to develop through our experience with the micro-flow sensor as a passivating film on the surface of the NiFe film. However, the sensor characteristics differed with different deposition conditions, and therefore we optimized the deposition process to minimize characteristic shift for MR sensors. In addition, since the resistance of NiFe film also reacts sensitively to the residual stress from the adhesive used to attach the chip or from the surface coating agent, we selected an adhesive and coating agent with a low Young's modulus to prevent stress on the sensor chip, and we also optimized the amount applied and the application conditions.

If the center of the sensor chip and the center of rotation of the magnetic field are misaligned, the sensor output will deviate from the ideal sine curve, which lowers measurement accuracy. To resolve this problem, we determined the acceptable range as well as the placement of components through simulation and experimentation, designing tolerances for each component. In particular, for the sensor holder where the sensor chip is mounted, we use a thermosetting resin with high dimensional accuracy for resin molding, and we devised a method to integrate an alignment mechanism to keep spatial deviation within tolerances when mounting the sensor chip.

2.4.2 Future prospects

We have acquired the fundamental technologies needed for magnetic sensors through the development of an MR sensor for valve positioners. However, there are many objects other than valves in our field of business that require position detection. Magnetic sensors are capable of contactless position detection and are advantageous in terms of environmental resistance and reliability, along with low operating cost due to low current consumption. While continuing to apply this technology to detect the position of objects, we will also analyze positional data for use with other applications, such as detecting warning signs and symptoms of abnormality and predicting service life.

3. Conclusion

We have discussed Azbil sensors made with MEMS technology. As the trends seen in figure 12 suggest, the range of application of MEMS technology will surely continue to expand beyond simple quantity measurements and transition to quality measurement, applications combined with AI, synergy with digital transformation, autonomy in automation, and evolution from the sale of products and services to the sale of experience. Accordingly, we will continue to cultivate MEMS technology, which is at the heart of the measurement and field devices in our core competence areas of measurement and control. Additionally, we will take on the challenges of new areas and new critical technologies, aiming to make contributions leading directly to the achievement of the SDGs, which serve as milestones on the road to a more sustainable society.

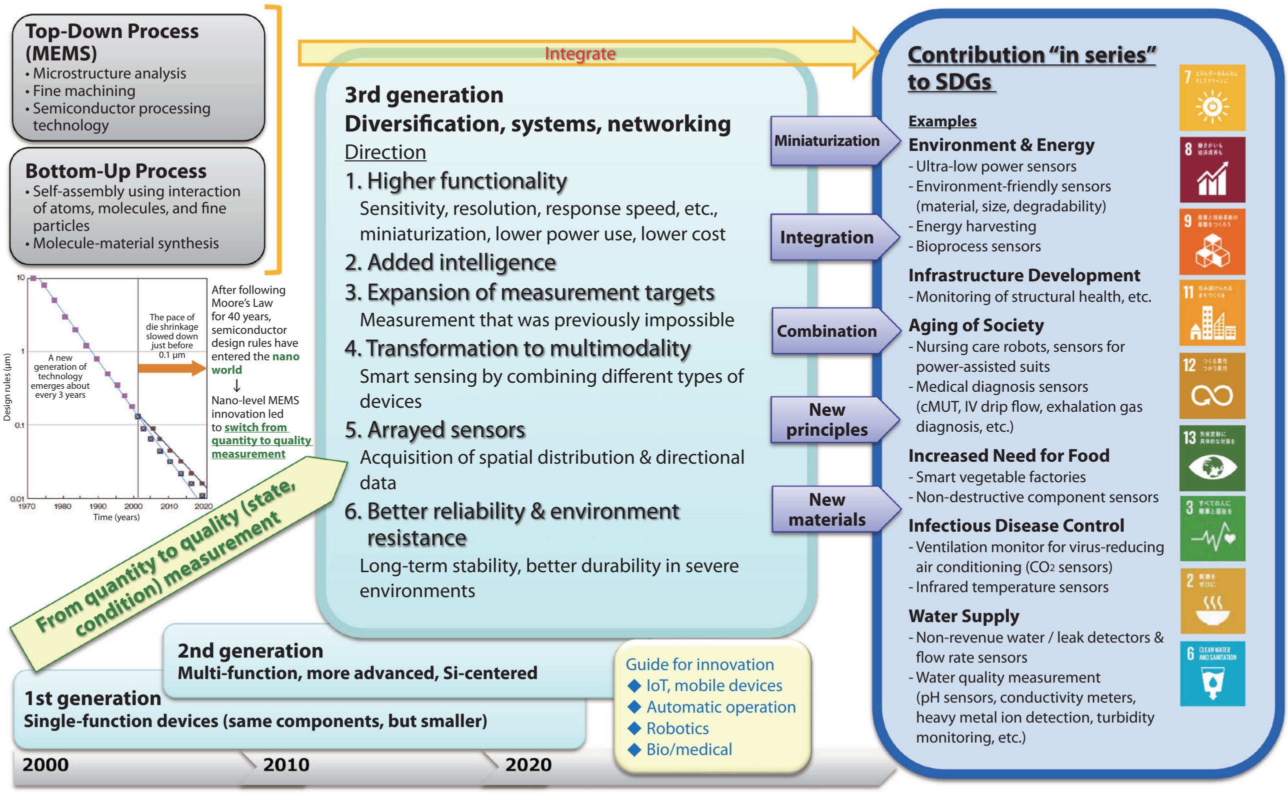


Fig. 12. Trends in MEMS

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