Microsystems at work

A fast oxygen sensor for continuous gas analysis

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Drawing on 40 years of experience in the design and development of continuous gas analyzers, ABB has devised a more effective, harder-wearing, lower-cost solution from scratch. By combining new materials with cutting-edge micro-electromechanical system technology, the company has come up with a radically new sensor system that competes well with its rivals in terms of performance, durability and cost.

These lower costs, gleaned largely from the ability to mass-produce the new instrument, along with a faster response time and an ability to cope with variable gas flow rates, will significantly influence the future of oxygen concentration measurement.

ABB's continuous gas analyzers, the Advance Optima 1 and EasyLine series, use high performance technology to measure the concentration of gases in various aspects of processing industries. Such measurements are vital to environmental protection, process optimization, quality assurance and cost reduction. The analyzers are used for continuous emission-monitoring of power plants and waste incinerators 2, and, among other applications, to guarantee the purity of gases in air separation plants, to measure flammable gases in hazardous locations, to protect electrostatic dust filters, and to optimize combustion processes in harsh environments such as cement plants. Both the Advance Optima and EasyLine gas analyzers are based on modern modular analyzer technology that uses state-of-the-art electronics, intelligent algorithms and improved continuous measuring technology.

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A gas that is of interest to nearly all industrial processes is oxygen. Its concentration is usually measured using electrochemical cells or paramagnetic sensors. Electrochemical cells offer a significant cost advantage over paramagnetic sensors, but have longer response times (in excess of 20 seconds) and reduced lifetimes when exposed to dry gases. Their high cross-sensitivity (sensitivity to gases other than oxygen) and low compatibility with corrosive gases (eg, sulfur, chlorine and fluorine compounds) generally limit their use to applications in which the components of the gas mixtures are known. Paramagnetic sensors, despite their cost, offer a number of advantages over electrochemical cells. In these sensors, the interaction of the gas with the sensor is physical rather than chemical, so the poisoning that is typically observed in electrochemical sensors does not occur. In non-corrosive atmospheres, paramagnetic sensors have, in principle, an endless lifetime. And if the correct materials are chosen, they can achieve extended life times, even in dedicated corrosive atmospheres. In addition, the cross sensitivity of paramagnetic sensors is negligible. Overcoming the present production drawbacks and further enhancing the performance of paramagnetic oxygen sensors will open up new market segments and allow production volume to be increased.

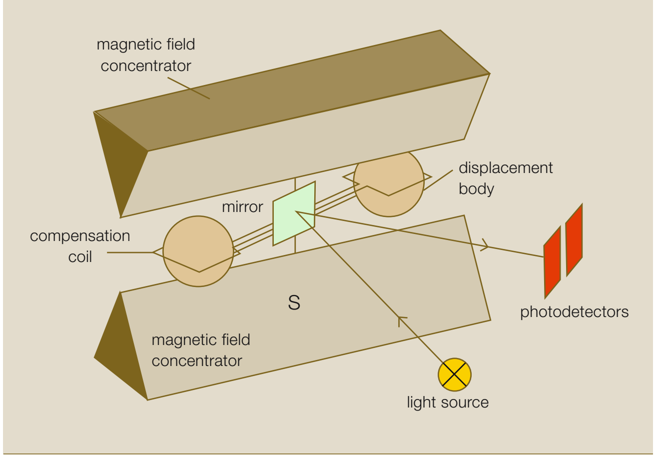
Paramagnetic oxygen measurement, the basics

Paramagnetic oxygen sensors are used to evaluate the magnetic properties of

2 Typical application area for oxygen sensors: emission monitoring in power plants

1 The Advance Optima range of continuous gas analyzers

3 Arrangement of the displacement body in a paramagnetic oxygen sensor



gas mixtures. Unlike most other gases, oxygen molecules exhibit a relatively strong, positive susceptibility and are therefore paramagnetic. Since most other gases exhibit a low diamagnetic susceptibility, the magnetic susceptibility of a gas mixture depends strongly on its oxygen content. This property is exploited by so-called magneto-mechanical oxygen sensors, which measure the magnetic susceptibility of a mixture and thereby determine the portion of oxygen present. Measurements are taken using a displacement body located in a strong magnetic field gradient and a torque measurement setup 3. Briefly, the torque generated on the probe body in the presence of oxygen is compensated by a small current in a coil that is fixed to the same probe body. To keep this compensation in balance, an optical detection unit measures the position of the probe body. The sensor driver electronics chooses the compensation current such that the position of the probe body is kept constant at all times. The current needed to compensate for the torque generated by the oxygen is a direct measure of the oxygen concentration in the sensor cell.

Conventional paramagnetic oxygen sensors

The geometry of the sensor elements used in conventional paramagnetic oxygen sensors is as shown in 4. The sensor itself consists of classically machined parts that are assembled manually. The core of the sensor, with a dumbbell-shaped probe body (with a diameter of approximately 2 mm and a length of 20 mm), is depicted in 5. To manufacture this element with sufficient reproducibility, highly skilled staff are needed. The construction of the small glass bulbs and their installation is time-consuming and the materials used for the mounting brackets are not compatible with highly corrosive gases. The performance of today's sensors is, however, excellent for many applications, especially for emission monitoring in fossil-fired power plants. Based on this paramagnetic principle, ABB offers a module for the measurement of oxygen concentration that can be used with both the Advance Optima and EasyLine series of continuous gas analyzers.

The main characteristics of the sensors are:

- minimal measuring range of 0 .. 1 vol% O_2
- detection limit of 50 ppm O_2
- response time of 3 seconds

The cross sensitivities to other gases are listed in the Factbox. The table shows the zero-point shift of the output signal when undiluted gases are present. The values indicate that this zero-point shift is caused by the magnetic properties of the gases and are the unavoidable remaining – and therefore accepted – zero point errors for paramagnetic oxygen sensors.

Performance drawbacks of the classical paramagnetic sensors include an insufficient compatibility with certain media (eg, chlorine or inorganic acids such as hydrochloric acid), and the slow response time caused by the large inner sensor volume.

> The evaluation of magnetic properties of gas mixtures is used in paramagnetic oxygen sensors.

Complete change: materials, geometry and manufacturing

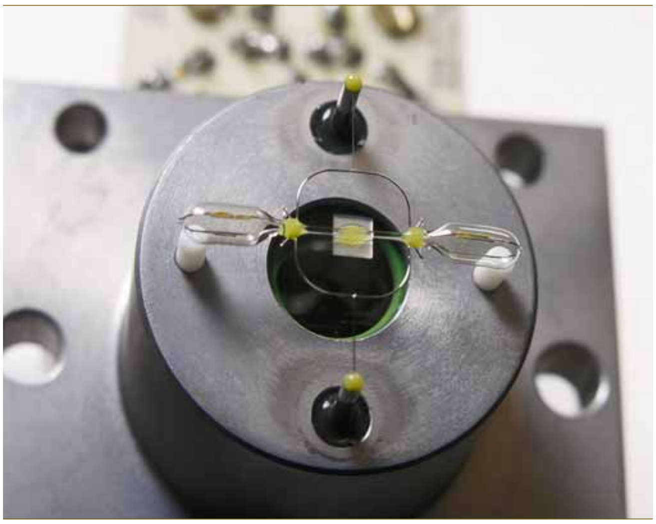
ABB has been pushing conventional paramagnetic sensors to the limit in terms of cost and performance for more than 40 years. To achieve yet more improvements, the company has gone back to the drawing board, initi-

Factbox Zero-point shift (in vol% 0_2) of the new sensor's output signal in the presence of undiluted (100 vol%) gases

Argon	-0.26
Carbon monoxide	-0.01
Hydrogen	+0.28
Hydrogen sulfide	-0.45

4 A conventional paramagnetic oxygen sensor: parts are assembled manually

5 The core of the conventional sensor: highly trained staff are required to manufacture this element



ating a new high-risk development from scratch. The aim of the exercise was to achieve a significant reduction in cost, while at the same time improving the performance of the sensors. With this in mind, the developers changed both the sensor element and its surrounding sensor cell, maintaining only the sensing principle. Changes included:

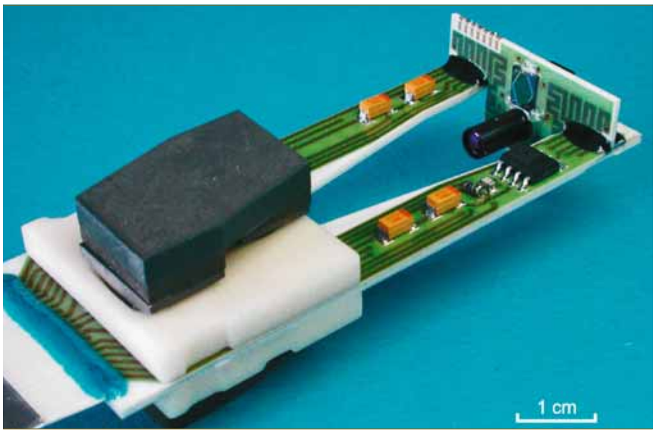
- Materials used (silicon and ceramics are used instead of glass and steel)
- Geometry (a planar setup replaces a complex three-dimensional arrangement)
- Manufacturing (silicon etching and automated batch processing is used instead of metal machining and manual assembly)

The result of this effort is shown in 6. Comparing this new sensor with the current sensor shown in 4, it is clear that the new design and technology used embody a paradigm shift in paramagnetic oxygen sensing.

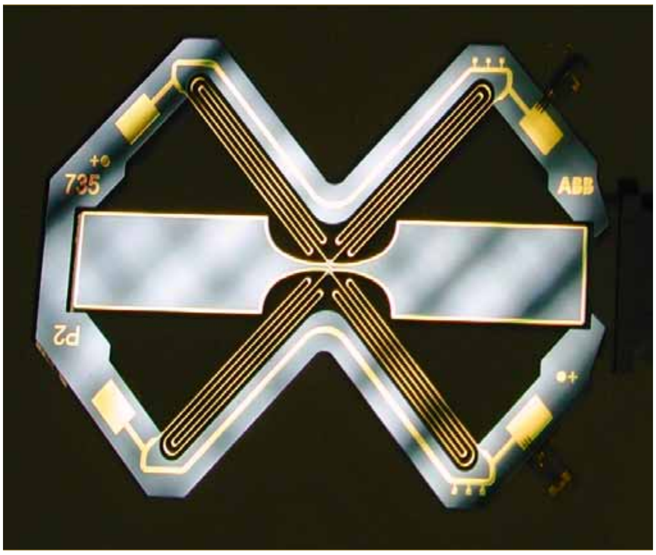
The "heart" of this new sensor is a micro-machined silicon chip 7 that provides fast response times and reproducible fabrication in large production volumes. The advantages over the old sensor are obvious: There is no 3-dimensional, manually-assembled setup. Instead there is a single planar chip. Nevertheless, this chip uses the same measurement principle: transforming oxygen concentration into rotational movement that is read out by a light beam.

The new setup follows a layered approach in a highly compact arrangement. The sensor basically comprises flat structures, bonded together to form the sensor cell 8. Ceramics are used to achieve high media compatibility and thermal stability. Electrical functions such as pre-amplification are integrated into some of the ceramic parts.

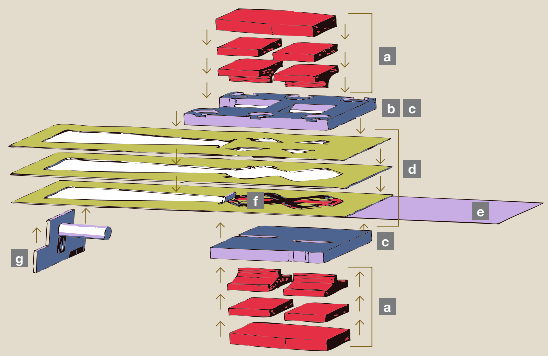
6 The new, highly integrated sensor module embodies a paradigm shift in paramagnetic oxygen sensing



7 New, planar micro-electromechanical system (MEMS) sensor chip (inner volume approximately 100 mm^3)



8 The layer concept to create a three-dimensional structure using "two-dimensional" parts



a magnetic circuit	e electrical interface
b gas inlet system	f sensor chip
c magnet carrier	g opto-electrics
d sensor cell	

Breaking the rules: silicon chip oxygen measurement

The key decision made by the ABB developers was to combine a proven and well-known measurement principle with cutting-edge micro-electromechanical system (MEMS) technology and put MEMS technology to an entirely new use. The main performance advantage of the chip solution compared to the classical paramagnetic solution is the extreme reduction of the gas volume inside the sensor. The result is a much faster sensor, with response times about one second, a vast improvement on the three-second responses of conventional sensors. This opens up additional market segments where speed is essential (eg, the monitoring of combustion engines).

The planar sensor chip can be integrated easily into the layered structure of the sensor, allowing simple, automated assembly, as required for large production volumes at affordable cost.

Transferring the conventional, three-dimensional setup into a planar chip was made possible by a smart idea and a massive effort in the development of chip manufacturing technology.

This effort resulted in some outstanding features, including:

- Durability in aggressive gases (due to a bulk silicon structure with corrosion-resistant metal tracks)

- High reproducibility (due to the highly accurate etching process used)
- Fast response-time (about one second, due to thinness of the chip)
- Significant cost advantages in mass production

For ABB customers, the development will provide a new paramagnetic sensor with outstanding media compatibility and a range of other advantages. Long service intervals, together with low cost spare-parts, will significantly decrease life cycle costs. Increased reliability of process parameter measurements in highly corrosive media will improve product quality and safety.

The sensor basically comprises flat structures, bonded together to form the sensor cell.

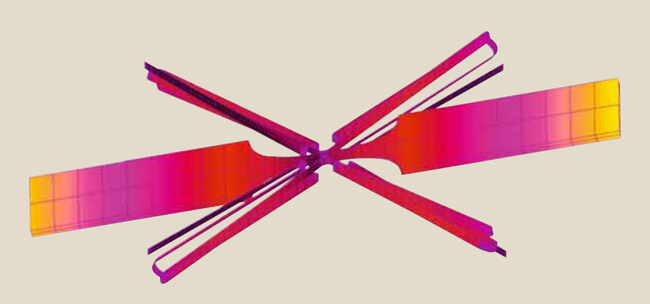
Development tools

Turning away from 40 years of experience and initiating a new development from scratch would have been impossible without the use of powerful simulation tools to speed up development. During the development process, numerical simulation tools were used to optimize the mechanical, fluidic, magnetic, thermal, electrical and optical properties of the sensor.

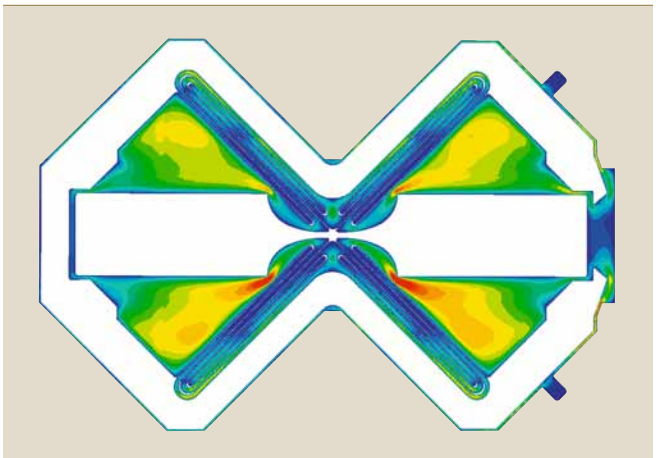
The use of planar silicon-chip technology was made possible by the development of a new suspension system for the displacement body. There is no obvious way of creating a planar structure that will rotate easily and that is also relatively resistant to linear acceleration. 9 shows the simulated mechanical behavior of the newly developed suspension system that is included in the silicon sensor chip.

An ABB-proprietary magnetic field simulation tool was improved expressly to simulate not only the field distributions, but also their influence on the displacement body, taking into account the magnetic properties of the gas. The magnetic circuit is optimized to generate a maximum magnetic field gradient in the region of the displacement body.

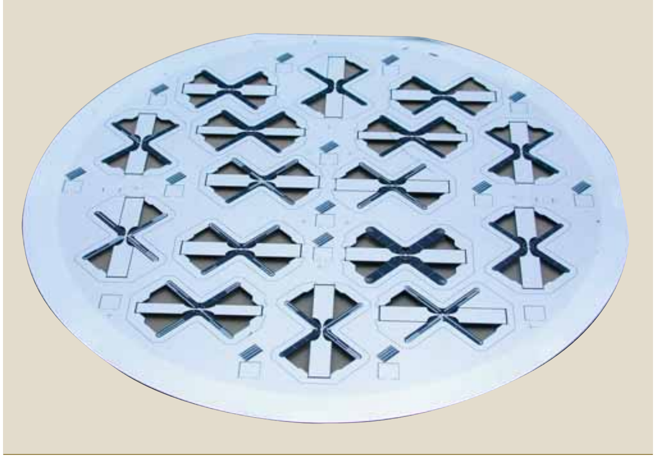
9 Simulation of mechanical behavior of the newly developed suspension system in the silicon sensor



10 Simulation of gas velocity distribution in the sensor cell



11 Silicon wafer with oxygen sensors



Fluidic simulations helped to achieve the fast response time of the new sensors. The challenge was to bring a large volume flow (up to 100 l/h) close to the micro-sensor and exchange the gas inside the sensor cell as quickly as possible. At the same time, the influence of the gas flow on the displacement body had to be minimized. 10 shows the result of a gas flow velocity distribution simulation in the sensor cell.

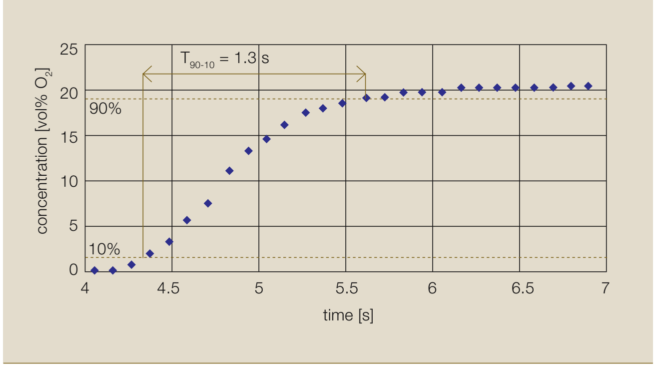
Chip manufacturing technology

The silicon chip in the new sensors is fabricated in two basic steps. First, the coil that compensates for the force generated by oxygen molecules is formed on the surface of the wafer by metal deposition and structuring. In the second step, deep reactive ion etching (DRIE) is used to etch fully through the wafer. The result of this process is shown in 11. Compared to the standard DRIE processes that are widely used in the production of micromechanical gyroscopes, the requirements of this application are rather more specialized.

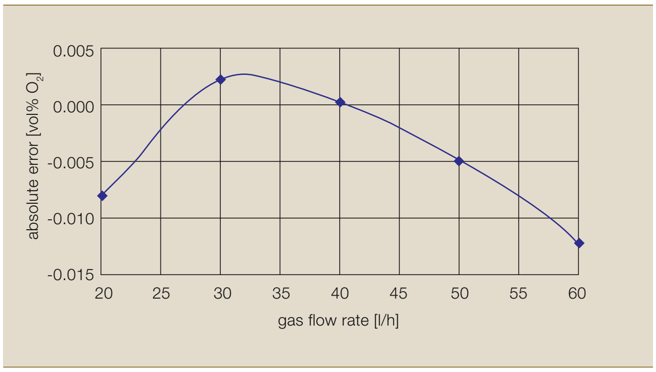
The main performance advantage of the chip solution is the extreme reduction of the gas volume inside the sensor.

The etched structure forms the suspension system for the displacement body with a minimum width of approximately 20 µm, over the total wafer thickness of several hundred microns. As the etched sidewalls are also used as a mirror to reflect the

12 Response time of the new sensor



13 Absolute measurement error as a function of gas flow for air



light beam, there are additional extreme requirements with respect to roughness. Process development and design optimizations produced a sufficiently homogeneous and perpendicular side wall to fabricate the fine suspension system and the displacement body with its reflective side wall, thereby allowing a cost-effective, one-step etching process.

> Fluidic simulations helped to achieve the fast response time of the new sensors.

The media compatibility of silicon and silicon oxide is sufficient for most gases, even those that are highly corrosive to other materials. The corrosion-sensitive points of these new sensors are the metal tracks. Using corrosion-proof rather than non-corrosion-proof metals that are commonly used in MEMS technology (eg, aluminum, gold) and specially qualified protective coatings on bond wires results in a sensor that can withstand wet chlorine atmospheres over months. This compares to a lifetime of less than a day in other “state-of-the-art” sensors.

Factbox Patents arising from this work

- US patent 20020075007
  Device for measuring the oxygen concentration in gases.
- European patent 1 202 051
  Vorrichtung zum Messen der Sauerstoffkonzentration in Gasen unter der Verwendung eines inhomogenen magnetischen Feldes
- US patent 20040108442
  Device for suspension of a sample body.
- European patent 1 424 553
  Einrichtung mit Aufhängung eines Probenkörpers.

Characteristics and performance

The new sensor system offers significant performance improvements with respect to response time and corrosion resistance. The response time (gas change from nitrogen to air at a volume flow of 60 l/h) of the new sensor is reduced to 1.3 seconds (see 12). Even more important than a fast response time is the stability of the sensor signal in the case of a variable gas flow rate 13. A flow rate varying between 20 l/h and 60 l/h causes a zero-point drift of only 150 ppm O_2, without any correction of the raw signal.

> The development of this novel paramagnetic sensor for the measurement of oxygen concentration is a major achievement in the field of continuous gas analysis.

Concluding remarks

The development of this novel paramagnetic sensor for the measurement of oxygen concentration is a major achievement in the field of continuous gas analysis. The new sensor combines the high performance of the classic, paramagnetic sensors with the cost advantage of electrochemical sensors. It will provide ABB and its customers with a competitive advantage and will be a major influence on future trends in the measurement of oxygen concentration.

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