The piezoresistive technology on the right track

Statement: The pressure transmitter which will dominate the industrial market, has a silicon sensor chip with integrated electronics manufactured using IC (Integrated Circuit) technology, and built into an oil-filled housing with an isolating diaphragm.

History:

35 years ago, the Author found his first job in the pressure measurement industry, and the cost of a typical pressure transmitter was in the range of $350 to $600. The predominant technology at that time was the unbonded strain gauge from Bell and Howell or the bonded strain gauge from Hottinger and Baldwin. There was also an LVDT from Schaevitz, and capacitance, potentiometer and reluctance pick ups connected to deflecting diaphragms and bellows; apart from dozens of other measuring systems which roamed around the market place.

These technologies were either too expensive or possessed inadequate stability for most requirements.

At the beginning of the 60s, Statham brought the first thin-film transducers with good stability onto the market and at about the same price as existing strain gauge types. This marked the start of the breakthrough for this technology. Large price reductions for high quantities were not aimed for, however.

The demand for inexpensive, stable transducers however could not be ignored and there were hectic developments at various levels. The majority were based on the piezoresistive effect discovered and published by Pfann and Thursten. The Gauge Factor (the unit change of resistance with unit change of length) for metallic wires is ~ 2 and is mainly caused by the extension and "thinning" of a wire under strain, with a small additional piezoresistive (change of resistivity with strain) effect.

However, the piezoresistive effect in doped semiconductor resistors can be up to 50 times greater, giving Gauge Factors of ~100.
There were many developments to process the brittle semiconductor materials into thin whiskers (semiconductor strain gauges) and to bond them to carriers such as diaphragms or flexible beams. Some Companies, who mastered this difficult problem, such as Data Instruments, Sensometrics and Microgauge still offer this technology today.

The researchers became extremely enthusiastic when, in 1964 the first planar transistor came onto the market- the beginning of integrated circuit (IC) technology, and complete resistance bridges could be integrated into a small silicon circuit. There were many attempts at this time to bond these small flat chips onto metal diaphragms etc. Renowned companies such as Philips stuck their necks out and went under. These failures gave piezoresistive technology a disastrous image and strengthened the general conviction that only thin-film gauges could be really stable. An attitude which continues to be felt today...

Honeywell first came up with the idea of using the silicon chip with diffused resistors as the pressure diaphragm. Now the tiny brittle diaphragm has to be bonded to a carrier of steel or glass. The problem of bonding materials as different as silicon and steel was partly overcome because the sensor elements were only indirectly influenced by the body stresses of the bond and the majority of these stresses could be eliminated by the configuration of the resistors on the diaphragm.

Tony Kurtz left Honeywell at this stage of the technology and founded Kulite. Druck, in England also founded their company on this technology.

The great breakthrough in piezoresistive technology came with the reproducible, integrated, homogenous silicon measuring cell, for which Honeywell designated the Author as inventor on the original patent. It was immediately foreseen that these pressure sensors could be produced cheaply and in high quantities. Art Zias brought this technology from Honeywell to National Semiconductor, who expected this to bring in big business. The first large-scale production for these measuring cells was, however launched by Delco for the MAP sensor (Manifold Pressure). In 1966, the Clean Air Bill was passed by the American Congress, which restricted the pollutant discharge for cars.

The automotive industry demanded a deferment because the technology, and above all economic sensors, were not yet available.

At the beginning of the 70s, the first cars came onto the market with electronic control systems and MAP silicon sensors, which could fulfill the conditions of the Clean Air Bill. The silicon sensors were built into the cars either naked or with gel protection. This provides insufficient protection for industrial applications or level measurements, but apparently sufficient for this requirement.

Considerable indecision predominated at National Semiconductor about how the product should be brought to the industrial market. The Parylene coating promoted as water protection had to be recalled after 6 months, for example!

The handbook from National Semiconductor written by Art Zias – the Mister Piezo of America - showed, for example, instructions for a level transmitter. You take a rubber glove, fill it with silicon or olive oil, stick the cable with the sensor and electronic circuit into the glove, tie together the opening of the glove with string and submerge the whole thing in the sauce.

In theory however, there was a lot of genius in the handbook and, according to a statement from Art Zias, the income which National Semiconductor got from the sales of the book was for a time larger than the sales of the measuring cells, which just shows how many were occupying themselves with the problem of pressure sensor technology! In a last desperate attempt, National started an advertising campaign under the slogan:

"A brand-new way to measure pressure: With the naked silicon sensor."

The Author parodied back:

"A brand-new way to make love: Naked"

Finally, National Semiconductor sold the sensor division, which passed through various hands before finally emerging as Sensym.

The inability of the US manufacturers to develop a protective housing for the silicon sensor enabled new technologies to breakthrough into the industrial as well as the automotive sector: The capacitive ceramic measuring cell from Kavlico, (which is also produced today by Texas Instruments) in quantities of millions.

The Europeans and Japanese were not much cleverer. In Europe, Magnetti- Marelli (Fiat) developed the ceramic thick-film strain gauge measuring cell, which however has not achieved the success of the capacitive measuring cell. Technologically speaking, this is due to instabilities caused by the influence at the point of adhesion of the ceramic/sensor element, and also by its extremely high bridge resistance. Here again, the experiences of silicon technology were neglected.

From Japan came a product from Nippon Denso where the pressure on the naked silicon sensor is applied from behind, allowing the electronics and the sensor gauges to be protected by a gel layer, but they are still exposed to the reference pressure atmosphere. Apart from the fact that absolute pressure sensors can hardly be manufactured at all, the Author's analysis of the transmitter design creates the same impression of helplessness as shown by National Semiconductor.

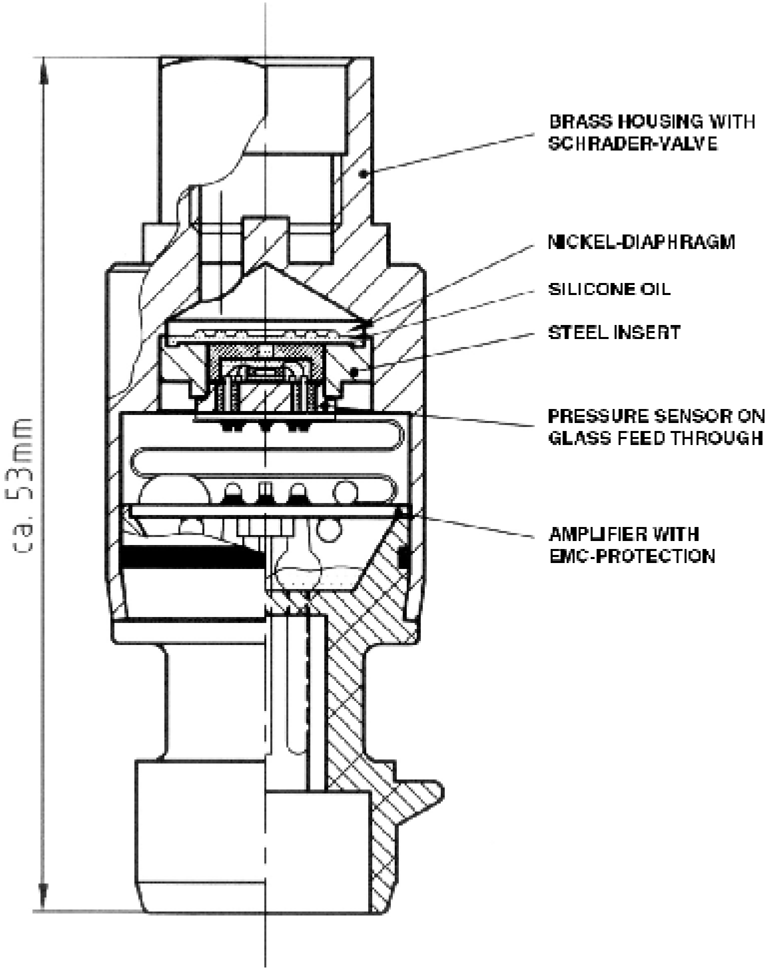
The Present and the Future

In 1993, in the article "Marketing of Pressure Sensors" in the Trade Fair News we had already predicted the following:

"Sooner or later, the market positions will be determined by the competing technologies. In an open market, we estimate that the majority of industrial applications in the range of 10 mbar to 1 bar will be dominated by the capacitive ceramic measuring cell. In the range of 1 bar to 1000 bar, monolithic silicon piezoresistive technology (IC) will dominate the field. Other technologies will have to operate in niche markets because, for example, the costs of thin-film technology are too high for very large-scale projects."

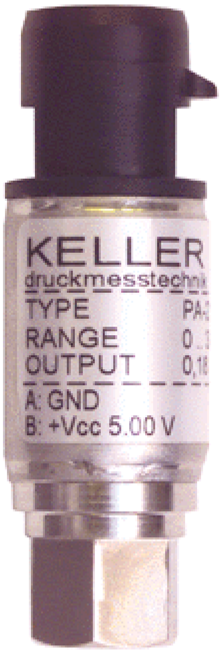
That was written 6 years ago. In certain areas - such as cooling compressors - silicon piezoresistive technology has succeeded in breaking the dominance of capacitive ceramic technology. But large volume automotive projects continue to run with ceramic capacitive sensors. Nevertheless, we stand by our statement.

Keller AG introduces a new silicon piezoresistive transmitter (Figure 1) which, in our opinion, has fundamental technological advantages over the capacitive ceramic sensor and will in the future attempt to break its dominance, even in demanding automotive applications.



The development of the housing with a separating diaphragm has been the focal point of development at KELLER AG since its foundation 25 years ago. Today, Keller has processes in-house for the complete silicon sensor housing, which have comparable manufacturing costs to the ceramic sensor housing.

In a patented process, a continuous, belt fed furnace brazes together the brass housing, a steel insert and a nickel diaphragm in one operation. The process can be fully automated.



As far as electronics and trimming adjustment are concerned, no cost advantage can be determined for either technology. Accuracy is also no longer a topic for either of them. The stabilities are excellent, and customer-specific circuits (ASICs) can compensate for inaccuracies.

The advantages and disadvantages are therefore determined only by the costs of the sensors and of housing them. However, while 5000 silicon sensors can fit on one 6 inch silicon wafer, 10 large baking trays are necessary for 5000 ceramic cells.
5000 silicon sensors pass through the various screening processes together, but 5000 ceramic sensors have to pass through individually.

Mounting silicon sensors onto a TO5 header with glass feed-throughs and welding it into the housing are similar to packaging a transistor. All the processes are automated, utilizing machines from the semiconductor industry such as Die Bonding and automatic Wire Bonding, and is improving year by year. The final assembly is by welding beneath the oil, and has been proven for over 15 years.

Finally the silicon sensor lies protected from all adverse influences, in a sealed oil chamber. The only materials in contact with the pressure media are metals and braze.

Conversely, the ceramic sensors are sealed into the housing with an O-ring, which has to be selected to suit the pressure media. The same O-ring cannot be used for both hot water and petrol. Furthermore, the O-ring is always a potential cause of failure. Envec (Endress + Hauser) attempted to reassure customers by means of an advertising campaign with the following statement:
"Pressure transmitters may fail after 5 years; sure, and Bayern Munchen may be relegated next year."

To be accurate, Envec should qualify this statement and say: "Pressure transmitters with O-ring sealed ceramic measuring cells fail after 5 years."

With the Envec statement, a problem specific to their technology is generalised. But this is only an aside.

Currently, a large part of the material costs of a transmitter is taken by the associated electronics. However, a further reduction in costs is foreseeable with piezoresistive technology. Today, there are already piezoresistive sensors from Bosch and Fuji, with adjustment electronics integrated into the piezoresistive silicon chip. Adjustment is done by laser trimming on the surface of the chip. Work is now being done on similar circuits where the adjustment to the silicon chip takes place via interface leadouts from inside the oil chamber itself.

The component density of IC technology is increasing so fast that according to our estimate, in 10 years a pressure sensor, amplifier, and digital compensation with A/D and D/A converters can be integrated onto the piezoresistive silicon chip at unit costs of $1. Then the complete transmitter with electronics is optimally protected in the oil chamber and the capacitance of the glass feed-throughs will automatically guarantee excellent EMC protection.

30 years ago we aimed for the $10 / 2% transmitter.

Within the next 10 years it is the $5 / 0.1% transmitter.

Hans W. Keller