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SENSORS: A GREAT CHANCE FOR MICROELECTRONIC TECHNOLOGIES

Roberto Dell'Acqua
MiTeCo, Pavia, Italy

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Abstract: During the past few decades, the price of microprocessors has dropped below the cost of sensors that tie the processor to the analog world of pressure, position, temperature, acceleration, flow, and other physical and chemical variables. As result, real time control applications, were hampered by the lack of reliable, accurate , inexpensive, and digitally-compatible sensors. However, in the last years a growing trend in fabricating either micromachined sensors on silicon wafers and thick film sensors on ceramics is appeared. IC production techniques allow manufacturing of inexpensive silicon sensors chips that integrate moving structures with resistive Wheatstone bridges (or sometimes with variable capacitors), laser trimmable resistor networks for calibrations, and even signal processing circuitry. Thick (and sometimes thin) film technology, taking advantage of special materials developed on pourpose, provides extremely rugged physical and chemical sensors at very reasonable prices. In this paper the basic principles of these two technologies, when used for sensors, are recalled and some of the most interesting existing and future devices described. In particular , pressure, acceleration, and gas sensors will be discussed. Even if silicon and thick film sensors seem to be in competition each other, the two technologies should be considered as complementary. Having their own advantages and drawbacks, their choice must be well evaluated taking into account the type of application, the size, the environmental conditions, the performances, and so on. The future need for great amounts of high performance, low cost sensors will be fulfilled only by a perfect understanding and by a clever use of the new sensor-related developments which take place inside these already "old" technologies.

Senzorji: velika priložnost za mikroelektronske tehnologije

Ključne besede: mikroelektronika, senzorji silicijevi, senzorji tlaka, senzorji položaja, senzorji temperature, senzorji pospeška, senzorji pretoka, rezine silicijeve, senzorji na keramiki, tehnologije debeloplastne, tehnologije tankoplastne, obdelava najfinejša, zanesljivost delovanja, proizvodnja cenena, natančnost visoka

Povzetek: Tekom zadnjih nekaj desetletij je cena mikroprocesorjev padla pod ceno senzorjev, ki povezujejo procesor z zunanjim analognim svetom pritiska, položaja, temperature, pospeška, pretoka in drugih fizikalnih in kemičnih spremenljivk. Tako je pomanjkanje zanesljivih, točnih, poceni in digitalno kompatibilnih senzorjev povzročilo zastoj v razvoju elektronskih kontrolnih sistemov v realnem času.
Zadnja leta opažamo naraščajočo potrebo po proizvodnji bodisi mikromehanskih senzorjev na silicijevi rezini, oz. debeloplastnih senzorjev na keramičnih substratih. Tehnologija izdelave integriranih vezij omogoča tudi izdelavo poceni čipov, na katerih so gibljive senzorske mikrostrukture integrirane z Wheatstone-ovimi mostički, oz. včasih s spremenljivimi kondenzatorji, uporovnimi verigami, ki jih lahko lasersko doravnavamo ali z vezji za procesiranje signalov. Debeloplastna in včasih tudi tankoplastna tehnologija, ki izkorišča lastnosti prav za ta namen razvitih materialov, pa nam daje izredno robate fizikalne in kemične senzorje po sprejemljivih cenah.
V tem prispevku opisujemo izdelavo senzorjev z obema tehnologijama, kakor tudi nekaj najbolj zanimivih današnjih in potencialnih bodočih izdelkov. Konkretno pa obravnavamo senzorje pritiska, pospeška in plinske senzorje. Čeprav se na prvi pogled zdi, da so si silicijevi in debeloplastni senzorji konkurenčni, pa je potrebno obe tehnologiji obravnavati kot komplementarni druga drugi. Ob poznavanju njunih dobrih in slabih strani, pa moramo pri izbiri ustreznega senzorja upoštevati namen, fizično velikost, pogoje okolja, njegove delovne lastnosti ipd. Bodoče potrebe po velikih količinah kvalitetnih in cenenih senzorjev bomo lahko zadovoljili le ob ustreznem dobrem razumevanju in uporabi novih tehnoloških dognanj, ki so orientirana k senzorjem znotraj že "starega" področja obstoječih mikroelektronskih in debeloplastnih tehnologij.

INTRODUCTION

Sensor worldwide market is expected to grow, according to a recent survey, from 18.8 B$ in 1991 up to 39.9 B$ in 2001 (see table 1). This represents in terms of turnover a growth around 7 % per year. But taking into account the expected price reductions (at least 50 % in the same period), it means that the number of sensors will increase by a factor 4 in 10 years.

Table 1: Worldwide Sensor Market

Year 1991:	B $ 18.8	Year 2001:	B $ 39.9
U.S.A.	34.3 %		34.1 %
Japan	23.6 %		24.3 %
Germany	13.5 %		14.1 %
France	7.1 %		7.0 %
U.K.	5.9 %		5.5 %
Italy	5.7 %		5.5 %
Others	9.9 %		9.5 %

To support either the cost reduction and the production increasing, suitable manufacturing technologies are needed. The choice of such technolologies must be well evaluated since sensors are very peculiar components whose electrical, mechanical, and environmental characteristics are probably the most severe of the electronics world. In fact, when talking about sensors, most of the attention is paid to the sensing element itself; this is sometimes misleading since the sensing elements needs also a signal conditioning electronics for the suitable adjustments and a package for the environmental protection. Just to clarify this item, it can be useful to look at the manufacturing cost breakdown of a low-cost micromachined silicon pressure sensor, given in table 2.

Table 2: Micromachined pressure sensor manufacturing cost breakdown

Finished device cost: 6.3 $	
Processed die (sensing element)	5 %
Processing, assembly, and test	30 %
Package	65 %

This cost breakdown indicates that the choice of the silicon die can be debated if a different sensing element, yet more expensive, can be processed and packaged at lower costs. Beyond these considerations, it seems today clear that silicon and thick/thin film technologies can lead, when cleverly used, to very effective solutions in the sensor area.

1. SILICON SENSORS

Silicon has become a synonim for integrated circuits, thanks to its quite spectacular electronic properties that have already lead to the fabrications of several sensors like, for example, speed/position sensors based on Hall Effect. Now its equally amazing mechanical properties, together with a rather recent technique called micromachining, allow to shape silicon into the tiniest electromechanical systems ever built.

Silicon has several advantages for use in sensors; in particular, it has no mechanical hysteresis and is highly sensitive to mechanical stress. Its modulus of elasticity is the same as steel. Silicon is also as hard as quartz, yet less dense than aluminium. Perhaps most important, silicon sensors having tightly controlled submicron geometries can be built and packaged with the same mature process, equipment, and ultrapure materials used for producing high-volumes of integrated circuits.

A number of innovative fabrication techniques have recently been developed specifically for micromechanical structures and they fall into two cathegories: bulk micromachining and surface micromachining.

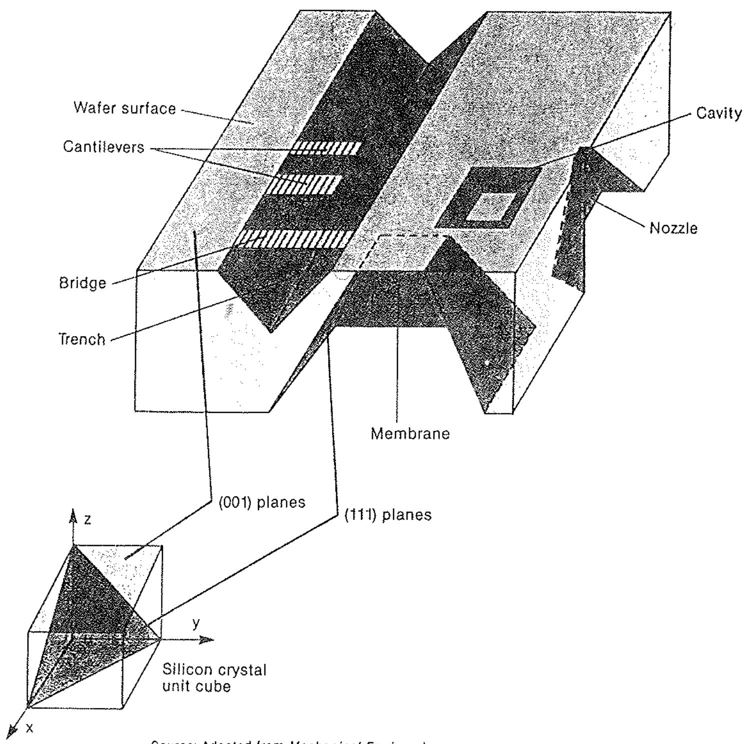
The first involves sculpturing the silicon substrate by means of chemical etchant, and the second etching layers of thin films deposited upon the substrate.

Etching with alkaline solutions, is the key technology for bulk micromachining either isotropic, anisotropic, or a combination of both. In isotropic etching, the etch rate is identical in all the directions, whereas in anisotropic etching (Fig. 1) the etch rate depends on the wafer's crystallographic orientation: an anisotropy ratio of 100/1 is possible in the <100> direction relative to <111> one. Etch process can be made selective by the use of dopants (heavily doped regions etch more slowly), or may even be halted electrochemically (etching stops upon encountering a region of different polarity in a biased p-n junction). The common microelectronic thin film materials as silicon dioxide or silicon nitride can serve to mask the portions of the wafer that are not to be etched.

Bulk micromachining, a proven high-volume production process, is routinely used to fabricate microstructures with crytical dimensions that are precisely determined by the crystal structure of the silicon wafer, by the etch-stop layer thickness, or by the lithographic masking pattern. To obtain complex structures, the ability to bond silicon to glass and silicon to silicon is an important adjunct to bulk micromachining.

In contrast to the bulk technique, surface micromachining does not penetrate the carrier, or handle wafer, as it is called. Instead, the wafer has thin film materials selectively added to and removed from it (Fig. 2). The handle wafer is often used for interface circuitry.

Wet and dry etching techniques and thin film deposition are essential in surface micromachining. Thin films (usually polysilicon, silicon oxide, and nitride) provide sensing elements and electrical interconnections, as well as structural, mask, and sacrificial layers.



Source: Adapted from *Mechanical Engineering*

Fig. 1: Silicon bulk micromachining

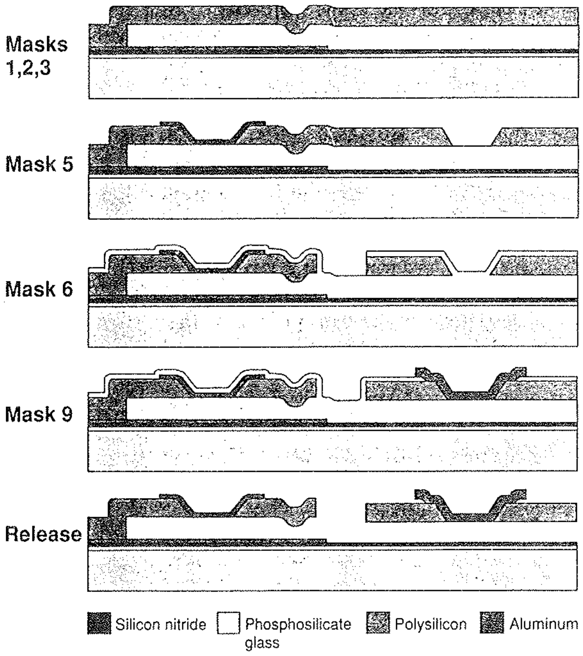


Fig. 2: *Silicon surface micromachining: a sacrificial layer is grown or deposited and patterned. Then the mechanical layer is deposited and patterned. Finally the sacrificial layer is etched away to release the mechanical structure.*

Sacrificial etching is the basis of surface micromachining. A soluble layer (often silicon dioxide) is grown or deposited for later removal from beneath other patterned materials, usually by wet chemical etching. Since the patterned materials left behind (the released layers) are separated from the substrate or from other surfaces by the thickness of the removed sacrificial layer, they are actually free-standing, thin film mechanical structures. Multiple depositions of structural and sacrificial films, each individually patterned, can build surprisingly complex micromechanical structures. Still there is a limit to the number of layers since each one increases surface roughness, gradually degrading the photolithographic process.

1.1. Silicon Pressure Sensors

Mostly based on bulk micromachining, silicon pressure sensors are produced in very large volumes for several applications. Capacitive and piezoresitive pressure sensors are available, but the piezoresistive device is more popular due to the lower cost.

The process of manufacturing a pressure sensor (Fig.3) begins with a silicon substrate that is polished on both sides. An epitaxial layer is first deposited on the surface of the wafer; the typical thickness of the layer is 15 microns and depends on the required sensitivity of the pressure sensor.

Boron-doped piezoresistors and both p+ and n+ enhancement regions are introduced by means of diffusion and ion implantation. Because their resistances vary with stress, piezoresistors are the sensing elements in pressure and acceleration sensors. A thin layer of deposited alluminium or other conductors creates the ohmic contacts and connects the piezoresistors into a Wheatstone bridge. Finally, the device side of the wafer is protected and the back is patterned to allow formation of an anisotropically etched diaphragm. After stripping and cleaning , the wafer is anodically bonded to Pyrex and finally diced.

The anodic bonding is a process that requires a high voltage of 1500 V between the two parts to be bonded and a temperature of 400 degrees centigrade; an alternative to silicon-Pyrex bonding is given by the silicon-to-silicon fusion, a high temperature process which fuses silicon wafers together at the atomic level without a "glue" layer or an applied electric field.

In most cases, silicon pressure sensor dice are unusable without signal processing circuitry and adequate packaging. The bridge output signal must be amplified and several adjustments and thermal compensations are needed to obtain the proper output characteristics. The

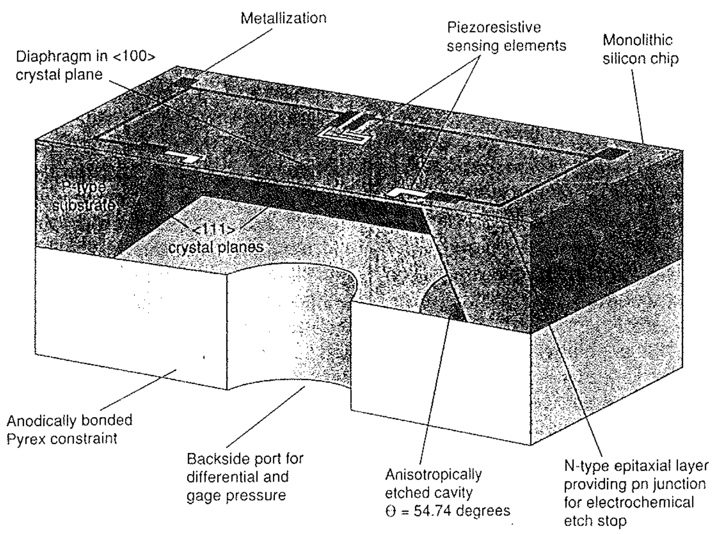


Fig. 3: *A bulk micromachined pressure sensors with the thin silicon diaphragm; its deflection depends on the pressure and it is sensed by the piezoresistors.*

die attach is a crucial step since mechanical stresses can be induced into the chip; moreover, the chip cannot be directly exposed to the environment since it could be damaged by corrosive media.

Due to the difficulty found in putting together the micro-machining and the IC manufacturing processes, most of the today silicon sensors are produced by mounting the silicon sensor die on a ceramic substrate where the signal conditioning electronics is implemented. On the other side, the market shows also a strong demand for entirely monolithic solutions that can lead to:

- remarkable miniaturisation
- reduced cost for high volumes
- better performances due to the fact that the sensor and the relevant circuitry are on the same subtsrate.

However, the monolithic pressure sensor has still several limitations when operating in tough environmental conditions and a rather high cost mainly due to low production yields. Instead, the monolithic sensor is widely used when the small size and the need for an amplified signal are mandatory.

In fig. 4 it is shown, for example, a pressure/temperature integrated sensor produced by Ascom Microelectronics (now Micronas) in Switzerland and used to build a catheter for medical applications. On the die (1 by 5 mm in size) a pressure and temperature sensor are located together with a voltage reference and the amplifier. The thermal compensation is provided via software by the computer to which the output of the sensor is directly connected.

1.2. Silicon Accelerometer

Even if the feasibility of silicon accelerometers have already been demonstrated several years ago, their mass production is starting just now under the push of automotive industry which needs them for active suspension control and air-bag deployment. These applications require only intermediate performances but very high reliability and low cost. Both bulk and surface micromachining seem to be suitable for high volume production of silicon accelerometers.

1.2.1 Bulk-micromachined Accelerometers

A typical design incorporates a bulk-micromachined silicon mass (called proof mass) suspended by silicon beams (Fig. 5).

Ion-implanted piezoresistors on the suspension beams, sense the motion of the proof mass produced by acceleration. Even here, as in the case of pressure sensors, a temperature compensation, mainly due to the implanted piezoresistors, is needed. The compensation is usually performed by mounting the sensor chip on a ceramic board, by connecting it with a proper circuitry, and by actively or passively trim suitable thick film resistors.

For high precision applications, such as inertial navigation, high-quality silicon accelerometers are needed. In this case, the preferred mean for detecting movement of the proof mass is a change in capacitance. In some design, capacitor plates on top and bottom capping wafers (the two wafers that enclose the proof mass) also apply a restoring elettrostatic force to the mass to null

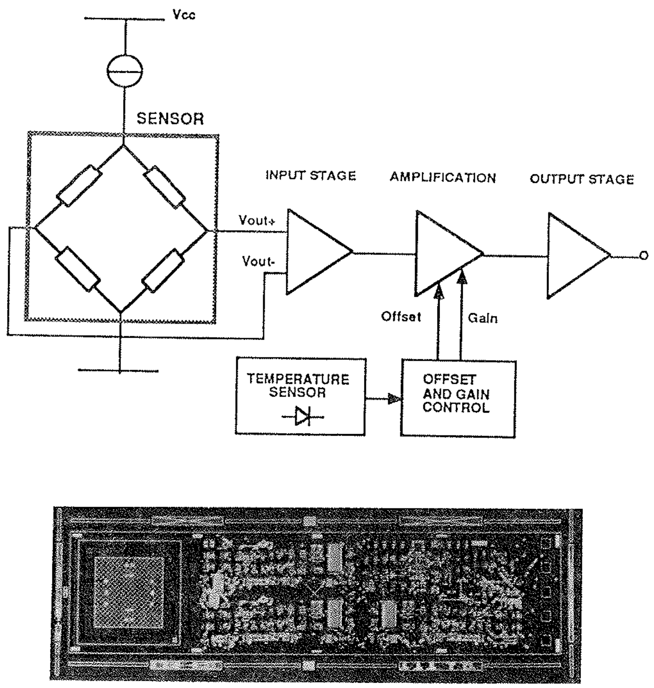
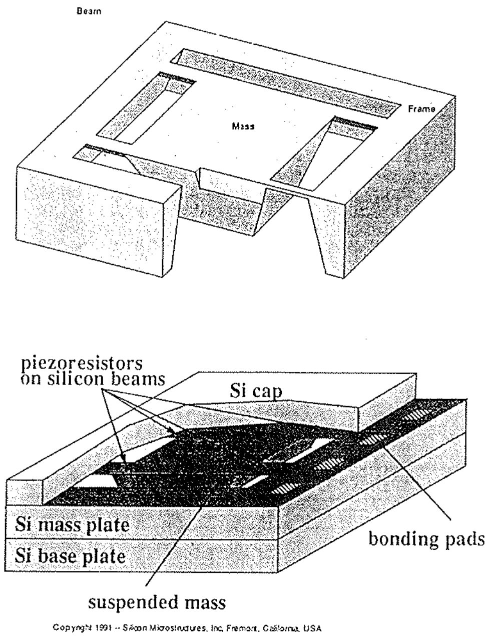
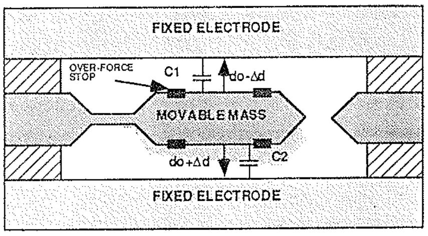


Fig. 4: Block diagram and layout of a monolithic pressure and temperature sensor (Ascom Microelectronics)



- IC fabrication
- anisotropic etching of membranes with electrochemical etch-stop
- plasma etching of beams supporting the inertial mass
- dicing

Fig. 5: Structure of a piezoresistive accelerometer.



$$\frac{C_1 - C_2}{C_1 + C_2} = \frac{\Delta d}{d_o}$$

Fig. 6: *Structure of a capacitive accelerometer*

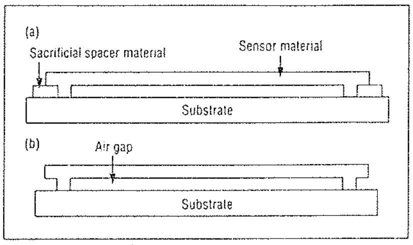
its displacement, offering improved reliability and dynamic range over "open loop" devices (Fig. 6).

1.2.2. Surface-micromachined Accelerometers

A fully integrated surface-micromachined accelerometer developed for air-bag deployment, with a range of 50 g, has been recently presented by Analog Devices (Fig.7).

A 3 by 3 mm, 3-microns minimum feature size BiCMOS chip contains a micromachined polysilicon sensing element and complete circuitry, including a self test function.

Unlike bulk-micromachining, where substrate silicon comprises the sensing element, surface-micromachining utilizes deposited films, such as polysilicon, silicon nitride, and nickel. The simple fixed-beam spring design used in the accelerometer necessitates tight control of



Surface micromachining (a) with sacrificial layer (b) after sacrificial layer removal.

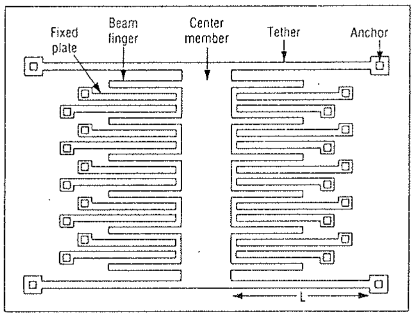


Fig. 8: *Simplified view of sensor geometry*

the intrinsic stress present in the polysilicon film. The center member and movable capacitor plates (or beam fingers) are suspended by four springs or tethers (Fig. 8). Fixed capacitor plates are interspersed between the beam fingers (Fig. 9). When subjected to an acceleration, the proof mass (center member and attached fingers) move while the fixed plates remain stationary. The separation between the plates and beam fingers therefore changes. Each set of fingers and fixed plates comprises a parallel plate capacitor with the air gap as the dielectric: therefore, the capacitance changes as this gap varies.

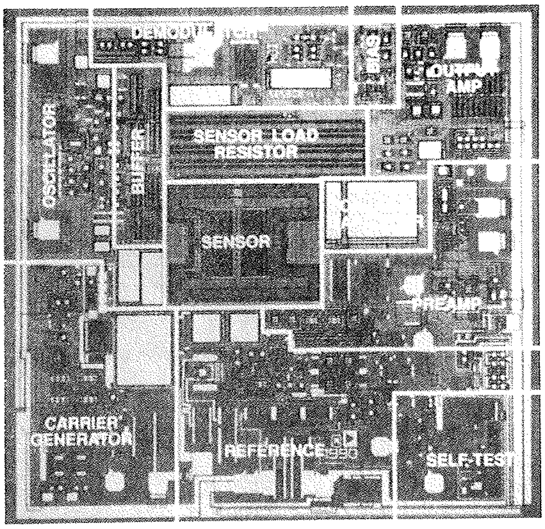


Fig. 7: *The Analog Devices accelerometer*

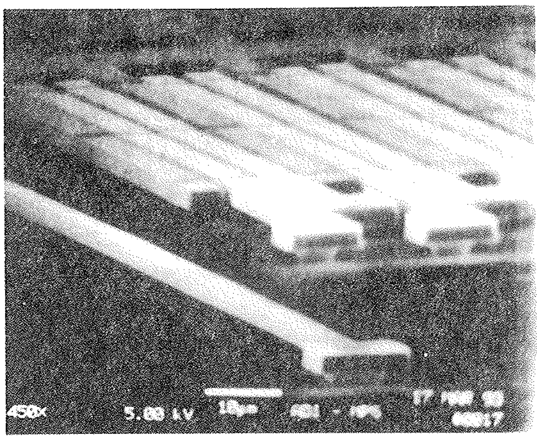


Fig. 9: *Magnified view of tether and fixed plate anchors of polysilicon*

The manufacturing process of the sensor and of the relevant circuitry, that also includes thin film resistors for functional trimming, is rather complex (it needs more than 25 masking steps) but it leads to a device which could represent a turning point in low cost accelerometer manufacturing.

2. THICK FILM SENSORS

Thick film sensors are based on the outsdanding properties of several different materials developed on purpose and deposited on suitable substrates by screen printing techniques. The intrinsic simplicity of manufacturing process, the increasing availability of new sensing materials, the possibility of using many kinds of substrates (including cofired multilayer ceramics) have already lead to the implementation of temperature, pressure, force, acceleration, displacement, oxygen, gas, humudity sensors, and so on. The achievable integration and miniaturisation are those typical of hybrid circuits.

The most important features of thick film sensors are the very high flexibility, the low development cost and time, the easy handling, the low investment cost, and the exceptional environmental behaviour. When needed and possible, the signal conditioning electronics can be implemented on the sensor substrate by adding to the passive thick film sensor network the suitable semiconductor dice to complete the circuitry. This can be done in a very short time by using standard ICs thus greatly reducing the time to market. Of course, incidental design changes can be quickly performed and the functional trimming of the whole circuit can easily taylor the sensor parameters to the customer requirements.

Generally speaking, the cost of a thick film sensing element is higher than that of the equivalent silicon device, at least for very high volumes, but it becomes very competitive for medium and low volumes.

An other interesting feature which gives some bonus to thick film sensors is the environmental behaviour. Usually, they are less affected by temperature and poisoning media thus offering a better global reliability. To emphasize and possibly better explain the above mentioned concepts, a few examples are given below.

2.1. Ceramic Thick Film Pressure Sensors

The classical structures of a thick film capacitive and of a piezoresistive pressure sensor are shown in fig. 10.

In both cases a thin (how thin depends on the pressure to be measured) ceramic diaphragm is bonded by means of a suitable screen printed glass to a robust baseplate. In the case of the capacitive device, two metal layers are previously printed on the diaphragm and on the baseplate to form a capacitor; in the case of piezoresistive sensors, four thick film resistors, connected into a Wheatstone bridge configuration, are deposited in the points of diaphragm maximum deflection, thus maximizing the bridge unbalancing when deformated.

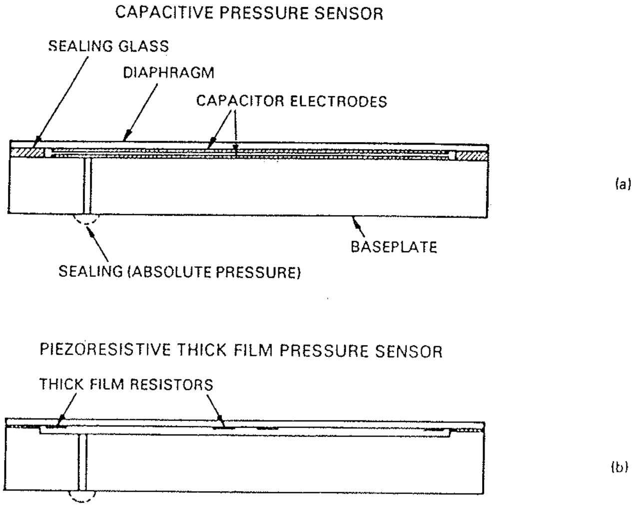


Fig. 10: Structure of thick film pressure sensors: (a) capacitive, (b) piezoresistive

The electrical contacts between the diaphragm and the signal conditioning electronics, usually located on the back of the baseplate, are obtained by means of metallized through holes (Fig. 11).

Either capacitive and piezoresistive thick film pressure sensors have been produced in very large volumes during the last 15 years fulfilling the requirements of a wide variety of applications like automotive, medical, industrial, aerospace.

The overall accuracy, usually better than that of silicon, the linearity, the insensitivity to most of the dirty media have been their strong points.

The size of the ceramic sensing element is larger than that of silicon chips and usually ranges from 15 mm up to 40 mm in diameter (silicon chips are ranging from 1 by 1 mm up to 5 by 5 mm). If this fact makes the ceramic sensors unusable for certain applications, on the other side it allows a much easier handling. It should also be

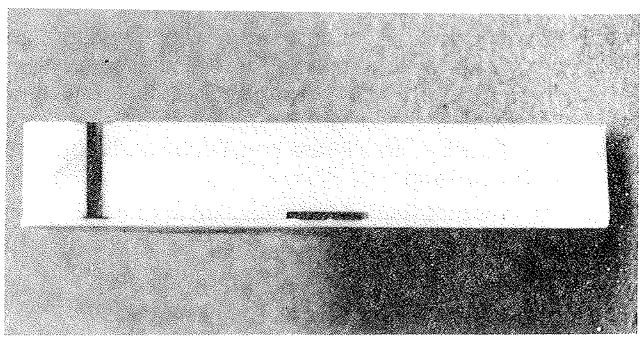


Fig. 11: Cross section of a ceramic piezoresistive pressure sensor

noted that in most cases the dimension of the finished sensor depends mainly on the packaging and on the signal conditioning electronics size.

Unfortunately, the cost of the ceramic structure above described is much higher (five to ten times) than that of the silicon pressure sensor chip. On the other side, processing and assembly of thick film sensors as well as their packaging (when the medium to be measured is air) are slightly less expensive than those of silicon devices.

In fact, even if the gauge factor of thick film resistors is lower (15 versus 50) than that of silicon, thus leading to a lower sensitivity, the better temperature coefficient of resistance (50 versus 1500) and of gauge factor (200 versus 2000) allow a simpler signal conditioning electronics and an easier functional adjustment. When the pressure of dirty or wet media must be measured, the package of the thick film sensor remains inexpensive (Fig. 12), while the silicon sensor needs usually a very expensive protection.

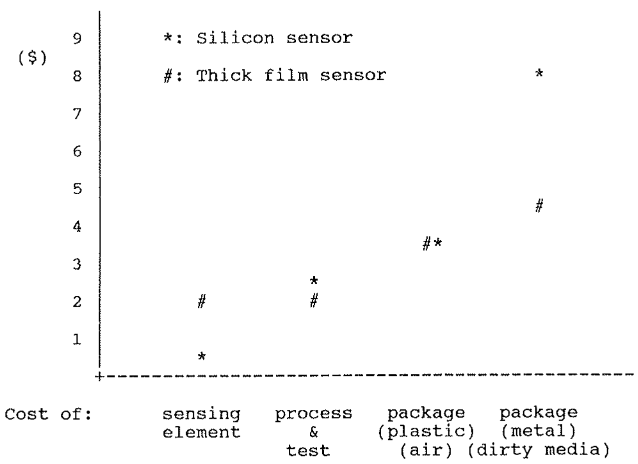


Fig. 12: *Manufacturing cost breakdown comparison between silicon and thick film pressure sensors (hig volume production)*

2.1.1. Trends in Piezoresistive Pressure Sensors

There are several applications where silicon sensors are not economically and sometimes technically convenient. This is the reason why a lot of space still exists for the thick film piezioresistive sensor technology evolution. This evolution is based either on a better knowledge and reputation of these devices and:

- on the improvement of the thick film resistive compositions in terms of gauge factor, noise, and long term stability
- on the use of different types of substrate.

Partially stabilized zirconia, for example, with a flexural strength three times higher than that of alumina, can broaden the pressure range already covered either towards the low and the high pressures.

High precision hot pressed ceramic parts with a built in cavity/diaphragm will greatly simplify the sensor structure. High and low temperature green tape multilayers can be also used to reduce the costs.

Most likely, the next thick film pressure sensor generation, shown in fig. 13, will considerably reduce the price gap with the silicon sensors, where it exists, still mantaining the today outstanding performances.

2.2 Ceramic Thick Film Accelerometers

The rather low sensitivity of thick film piezoresistors and the fragility of ceramics have restrained the development of such devices. However, the intrinsically high cost of silicon accelerometers can leave a lot of room to intermediate performance thick film accelerometers. For example, a ceramic cantilever type thick film accelerometer has been produced since 1987 by Magneti Marelli, Italy, for suspension control of Lancia cars.

2.3. Ceramic Thick Film Gas Sensors

Thick film technology seems particularly suitable for gas sensing. The very tough environmental conditions, the long term stability requirements, the low production costs can be usually met with ceramic-based thick film devices. A lot of research and development activity has been carried out in the past ten year on the gas sensors since the existing ones were expensive and sometimes unreliable. One of the most interesting works in this area is tied to the exhaust gas sensor used on cars to control the air/fuel ratio in fuel injection systems. The classical structure is, in this case, a thimble-shaped zirconia solid electrolyte cell, obeying the Nerst law. As the requirements became more stringent, planar solutions based either on a multilayer ceramic structure and on full thick film structure have been developed, reproducing and improving the Nerst cell, that will be soon on the market. Since a lot of literature exist on this matter, it is probably most interesting to look at an other very interesting device.

2.3.1. Thick Film Methane Sensor

Gas sensing properties of semiconductor oxides films, like ZnO and SnO_2, are well known since a long time and in fact, SnO_2 sensors have been available for more than 20 years.

The basic mechanism that gives these oxides their sensitivity to reducing gases is well known: the reduction of their surface makes electrons available for electrical conduction and causes the electrical resistance of oxide to decrease.

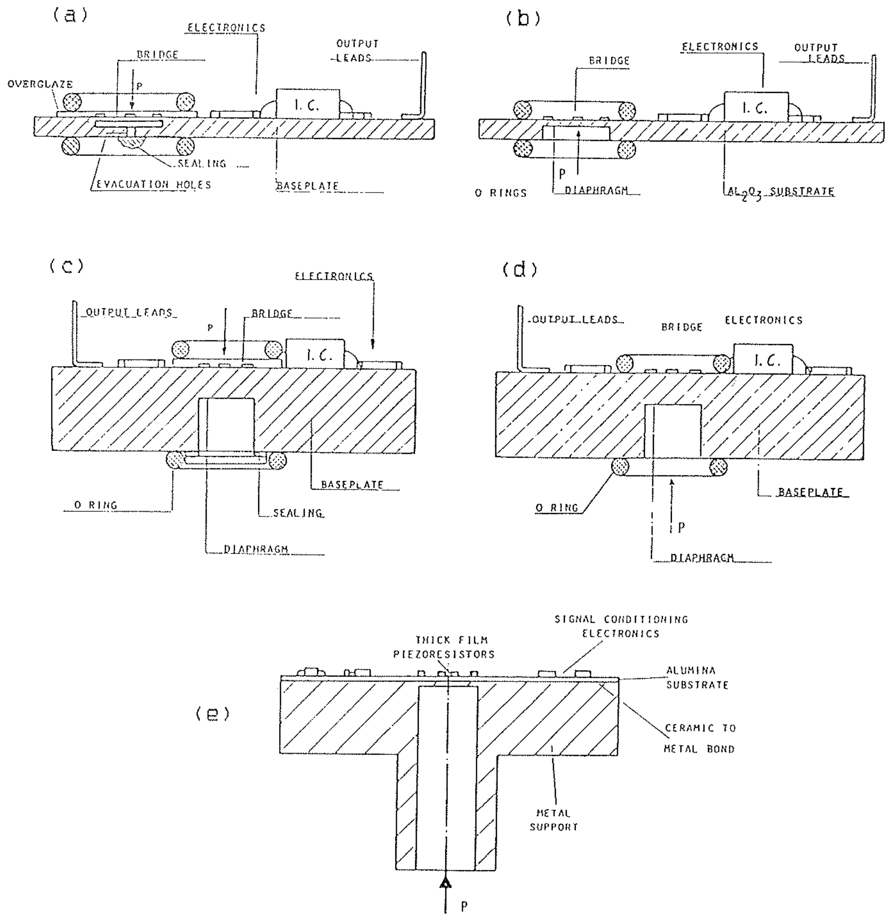


Fig. 13: Possible configurations of thick film pressure sensors: (a) low pressure, absolute; (b) low pressure, gage; (c) high pressure, absolute; (d) high pressure, gage; (e) very high pressure (metal/ceramic diaphragm).

Gas sensors generally consist of a mixture of SnO_2 and electrically inert oxides as Al_2O_3 and SiO_2 with some noble metals acting as catalyst. Usually the properties of gas sensors depend very strongly on composition and preparation conditions.

Characteristic features for a sensor to detect fuel gas leakage are:

- reliable detection of the alarm threshold concentration, independence from the history of the sensor and in particular of previous exposures to other gases;
- selectivity versus the main interfering gases possibly present in the same environment (a false alarm produces disregarding the true danger signal);
- high reliability in terms of working life.

To fulfil these requirements, not always fully satisfied by the today available sensors (one of wich produced by Figaro, Japan, is shown in fig. 14), ENIRICERCHE S.p.A., Italy, has chosen as manufacturing technique the thick film on ceramic approach which also provides high reproducibility and low production costs.

Screen printing can be used both for sensing and for heating elements, with possibility of array integration of smart sensors.

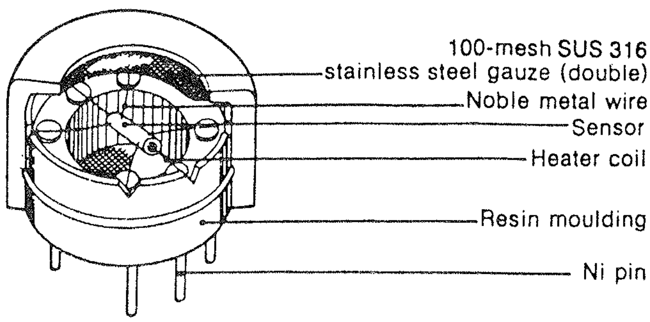


Fig. 14: Configuration of the Figaro gas sensor: the sensing material is deposited on a ceramic cylinder and heated by a coil.

The material for the sensing element is a blend of tin and aluminium oxides with dispersed catalyst which is screen printed on a ceramic substrate. The heater is a resistive platinum stripe printed on the other side of the ceramics. The material chosen for the sensing element exhibits high sensitivity to methane at an operating temperature around 500 degrees centigrade (Fig. 15).

Fig. 15 displays sensitivity versus operating temperature curves for the following gases: CH_4, CO, NH_3, C_2H_5OH, and CH_3COCH_3. The concentrations for the interfering gases are the highest expected in a home environment.

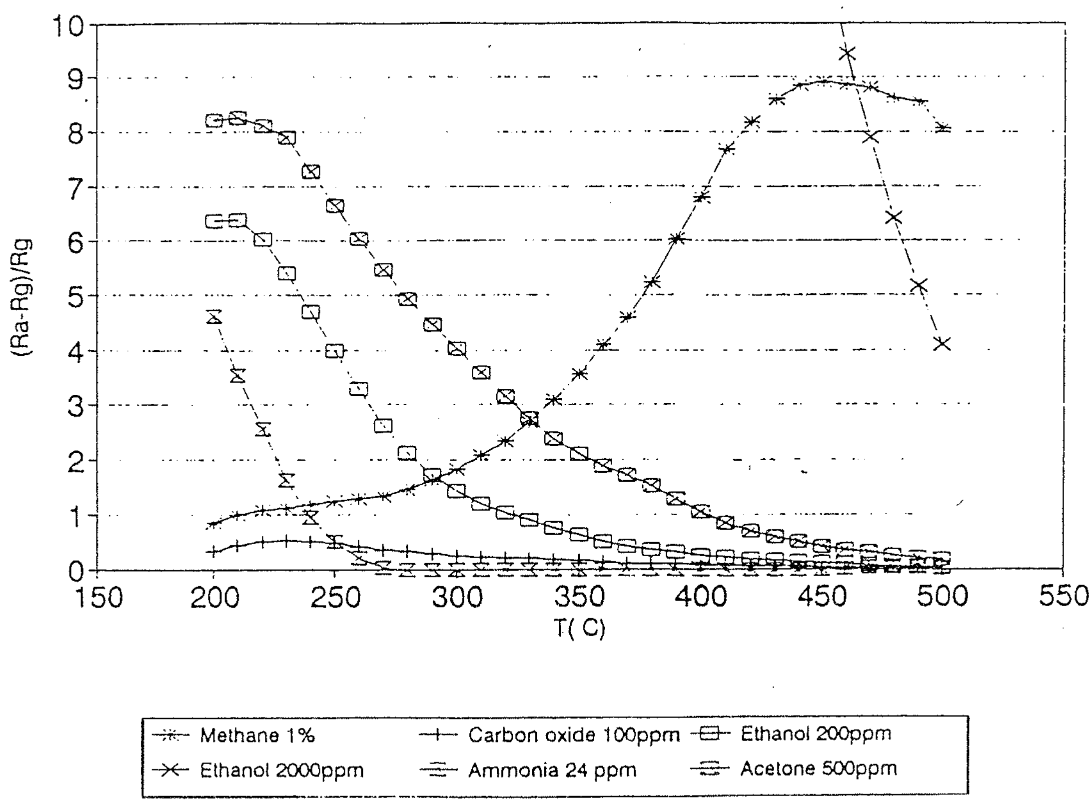


Fig. 15: *Sensitivity vs temperature to methane and interfering gases of the ENIRICERCHE gas sensor. The sensitivity is given as (Ra-Rg)/Rg, where Ra is the resistance of the sensing element in air and Rg its resistance in an atmosphere with the selected methane concentration.*

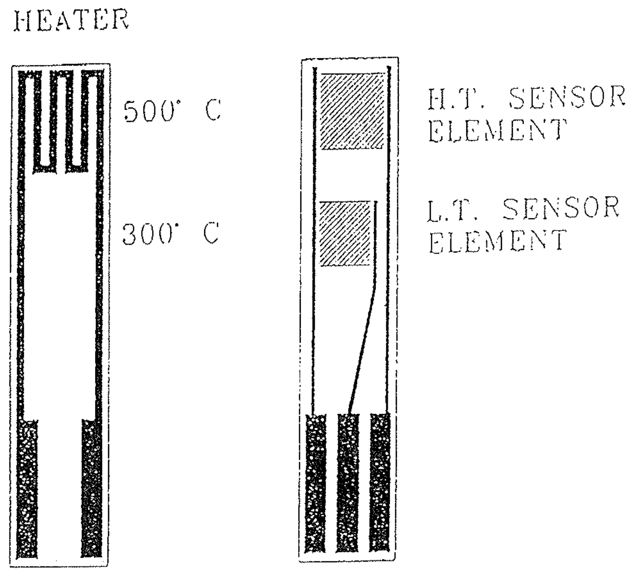


Fig. 16: *Layout of the ENIRICERCHE methane thick film sensor*

As shown, the sensitivity to methane is the highest at high sensor temperature while the highest sensitivity to the interfering gases occurs at low temperatures. An improvement of the selectivity against high concentration of interfering gases is obtained through comparison of measurements taken at different temperatures, e.g. 300 and 500 centigrades.

The comparison is easily done taking advantage of a simple arrangement integrating two sensing elements on the same substrate: the pattern of the heater has been designed so that the two elements are heated at two different temperatures (Fig. 15).

CONCLUSIONS

The increasing demand for real time electronic control systems drives the growth of the sensor market and the improvement of their features.

Very large volumes are already demanded in automotive, industrial, medical, safety, and home appliance field.

Since the volume request already exists, silicon and thick/thin film technologies can show at least their potentiality. The need for higher accuracy, reliability, and lower cost can be fulfilled by their proper and clever use. The few examples given in the paper, show that these two technologies have their own advantages and drawbacks; they should be very well understood and evaluated by sensor designers.

Silicon micromachining and the integration of signal conditioning electronics on the same chip offer incredible chances for several applications and when very high volumes are involved.

Silicon micromachined devices mounted on ceramic hybrids can represent the fastet approach to the market with still reasonable cost for several types of sensors.

Thick film technology seems particularly suitable and economical for very hard working conditions sensors.

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R. Dell'Acqua
MiTeCo
Corso Cairoli 96,
27100 Pavia, Italy
tel. /fax+ 39 382 27376

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