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SMART SENSORS -- A DEVICE RESEARCH AND ENGINEERING CHALLENGE

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A B S T R A C T

Control systems have need of sensors with signal processing capability. Dedicated electronics give functionality to sensors, independent of any support system, rendering them, in some degree, "smart." Silicon planar-processing technology coupled with chemical micromachining offers opportunities in the development of smart sensors with cost effectiviveness. The technology and examples are pr

Smart sensors, micromachining, monolithic sensors.

1. The Need

Critical components of control systems are electronic sensors -- devices that couple environmental variables (input) such as, temperature, pressure, position, or speed, to electrical variables (output) such as, voltage, current, resistance, inductance, or frequency (see Fig. 1). This discussion concentrates on miniature electronic sensors

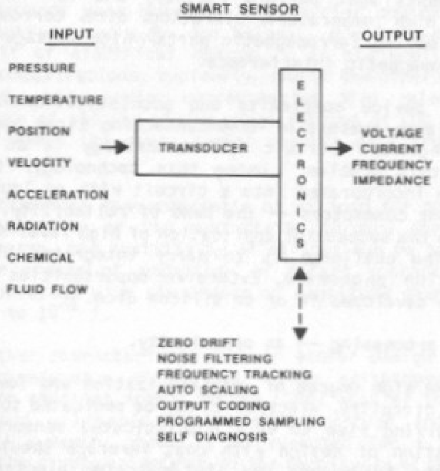

Figure 1. A "smart" sensor is defined here to be a transducer with dedicated electronics. The electronics can be used for signal conditioning and other functions as in the examples shown.

derivable from silicon planar processing technologies. Examples are related to automotive applications because these demonstrate a considerable challenge in research and development due to the sophistication of controls needed, the environmental conditions of their applications, and requirements on reliability.

Automotive electronic control systems already include automatic control of fuel injection, exhaust gas recirculation, idle speed, spark, vehicle speed, anti-skid, air suspension, and others. Microprocessors have been developed specifically for electronic engine controls and are in many lines of current production cars. The benefits of digital electronic controls are clear and practicality has been demonstrated. More automation is in development, including adaptive controls, and more complex and sophisticated control systems are contemplated. Thus, the need arises for advanced sensor technology to support the development of reliable, more sophisticated sensors.

2. The Challenge

Issues in the development of sensors are functionality, sensitivity, reliability, miniaturization, environmental passivation (corrosion protection, for example), packaging, and cost. Cost should be kept in proper perspective. While cost can be the final determining factor in commercialization of a particular sensor, there are other constraints that have to be met. The issue of quality must dominate the development of any sensor expected to have a successful market. Assuming a particular sensor concept meets system specifications, it must be demonstrated to have reliability. It must also have functionality which is its intrinsic value to a control system.

The automotive application of sensors introduces a new world for adaptation; the world of the "under-the-hood" environment. Here electronic components must perform reliably and for long durations in the presence of high temperature, vibration, dirt, corrosive liquids, corrosive vapors, moving ferromagnetic parts, high voltage discharges, and general electromagnetic interference.

Conventional device complexity and sophistication implies many transistors with large numbers of interconnecting wires and associated connectors. Integrated circuit (IC) technology is an alternative that may lessen this problem. Using this technology, thousands of transistors can be incorporated into a circuit with no loosely hanging wires or independent connectors -- the bane of reliability. Integrated circuitry is key to the successful application of high level functionality in electronics. The challenge is to marry integrated circuitry and useful transduction phenomena. Extensive opportunities exist where transducers can be developed in or on silicon dice.

3. Silicon planar processing -- an opportunity.

Because of the high degree of miniaturization and low incremental cost of integrated circuitry, electronics can be dedicated to a transducer cast in silicon giving rise to very sophisticated sensors -- "smart" sensors. Optimization of design with cost leverage should occur with the marriage of the transducer and its dedicated electronics on the same piece of silicon; a monolithic device. In most cases, the size of the transducer will determine the die size. Then, little incremental cost will accompany the addition of dedicated electronics. However, research on silicon based, monolithic, smart sensors has been under way in laboratories around the world for some years now, yet not one monolithic smart sensor has been adapted in mass produced automobiles.

Silicon offers mechanical, optical, and chemical properties[1] that can be exploited in the development of transducers. Silicon can be "chemically machined" using isotropic and anisotropic etchants. When this etching is combined with photolithography of microscopic geometries, micromachining of silicon results. This has been used to develop microgrooves, thin diaphrams, micro-orifices, microcantilevers, and other miniature structures in silicon. Structures such as integrated diaphrams have been produced also by selective etching of sacrificial inner layers.

Although silicon is brittle and is easily cleaved on {111} planes, it has excellent tensile strength, several times that of a stainless steel wire, and its Young's modulus is near to that of stainless steel. Silicon is transparent to infrared wavelengths longer than 1.2 microns. It is chemically active forming silicides that are used in planar processes and forms very useful passivating oxide and nitride. A major characteristic of silicon is its naturally passivating oxide, for without this oxide, silicon would not hold its position as the key material of the semiconductor industry.

An important "handle" to silicon's transduction capability is its electrical resistance. The resistance, R, of material in the shape of a rectangular parallelepiped of length L and cross-sectional area A, is the product of the material's electrical resistivity, ρ, and the ratio of geometrical quantities, L/A. Thus, the electrical resistance offers two handles. One is through the variation of the geometrical quantity, L/A, and the other through variation of the physical property; resistivity. In a metal, the resistance can be changed through an induced strain without any accompanying change in resistivity. In silicon, these are coupled. The electrical resistivity of silicon depends upon mobility and carrier concentration products; $\mu_N N$, for electrons and $\mu_P P$, for holes: $\rho = [q(\mu_N N + \mu_P P]^{-1}$, where q is the unit of electrical charge, u is the mobility, and N and P are carrier concentrations; typically, one or the other product dominates. Both mobility and carrier concentration play roles in the overall piezoresistance of silicon giving gauge factors of 100 to 200 as compared with a metal where the gauge factor results only from the geometrical effect.

A most important characteristic of silicon for the sensor designer is the adjustability of its resistivity through doping. Using n-type or p-type dopants, the resistivity of silicon can be tailored to desired values: seven orders of magnitude of dopant concentration (10^{15} to 10^{20} cm^{-3}) correlate with six orders of magnitude change in resistivity values (10^3 to 10^{-3}).

Yet another characteristic used in sensor design is the anisotropy of the piezoresistance of silicon. This anisotropy is illustrated[2] in Fig. 2 for sections normal to the [100] axis of the piezoresistance representation ellipsoid in two cases; n-type and p-type silicon. The four-fold symmetry shown is as expected for a cubic crystal. To be noted are the strong anisotropy of the magnitudes of the piezoresistance coefficients and the change in orientation of the anisotropy between n-type and p-type silicon. The coefficients are represented as tensor values, $\Pi_{\omega\lambda}$, coupling changes in resistivity, $\Delta\rho_{\omega}$, with changes in stress, σ_{λ}; where σ_{λ} is a component of the stress tensor in six-component vector notation (λ = 1, 2, 3, 4, 5, and 6 corresponding with index pairs 11, 22, 33, 23, 13, and 12, respectively):

$$\frac{\Delta\rho_\omega}{\rho_\omega} = \sum_{\lambda=1}^{6} \Pi_{\omega\lambda}\,\sigma_\lambda$$

Being cubic, silicon has three principal piezoresistance tensor components.[3]

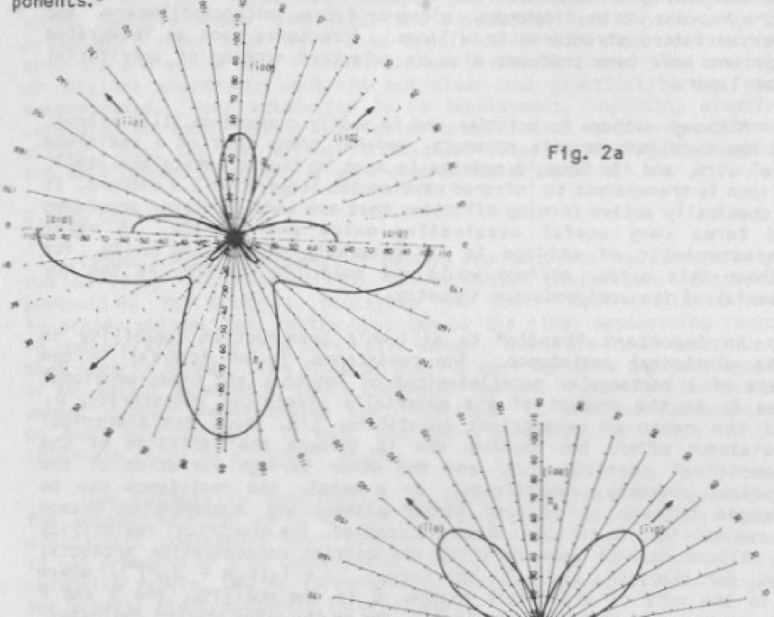

Figure 2. Room temperature piezoresistance coefficients in the (001) plane of n-type (2a) and p-type Si (2b) (units: 10^{-12} cm^2/dyne). Courtesy Dr. Y. Kanda, Hamamatsu University School of Medicine; see ref. (2).

4. Micromaching and other tools.

Through windows in oxide or nitride overlayers delineated by photolithography, etchants can be introduced to the silicon wafer to cause isotropic or anisotropic removal of silicon. In anisotropic etching the {111} crystallographic planes are the more slowly attacked and become, consequently, the boundaries of regions removed. Therefore, by aligning the edges of mask windows with the lines of intersection of {111} planes and the silicon wafer surface, grooves, orifices, and other shapes can be formed having smooth walls ({111} planes) and straight boundaries. The angles available for designing intersecting planar boundaries are the angles between internal {111} planes (70.53 deg.), between internal {111} planes and surface planes (54.74 deg. for a {100} surface and 35.26 and 90 deg. for a {110} surface). Etching with KOH and water permits etch rate anisotropic ratios of 400:1 for {100}:{111} orientations. This admits to the machining of deep grooves with large aspect ratios. An example of anisotropic micromachining is shown in Fig. 3.

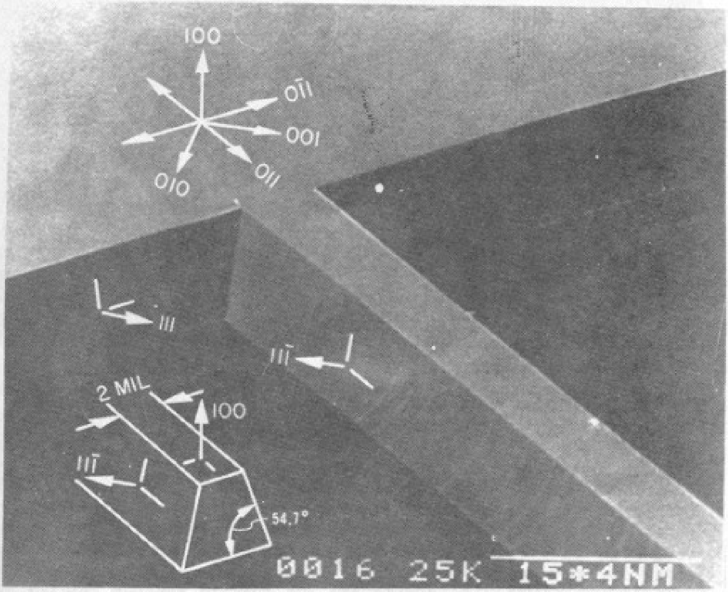

Figure 3. Micromachined beam in a {100} silicon wafer. While surface orientation is {100}, the exposed internal boundary planes are {111} and the intersections of these planes with the wafer surface have <110> directions. The beam width at the top is 50 microns (2 mils.). Courtesy of Dr. S.McCarthy, Ford Motor Company.

In addition to differing etch rates for different crystallographic planes, the selectivity of an etchant for various masking materials is important. Dopants also affect etch rates and can be used as etch stops. Etch rates of undoped silicon are typically about 1 micron/minute. Isotropic etching can be used intentionally to undercut , for example, an SiO_2 mask creating bridges, webs, cantilevers, and eaves; making structures characterized by the mechanical properties of the SiO_2. Three important silicon etchants are (1) ethylene diamine mixed with pyrocatechol, and water (EDP), (2) KOH and water, (3) and HF, HNO_3, and acetic acid (HNA). Some of their properties[1] are shown in Table I.

Micromachining can be combined with wafer bonding, wafer-to-wafer or wafer-to-glass-plate bonding, bringing yet another degree of freedom to sensor design. The bond is accomplished by applying a high d.c. voltage (ca. 1 kV) between the two pieces while holding the assembly at several hundred degrees centigrade temperature. Glasses containing alkali ions are used and the glass is held at the negative potential while

Table 1. Properties of some Si and Si-mask etchants[1].

Etchant	Etch rate m/min	Mask	Mask etch rate /min
HF, HNO_3, CH_3COOH	0.7 - 3.0	SiO_2	300
Ethylene diamine, Pyrocatechol, H_2O	0.75	Si_3N_4, SiO_2	1, 2
KOH, H_2O	1.4	Si_3N_4, SiO_2	14

the wafer is made positive; referred to as anodic bonding. The bond is conformal, hermetic, strong, and is formed quickly with ordinary alkali-silicate glasses. An entire wafer with seals around each of its many dice can be bonded at one time. With this technology, a recessed volume in a wafer can be covered and sealed. This can provide a volume to serve as a vacuum reference for an absolute pressure gauge, a pressurized volume, or a protective enclosure for on-chip electronics, for example.

A technique for producing ultrathin enclosed volumes has been developed by Professor H. Guckel and D. Burns[4]. A thin sacrificial layer of one micron or less thickness of oxide is patterned on a silicon wafer and then covered with polysilicon or a metal. Allowance is made for exposing the thin oxide along edges of the overlayer pattern. Dipped in HF, the oxide is removed without etching the wafer or the outer layer. The HF wets the oxide and "follows" it into the thin volume as it etches. When all of the oxide has been removed, the HF, which does not wet the oxygen-free surface of the wafer or the overlayer, withdraws automatically due to its own surface tension leaving behind a clean, smooth boundary, enclosed volume. At this point, one can have formed open cells, bridges, cantilevers, suspended webs, etc., see Fig. 4. A closed cell can be formed by subsequent oxidation. This seals the openings at the edges and traps oxygen in the thin chamber. Further reaction by the oxygen in the chamber reduces the chamber pressure to zero and produces very smooth chamber walls -- an ideal reference for an absolute pressure sensor.

5. Some Examples of Smart Sensors

Dedicated electronics assembled as separate dice placed on a common substrate with a transducer are referred to here as hybrid smart sensors. A hybrid, capacitive-type, smart pressure sensor is used in current production cars. It is an absolute pressure gauge used to monitor manifold and barometric pressures. Here a silicon die with a recessed area forms a pressure sensitive diaphram and, at the same time, one side of a parallel-plate capacitor. A thicker glass plate having a metalized area is anodically bonded to the wafer forming the other half of the capacitor and enclosing an evacuated reference volume against which to refer absolute pressure measurement. This sandwiched piece is one component of a thick-film circuit that includes two laser trimmed resistors: one for adjusting sensitivity and the other for offset.

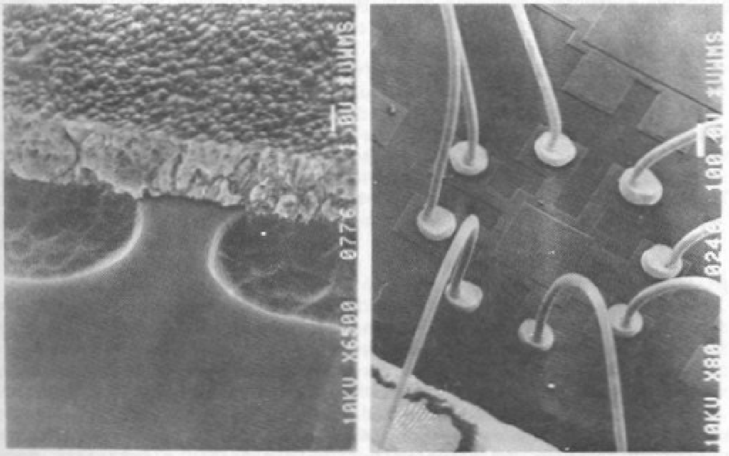

Figure 4. 4.a Etchant entrance to cavity: note one micron reference bar. 4.b Vacuum transducer with four bridge resistors. A 200 micron by 200 micron device with 1 micron gap under a 2 micron thick polysilicon overlayer. Bonds are 1 mil Au on Al. Courtesy of Professor H. Guckel, University of Wisconsin, Madison, WS. (See reference (4)).

An integrated piezoresistive pressure sensor has been developed by Sugiyama, et al.[5], having two different dedicated electronic circuits. One produces a variable voltage output, the other a variable frequency output. The sensing element of this monolithic smart sensor is a bridge network of four piezoresistors fabricated into the surface of a thin diaphram which has been etched in a {100} silicon wafer. Advantage of the anisotropic piezoresistance of silicon is gained by orienting the piezoresistors along <110> directions in the diaphram; this optimizes the effective coefficient of piezoresistance. The dedicated electronics are placed off the diaphram on the neighboring silicon. A constant-current circuit is used to drive the bridge and two operational amplifiers provide gain (ca. 100x) and a variable-voltage output. The circuit is designed also for temperature compensation needs.

The Hall effect, which is used routinely to measure charge-carrier mobility in a semiconductor, is also an important transduction phenomenon for sensors. The so called "Hall plate" is readily scaled to transistor channel dimensions and easily fabricated in planar process technologies. The Hall plate is visualized as a parallelepiped through which a current, qv (where v is the average velocity of the current), flows parallel to one axis of the plate. Any magnetic induction, B, perpendicular to the current will cause an electric field, E, to appear perpendicular to both of these directions. The field is detected as a voltage difference between the faces of the plate that are perpendicular to E. The magnitude of this voltage, V_H, is proportional to the magnitude of the current and to the magnitude of the magnetic induction. Two figures of merit are used to characterize the sensitivity of a Hall effect transducer to magnetic induction: the absolute sensitivity, $S_A = V_H/B$, and the relative sensitivity, $S_R=V_H/(IB)$. The first miniaturized, silicon-based Hall plate was a MOS device proposed by Gallagher and Corak.[6] Such a device can achieve about 10^3 V/AT sensitivity (S_R, volts/ampere-tesla). N-channel MOS Hall devices are capable of S_A - 0.15 V/T and S_R - 10^3 V/AT at drain and gate voltages less than 5 V. A factor of four times improvement in conventional devices has been reported[7] using a novel structure fabricated from a standard double polysilicon CMOS process. Improvement was gained by avoiding the use of the source and drain as the means of supplying the current to the Hall plate. Instead, the source, and the Hall MOS device, are replaced by one double-gate NMOS transistor which is coupled to an array of p-channel current sources. In this way, the short circuit effect which occurs between the source and drain of the conventional device is avoided and higher sensitivity is achieved: S_A up to 0.7 V/T, and S_R up to 4.2 × 10^3 at a supply voltage of 5 V.

Anisotropic etching of silicon has been used effectively in the development of microcantilevers for acceleration sensors. Typically, a thin cantilevered beam is formed at one surface of a die. On this beam are placed strain sensors for monitoring beam deflection due to acceleration. Improved sensitivity has been found for beams etched with large proof masses attached.[8] A 2.8 mg proof mass of Si attached to the end of a 60 micron thick, 140 microgram cantilever gave a forty-four fold enhancement in sensitivity. The integrated electronics for this monolithic device consisted of a piezoelectric film, field-effect transistor. The sensitivity achieved was 5 mV/g with nearly flat frequency response from near d.c. to 2.5 kHz.

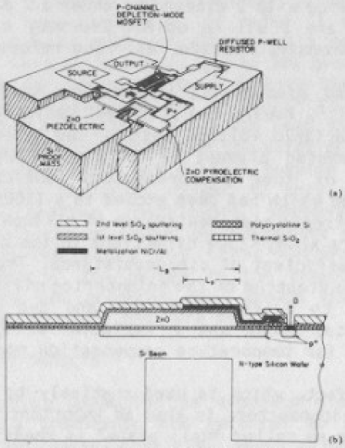

Figure 5. Integrated, Si-beam accelerometer with micromacined beam and proof mass. Courtesy Professor R. Muller, University of California, Berkely .See reference (8).

6. Packaging of smart sensors.

Packaging for smart sensors must satisfy several requirements: e.g., provisions may be required for a window to the surrounding environment for the transducer, for protection from the surrounding environment for the dedicated electronics (including electromagnetic interference), and perhaps the transducer, for electrical connection, and for mechanical mounting, while having durability, and reasonable cost. Then, of course, it must be engineered for compatibility with the system in which it is used. Package design must allow also for post assembly testing and calibration.

It might seem that a simple injection-molded plastic housing could satisfy these requirements. However, fabrication costs of the completed housing may include such things as installing electrical interface hardware, mounting hardware, internal wiring and connections, soldering, and installation of the sensor. Multiple parts imply increased installation operations which imply added labor costs. Together these easily can exceed the cost of a batch-produced monolithic device. Consequently, packaging can be the final determining factor in cost of a smart sensor.

7. Costs

The low cost of silicon chips derived from the batch processing of large wafers offers attractive economics for sensor manufacturing. A four inch diameter wafer may cost around $12.00. Masks can run about the same price (+/- 20%) per mask, per wafer. A bipolar process might require seven masks while a silicon-gate CMOS process could use eight to ten masks. Thus, masks costs can be around $100 (+/- 20%) per wafer for a specific device. The smaller is a die the more dice per wafer. However, various process issues and defect considerations come to bear on the final yield of good dice. Nevertheless, it is interesting to pursue the numbers a little further: A piezoresistive pressure sensor, for example, with a die size of 100 mil by 100 mil could have 1700 dice per 4 inch wafer. If four masks are required ($48) and a yield of 80% is assumed, the cost under these limited considerations would be ($48 + $12)/(1700 * 0.8) = $0.044 per die. Such low costs are certainly attractive but are not to be generalized to other sensors. The denominator of the calculation has a very large effect on the answer. This simple calculation demonstrates though the economic leverage associated with miniaturization and planar process, batch fabrication.

8. Conclusion

Opportunities are evident for developing cost effective, monolithic, smart sensors using transducers based on silicon. The environmental applications of such devices raise severe challenges to the sensor engineer. The development of transducer concepts in and on silicon offer new challenges to the scientist also. Already, examples of such devices have been developed in various laboratories around the world. Together, these give evidence of a new frontier of advanced technology.

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