

Smart sensors: Physics, technology and applications

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The semiconductor technology has advanced a rapid progress in the sensors which are heart of instrumentation systems. These days, most of the sensors are 'smart' in nature. In such sensors, the sensing elements and associated electronics are integrated on the same chip. Generally, silicon is preferred as sensor material because it can give a suitable physical conversion effect and can give suitable signal processing circuit, with integration of the sensing element and electronic circuits on the chip, by using standard planar technology. The smart sensors have main advantages of fast signal conditioning, higher signal-to-noise ratio, self testing, auto calibration, small physical size, high reliability, failure prevention and detection. In the present paper, recent advances in smart sensors along with their design and fabrication aspects, are discussed. The smart sensors developed in this Laboratory, mainly smart pressure sensors and smart lithotripsy sensor, are presented, besides smart sensors used in industrial controls, automotive and biomedical fields. Biochips and biosensors are also cited for some of the specific applications.

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1 Introduction

Sensors are needed to convert a wide range of physical parameters into electrical signals. In the relationship between the history of automation and sensors, it appears that a sensor-technology lag still exists. This can only be overcome with the concept of integrated smart sensors¹⁻¹⁹. Broadly, a 'smart sensor' is defined as a chip with sensors and digital interface.

It is interesting to see in a historical^{1,5,6} perspective how the sensors have subsequently developed. The development has dramatically changed human life. At first, people tried to extend their mechanical power by artificial means: the actuators, such as watermills, the steam engine, combustion engine and the electromotor. This development led to the 'industrial revolution'. Then, people tried to extend their routine intelligence by means of computers. Though this happened only twenty-five years ago, one can already say that this phenomenon has resulted into an 'information revolution'. Now, people are artificially extending their senses by making use of sensors. These sensors are needed to acquire data in order to correct errors in automated processes and to adapt the process to changing circumstances. When all the stages of the control loop become more and more economically available, one can expect that routine work will increasingly be taken out of the hands of

man by automatic machines and robots in the workplace and in the home. This will surely represent one of the main changes^{6,7} in future human life: the 'automation revolution'.

Sensors are absolutely essential in control and instrumentation, being the route through which processing electronics acquires information from the external world upon which they act. Neither instrumentation nor control systems have an existence unless measurements are made. There are wide ranges of measurands which are detected by a variety of sensors. The sensors have now become a key component in many areas, including automotive, medical, aerospace and industrial process control^{1,9,11,13}. A broad range of sensors is also required to provide automation in the manufacture of goods. These include some common sensors like 'tactile sensors' and 'pressure sensors' to detect the stress applied to the workpiece. One system could use many sensors to get an accurate reading of the system performance⁸.

With the advancement in silicon technology, instrument technology has progressed at a rapid speed. The sensors which are heart of instrumentation systems are 'smart' in nature now. A 'smart sensor' is an assembly of the sensing element and associated electronics for signal conditioning and data

processing etc., on the same chip (Fig. 1). Generally, silicon is chosen as a material for the sensing element because it can give a suitable physical conversion effect, is easy to design and fabricate an integrated system and can give suitable signal processing circuit, with integration of the sensing element and electronic circuits on the chip, by using standard planar technology. The smart sensors have main advantages of fast signal conditioning, higher signal-to-noise ratio, self testing, auto calibration, small physical size, high reliability, failure prevention and detection. In the present work evolution of smart sensors, is presented by giving trends in the sensor technology. The most significant development in sensors technology is the inclusion of a dedicated microcomputer in the sensor design as an integral component to make it smart^{5,7,8,10}. The 'smart sensors' incorporate a real time integral component to the microcomputer dedicated to the measurement intended^{1,5}.

In the present paper, evolution, physics, technology and applications of smart sensors are described. Development of different types of smart sensors for use in controls, communications, environmental monitoring, biomedical and other fields is given in detail.

2 Development

Sensors have progressed through various stages. The first generation devices had little electronics

associated with them, while second generation sensors were part of purely analog systems with electronics as remote control for the sensors and in the third generation, first stage of amplification occurred on the sensor chip itself. In fourth generation sensors, more analog and digital electronics were on the chip itself to make the sensor addressable and self testing. In fifth generation, data conversion is accomplished on the same sensor chip. The fifth generation sensor is addressable, self testing and communicates over a bi-directional digital bus^{1,5,7} (Fig. 2).

3 Technology

A modern microprocessor-cum-micro-sensor is composed of (i) the sensing element (ii) a signal processing part and (iii) the microprocessor. Parts (i) and (ii) are fabricated on a single chip to form a smart sensor^{1,10}. Integration⁵ of interface electronics and signal processing circuitry at sensor chip serves a number of functions like amplification, impedance transformation, signal filtering and multiplexing. Many sensors are based on resistors. When a diffused silicon resistor is subjected to light strain, a temperature increase or a magnetic field, the resistance value changes. A very well known method for the measurement of the small resistance changes is the Wheatstone bridge. In most piezo-resistive pressure sensors the response of a bridge output to the application of a stress is measured⁴. The amplitude of output signal recorded by sensors is typically low, so

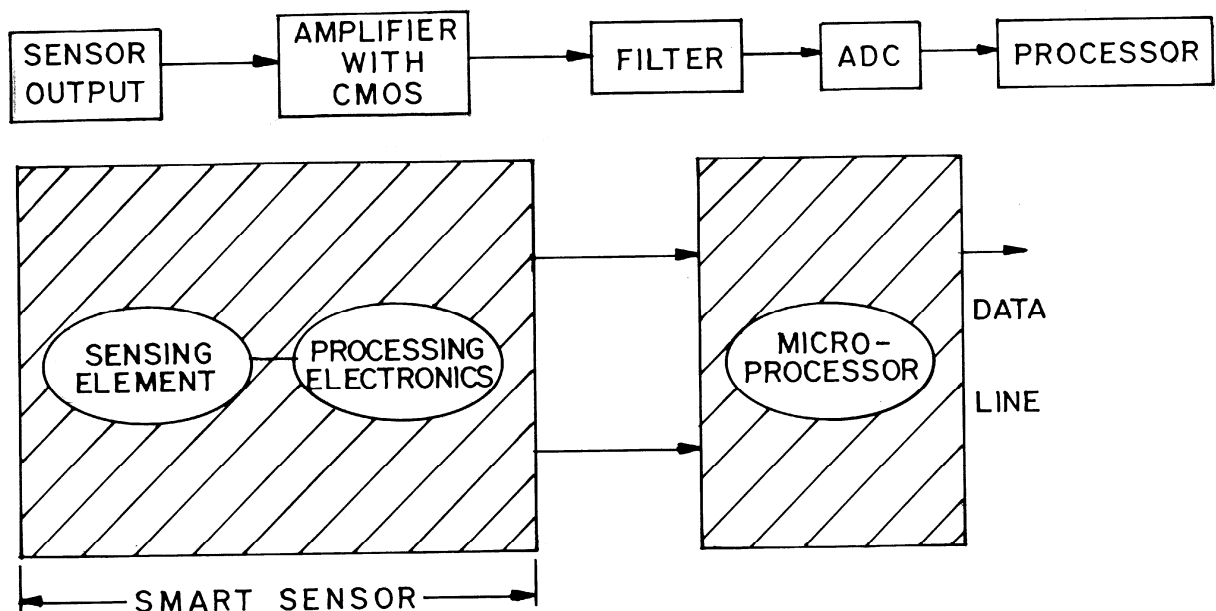


Fig. 1—Block diagram of a smart sensor

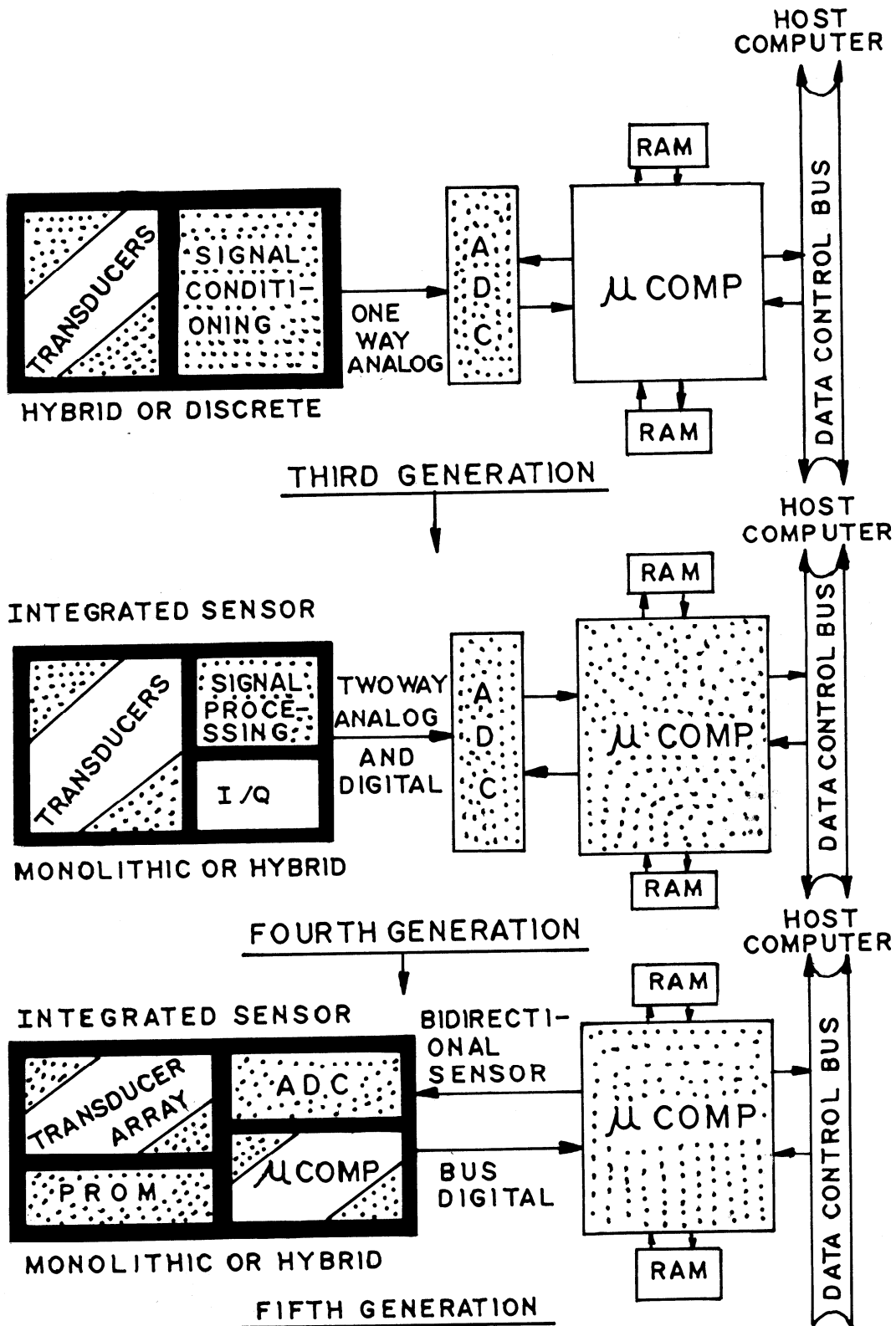


Fig. 2—Evolution of smart sensor interfaces

our first need is to amplify these weak signals before transmission to reduce the effect of noise from the environment¹⁰. Impedance transformation is also required (i) to ensure maximum signal transfer to the next stage, (ii) to reduce the susceptibility of sensed signal to environmental noise. Transconductance amplifier implemented in a typical CMOS operational amplifier are best suited for this purpose. For capacitive type circuits where gain is not required immediately, the simple buffer circuit can be integrated on the sensor chip⁵.

4 Fabrication

Solid-state integrated sensors are basically composed of four elements namely, custom films for transduction, microstructures, integrated interface circuitry and microcomputer based signal processing algorithms. Mainly, three techniques bulk micromachining, surface micromachining and wafer bonding process are used for fabrication of smart sensors. These days, there has been advancement in the fabrication technique of the micro-systems^{1,3}. Bulk micro-machining is used for making micro-sensors and MEMS (micro-electro-mechanical systems) and deep dry etching for sensor micro-machining¹⁻³. The fabrication of oxide membranes by deep dry Si etching has been investigated to get uniform membrane width over the wafer. A deep dry Si etch on the STS is etched through a 228 micron thick wafer and stops on the top oxide layer which is more uniform and leads to less membrane widening. The etching process has been optimized for the parameters like etch rate, uniformity and notching at the oxide interface. STS deep dry Si etching process was optimized through 650 μm thick wafer with a stop on the oxide layer which is more uniform and leads to less membrane widening flow rate for 30 minutes. The average data with standard deviation for different runs was plotted (Fig. 3) and analysed. Silicon etching is an essential process step for the fabrication of smart sensors and micro-electro-mechanical systems (MEMS). A surface micromachined accelerometer structure can be fabricated by deep trench etching from thick polysilicon grown in an epitaxy reactor. The device is useful in moving trolleys/cars as safety systems, in the hospitals. A micromachined gyroscope for vehicle dynamic control, for use in locomotion, can be manufactured in combination with the deep trench etching and thick bulk silicon membrane. Surface micromachined gyroscopes with roll over

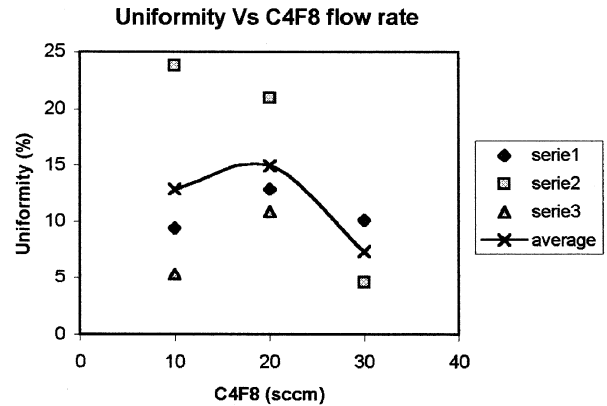


Fig. 3—Optimization results for smart sensor chip fabrication

automatic safety sensing are made with MEMS technology. Micro switches/micro relays are micro-machined devices, for high speed switching relays used in automatic test equipment, medical devices or communication devices. Membrane based micro-sensors and MEMS are possible to be fabricated for pressure and flow measurements^{4,11,12}.

5 Applications

5.1 Industrial

Smart sensors currently have established their strongest presence in the industrial market. Reasons which can readily be identified are: the higher cost associated with the more stringent specifications and medium to low volumes prevalent in the industrial market place the relative unimportance of package size the high level of importance attached to data reliability associated with very large plants and coupled with difficulty of access to sensors for diagnostics, and the development of a number of industrial digital databus standards^{1,8}. It is expected that the trend to introduce smart sensors in the industrial area will continue as databus standards are rationalized and the benefits of remote diagnostics are better understood. Design layouts of few smart sensors are shown in Figs 4-8 for pressure, flow and temperature etc.

5.2 Aerospace

The aerospace industry is looking to adopt smart sensors for different sensors. The issues of data integrity are equally important or more so, but another major concern is that of the weight of cable associated with large numbers of sensors which are frequently multiplied for redundancy purposes. Safety is

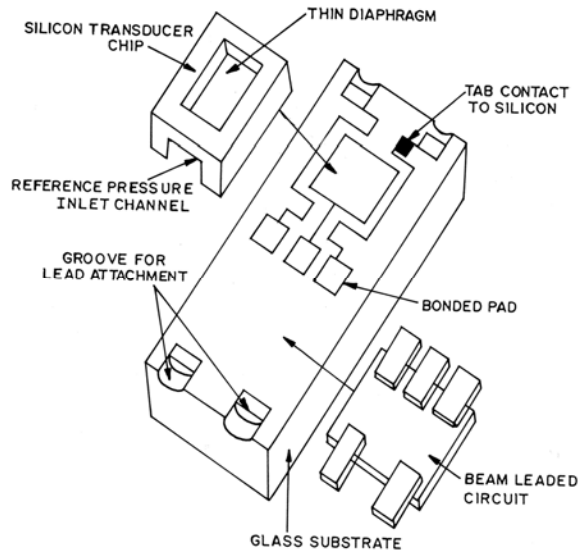


Fig. 4—Cross-sectional view of ultra-miniature solid state smart pressure sensor

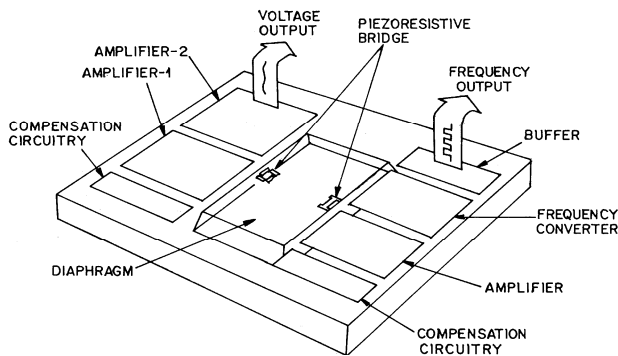


Fig. 5—Schematic diagram of on-chip integrated pressure sensor with both voltage output and frequency output circuits

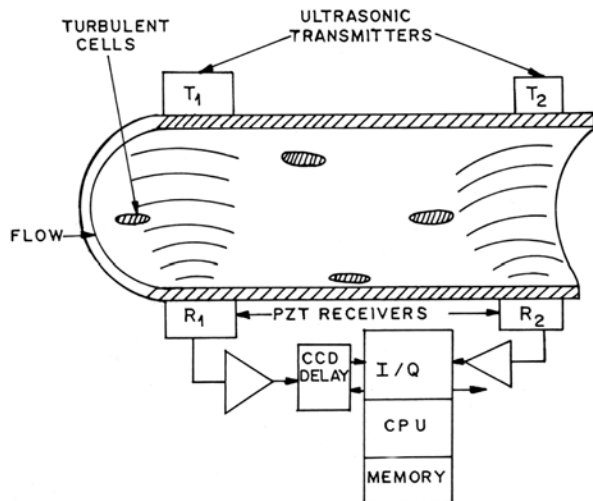


Fig. 6—Diagram of a smart non-intrusive flow sensor

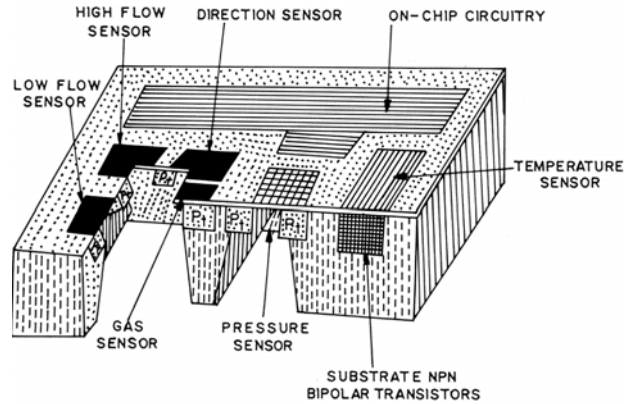


Fig. 7—Monolithic mass flow sensor with on-chip interface circuitry

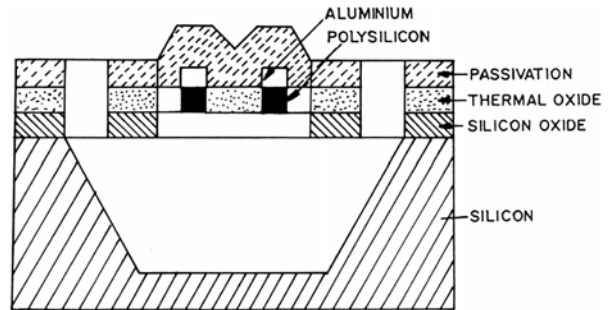


Fig. 8—Core body of a smart temperature sensor

potentially improved by self-monitoring sensors, the additional information generated by this new capability requires a multiplexed, i.e. digital data bus to return the information to a point where it is of value and the availability of multiplexed data buses allows the output of many sensors to be concentrated onto the minimum number of buses (Fig. 2) consistent with adequate redundancy^{6,9}.

5.3 Automotive

Automotive manufacturers are also closely monitoring the potential of smart sensors⁹, but here the cost constraints are paramount. Smart sensors attached to digital buses are unlikely to find their way into the majority of vehicles until the data buses themselves are introduced for other purposes. Communications between engine, transmission, suspension, braking and other controls has long been anticipated and a variety of automotive databus standards exist to enable this. Each automated process consists of different functional blocks. For example, to control the flight of an aeroplane, we need: (i) actuators, such as engines and rudders to propel the

plane; (ii) computers, such as the automatic pilot, to control the actuators on the basis of a flight plane; and (iii) sensors (Figs 4 and 5) for measuring acceleration, altitude, tilt, etc., to feed the computer with information about the actual flight and to enable corrections to be made.

5.4 Telecommunications

The existence of a processor within the package, however, opens up many more possibilities. The two most obvious of these are digital communication via a standard bus and sensor diagnostics. Others include improved response times based on prior knowledge of frequency characteristics and the ability to calculate a measurand on the basis of a variety of raw input data^{1,5,7}.

Smart cards are now increasingly popular in cellular systems, because these are used in an inexpensive way to enable e-commerce applications, additional security and roaming functions, without altering the basic design of terminals. Wireless-internet and mobile e-commerce will boom soon, as network operators aggressively pursue the merits of integrating security and transaction applications on the WAP (Wireless Application Protocol) platform. The phones based on WAP 1.1 often do not encrypt data, so they cannot guarantee authenticity or confidentiality of messages or prevent unauthorized modification and use of phones. Operators want the more secure WAP 1.2 standard and are pushing handset makers to deliver models. A smart card known as a Wireless Identity Module (WIM) incorporating WAP 1.2, is similar to the Subscriber Identity Module (SIM) used on existing GSM cellular phones. The card guarantees 100-percent security for e-commerce transactions over WAP phones by providing authentication of the parties involved, by means of encryption and digital signatures. Smart cards will thus definitely play a bigger role in mobile phones in the future. These will provide a secure environment for a variety of service applications, such as transactional-based services, which will facilitate the development of m-commerce.

A smart card called the Roaming Universal Identity Module (R-UIM) has been developed for CDMA phones during the third quarter. The card enables users to roam on GSM networks using a hired phone and their own smart cards, called 'plastic roaming'. CDMA/GSM dual-technology phones equipped with a R-UIM smart cards have also been developed. Future phones may have two smart cards, WAP

version 1.4 specifies two WIMs in each phone, enabling several secure e-commerce applications to be run. Major smart card manufacturers have developed a SIM-based browser that will make existing SIM Tool Kit-capable handsets-75 percent of the phones currently in use- interoperable with WAP-based services. This will allow short-term mass deployment of mobile access to the Internet. The SIM browser will be available soon. MasterCard is helping vendors develop turnkey solutions for secure applications on multi-application smart cards that will securely identify cardholders and initiate payments with credit or debit cards^{5,7}.

5.5 MEMS and Process Control

MEMS (MicroElectroMechanical Systems) is a class of systems⁵⁻⁸ that are physically small. These systems have both electrical and mechanical components. MEMS originally used modified integrated circuit (computer chip) fabrication techniques and materials to create these very small mechanical devices. Today there are many more fabrication techniques and materials available.

Sensors and actuators are the two main categories of MEMS^{5,6}. Sensors are non-invasive while actuators modify the environment. Micro sensors are useful because their physical size allows them to be less invasive. Micro-actuators are useful because the amount of work they perform on the environment is small and therefore can be very precise.

Polysilicon Resonator Transducers are an example of a MEMS sensor using a stress controlled thin film polysilicon process which is a modification of integrated circuit fabrication techniques. The sensor uses a mechanically free beam of polysilicon whose resonant frequency can be measured electronically. Environmental changes can be converted to a change in resonant frequency of the micro beam; and therefore, can be sensed. It is interesting to note that **the first MEMS device** was a gold resonating MOS gate structure⁷.

High Aspect Ratio Electrostatic Resonator was fabricated^{7,8} with a high energy photon light source and electrodeposition technique. The high energy photons come from an X-ray synchrotron which are used to define a thick PMMA (Plexiglas) mold for electroplated materials. In this resonator, the center mass, springs and electrostatic fingers are free while the rest of the structure is fixed to the substrate. Movement occurs by applying a voltage between the

centre structure and one of the side fixed structures. The overlapping fingers allow this voltage to occur over a larger area resulting in a larger attractive force. This is an example of a linear actuator which can be used as a switch, precise positioner, or part of a resonating sensor.

Magnetic Micro Motors can also be fabricated by a deep X-ray lithography and electrodeposition process. The rotor is magnetically salient to allow a magnetic field applied to each of the two poles to cause the rotor to turn. External loading gears are added to test the friction in gear trains by using an external magnetic field to drive the salient rotor. This is an example of a rotational actuator.

Precision Engineered Gears are fabricated^{7,8} by a deep X-ray lithography and electrodeposition process. Each gear is 100 microns tall, made of nickel, and are held to submicron dimensions. MEMS can be used to create parts of systems where high tolerances are necessary. These gears bridge the gap between MEMS and traditionally machined precise components.

Measuring success for smart sensors and particularly for MEMS manufacturers^{2,3}, has improved process control, faster process development, and quicker time-to-market. The new 3-D system gives fast, non-contact measurements, unmatched repeatability and sub-nanometer vertical resolution to help keep your process in control. With a vast range of applications, the chip gives exactly where the process needs improvement, or where research is leading, in seconds, without sample damage. The 3-D MEMS chip is the next generation of say optical profilers. With faster scan speed, larger measurement range, gauge capability, and full automation, quick visualization and analysis of devices, with necessary software provides extensive data analysis and immediate results that interface easily with the existing yield management systems. The 3-D system can be customized with stages, objectives, and options to fit a particular application.

5.6 Defence applications

Smart sensors, MEMS, including RF communication components and sensor arrays (Figs 5 and 7) with processing electronics, are used in the avionics and mechanical systems^{6,9} by monitoring a wide variety of parameters like EMI, fatigue loading, thermal cycling, vibration and shock levels, acoustic emissions and corrosive environments. A typical MEMS accelerometer^{5,7}, coupled with silicon micro-

structure (resonant microbeam) can provide a high sensitivity pick off for measuring inertial acceleration, inclination, low-frequency vibration, etc.

5.7 Biomedical applications

A number of smart sensors for biomedical applications^{1,3,4,12,13} have also been developed (Figs 9 and 10) by using chip technology. Calibration aspects of such sensors for use in standards have been studied in detail¹¹⁻¹³.

5.7.1 Biochips

A special class of biosensors, typically known as biochips¹⁴⁻¹⁸, has multiple transducer elements and is based on integrated circuit microchips. The term "biochip" is like a "computer chip", which is a silicon-based substrate used in the fabrication of miniaturized electronic circuits. Therefore, in the generic sense, there is a certain element of integrated circuit involved in the term 'biochip'. However, over the years, the term biochip has taken on a variety of meanings. A biochip is now generally defined as a material or a device that has an array of probes used for biochemical assays. In general, any device or component incorporating a two-dimensional array of reaction sites and having biological materials on a solid substrate has been referred to as a biochip. Biochips often involve both miniaturization, usually

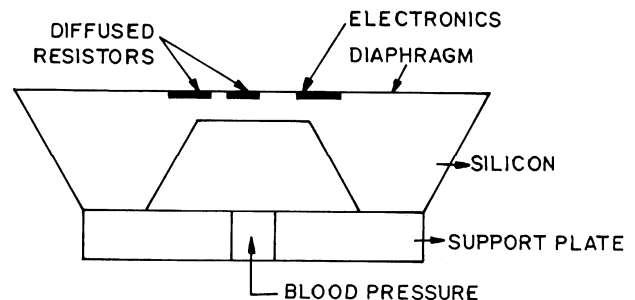


Fig. 9—Cross-sectional view of a blood pressure sensor chip

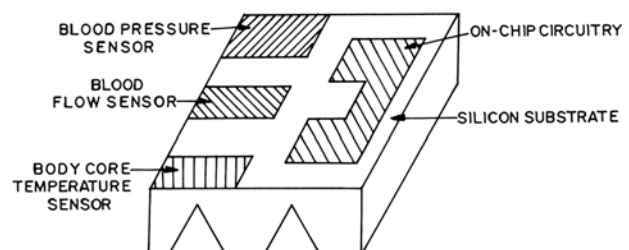


Fig. 10—Multisensor chip with on-chip circuitry

in microarray formats, and the possibility of low-cost mass production, are of two types,

- array plate biochips, which consist of plate-based or gel-based substrates; and
- integrated biochips, which also include the detector-array microchips.

Substrates having microarrays of bioreceptors are often referred to as biochips, although most of these systems do not have integrated microsensor detection systems. These array plate biochips usually have separate detection systems that are relatively large and are only suitable for laboratory-based research applications. They can have large numbers of probes (tens of thousands) that can potentially be used to identify multiple biotargets with very high speed and high throughput by matching with different types of probes via hybridization. Therefore, array plates are very useful for gene discovery and drug discovery applications, which often require tens of thousands of assays on a single-plate. On the other hand, integrated biochips are devices that also include an integrated circuit microsensor chip, which makes these devices very portable, and inexpensive. These devices generally have medium-density probe arrays (10-100 probes) and are most appropriate for medical diagnostics at the physician's office.

5.7.2 Microfluidic biochips

The attachment of enzymes to glass microfluidic channels has been achieved^{14,15} using a highly reactive poly (maleic anhydride-alt- α -olefin) (PMA)-based coating that is supplied to the microchannel in a toluene solution. The PMA reacts with 3-aminopropyltriethoxysilane groups linked to the glass surface to form a matrix that enables additional maleic anhydride groups to react with free amino groups on enzymes to give a mixed covalent-noncovalent immobilization support. In a typical microfluidics-based IC biochip system, the sample chamber and all access ports are machined into a 2.5 cm \times 2.5 cm \times 0.3 cm piece of Plexiglas. Glass or quartz plates (1 mm thick) affixed to the top and bottom of the Plexiglas seal the sampling chamber and serve as excitation and detection windows, respectively. While the bottom plate is permanently fixed in place, the top plate is removable for the routine replacement of sampling platforms within the chamber. A pair of rubber-lined Plexiglas rails is

attached to the bottom sealing plate allowing the microfluidic device to be mounted onto the IC biochip¹⁵.

5.7.3 DNA Biochip using a phototransistor integrated circuit

An integrated sensor based on phototransistor integrated circuits has been developed^{15,16} for use in medical detection, DNA diagnostics, and the mapping. The evaluation involves various system components developed for an integrated biosensor microchip. Methods of development include a microarray of DNA tubes on nitrocellulose substrate. The chip device has sensors, amplifiers, discriminators, with logic circuitry on board. Integration of light-emitting diodes into the device is also possible. To achieve improved sensitivity, an IC system having the phototransistor sensing element composed of 220 phototransistor cells connected in parallel may be used.

5.7.4 Cytosensor microphysiometer: biological applications of silicon technology

A silicon-based device, called a microphysiometer¹⁶⁻¹⁹, can be used to detect and monitor the response of cells to a variety of chemical substances, especially ligands for specific plasma membrane receptors. The microphysiometer measures the rate of proton excretion from 10⁴ to 10⁶ cells. This article gives an overview of experiments currently being carried out with this instrument with emphasis on receptors with seven transmembrane helices and tyrosine kinase receptors. As a scientific instrument, the microphysiometer can be thought of as serving two distinct functions. In terms of detecting specific molecules, selected biological cells in this instrument serve as detectors and amplifiers. The microphysiometer can also investigate cell function and biochemistry. A major application of this instrument may prove to be screening for new receptor ligands. In this respect, the microphysiometer appears to offer significant advantages over other techniques.

5.7.5 Microscale integrated sperm sorter: biochip-lab

Biomedical engineers have recently developed¹⁸⁻¹⁹ a prototype lab-on-a-chip for harvesting healthy sperm cells to increase male fertility. The microscale integrated sperm sorter (MISS) separates strong swimmers—sperm cells that are most likely to fertilize an egg—from aimlessly drifting spermatozoa that are essentially incapable of fertilization. The

system allows separation and detection of motile sperm from small samples that are difficult to handle using conventional sperm sorting techniques. The device, slightly larger than a penny, is an inexpensive, easy-to-use sorter that men could ultimately use at home to measure fertility or test the outcome of a vasectomy or vasectomy reversal.

Since sperm motility is a sensitive indicator of toxicity, the MISS may also be useful as a toxicology test. The rectangular device has been built using conventional techniques similar to those used in making computer chips. It has two input chambers at one end and two collection chambers at the other. A channel extends from each input chamber, merging into a single pipe for some distance, then separating before entering the two collection chambers.

The MISS requires no power source. Fluids are set into motion by the forces of surface tension and gravity, which combine to produce a steady flow. The device also takes advantage of laminar flow, in which two liquid streams can be made to run side-by-side without mixing. This is what happens in the middle of the MISS when the two fluid channels merge.

To operate the device, a semen sample is placed in one input chamber. A second chamber is filled with salt water. The two fluids move toward the opposite end of the device, combining in the middle into a single laminar flow. While the two streams are side-by-side, swimming sperm will cross the laminar boundary and enter the salt water. Nonswimmers go with the flow and stay in the original stream. When the two streams separate into the collection chambers, one chamber will have swimmers, the other will not.

The purity of sorted sperm samples that arrive in the collection chamber is nearly 100 percent. This approach to sperm sorting has additional advantages compared to conventional sorting techniques. It avoids processes, such as centrifugation, that can damage sperm. It can be combined with a colour-coded readout for a self-contained, easy-to-use home test. The MISS, which sorts by motility, coincidentally selects sperm cells that lack physical abnormalities, such as a misshapen head or crimped tail.

In theory, a single sperm cell is all that is needed to fertilize an egg. But it can be impractical to isolate and harvest the most viable sperm cells using conventional laboratory techniques. Doctors frequently resort to hand sorting through dead sperm and debris to find a 'good' sperm, a procedure that can

take hours in some cases. About one in 10 couples have fertility problems and 40 percent of these cases have absent or abnormal sperm. Conventional fertility treatments are effective in many cases, but are less effective when sperm counts are very low.

Investigations are also possible to sort cells using artificial blood vessel linings (endothelia). Clinical diagnosis of disease relies heavily on the ability to analyze the cellular composition of blood. New applications are possible now with such new devices²⁰⁻²³.

6 Conclusion

The evolution and technology development of smart sensors for various applications in different fields have been discussed. Fabrication aspects of smart sensors have also been discussed. The latest trends including biochips have also been presented. Measurements and instrumentation systems will be developed by using smart sensor in future.

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