Microsensations

Silicon fabrication processes are being adapted to produce miniature sensors so cheaply that a revolution is taking place in the field of instrumentation

by **Julian William Gardner (M),** University of Warwick

It is no exaggeration to say that all industrial processes – and a good many everyday domestic ones – use measurement at some level, and a great many use electronic measurement systems. At the heart of any electronic measurement is a sensor – a device that converts a physical or chemical quantity (e.g. pressure, humidity) into an electrical signal.

Thanks to the silicon revolution, we can now make small and reliable microelectronic devices at almost a throwaway cost. This advance has opened up a considerable demand for small sensors or microsensors, with sub-micron dimensions, that can fully exploit the enormous cost benefits of silicon processing technology.

An electronic measurement system. converts pressure (say) into a voltage signal, which is then modified by a processor (typically an A/D converter plus a microcontroller or microprocessor) and the output is used to drive another device, such as a display or actuator. A microsensor often has ultra-low capacitance – of the order of 1 fF – so it is essential to integrate some of the processor electronics to condition the signals. The resulting device is often called a smart sensor: it can process information itself, or communicate with an embeded microprocessor.

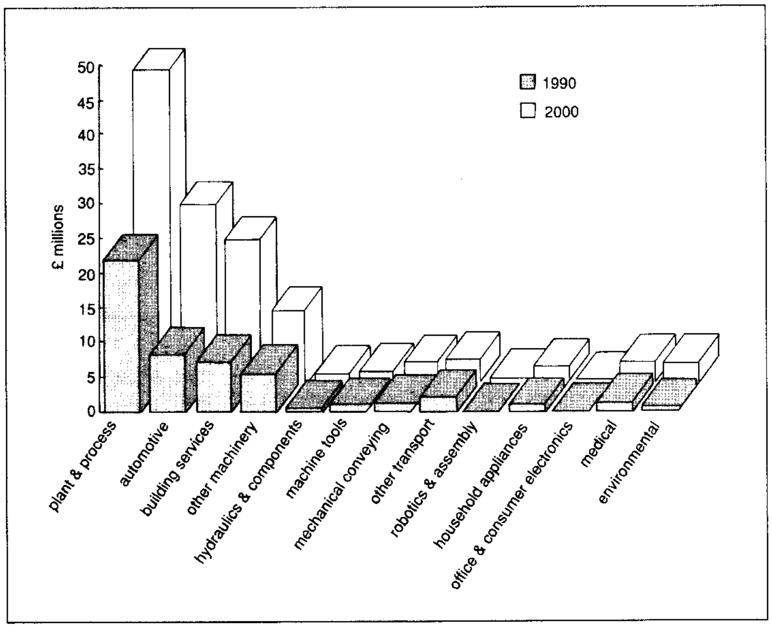
Similarly, an actuator can be made smart or, in principle, the entire system can be integrated to make a microrobot. One day we may even employ mobile microrobots, which will move unnoticed through air and water, like a microplane or microsubmarine.

Sensors have an important role to play in our everyday lives: we routinely need to gather information, process it and perform some task based on that information. Yet the commercial exploitation of any sensor is determined by its performance, cost and reliability; thus silicon microsensors, which perform well on all these criteria, are set to transform the world of instrumentation. The UK sensor market has been estimated to be worth £22 million in 1990 and about £46 million by 2000; the world sensor market has been estimated to be worth £7 billion in 1990 and is projected to rise to about £25 billion by 2000.

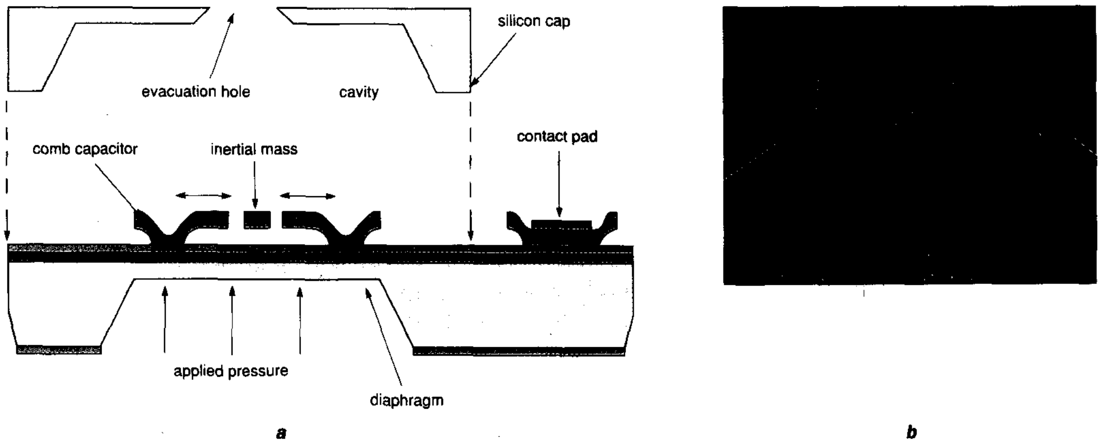
Fig. 1 shows the market value and range of commercial applications, from plant and process to medical and environmental applications.[1] Microsensors are not only taking an increasing share of this sensor market, but also generating new markets due to their unrivalled performance.

Materials and techniques

A wide variety of active and passive materials are used to make microsensors, and many of the processes developed for electronic silicon microfabrication have been adapted for sensor applications.



1 UK sensor market by application, 1990-2000[1]



2 Pressure microsensor using a polysilicon resonant structure made by a surface micromachining technique
(*a*) schematic (*b*) micrograph[2]

Thin-film processes, for example, have been developed to create devices for measuring thermal, radiation, mechanical, magnetic and chemical measurands.

Engineering a microsensor (sometimes called microengineering) requires appropriate microelectronic fabrication processes, developed from an understanding of micromachining, microfabrication, micromechanics and microelectronics. Standard silicon processing has been adapted to make many new types of microsensors. One important area has been the development of isotropic and anisotropic etching of single-crystal silicon, polysilicon and other materials to make small mechanical structures such as thin diaphragms, cantilever beams, bridges, cavities and mesas.

For example, it is possible to make a bridge structure by using phosphosilicate glass, as a sacrificial layer, and then surface micromachining a thin layer of polysilicon. Such processing can produce very complicated structures, such as the microflexural resonator shown in Fig. 2, which has been has been designed to act as a (mechanical) pressure sensor.[2] The deflection of the diaphragm induces a strain, which in turn changes the spring constant of the structure and hence its fundamental frequency (around 30 kHz).

The microstructure is electrostatically driven by one set of combs, and capacitively sensed by the others. These kinds of microresonant structures have a resonant frequency in the kilohertz range, and can achieve bandwidths and sensitivities that are impossible in the currently used large mechanical structures.

Table 1: Classification of sensors by the energy form of the input signal

Form of signal	Measurands
thermal	temperature, heat, heat flow, entropy, heat capacity
radiation	gamma rays, X-rays, ultra-violet, visible, infra-red, microwaves, radio waves
mechanical	displacement, velocity, acceleration, force, torque, pressure, mass, flow, acoustic wavelength and amplitude
magnetic	magnetic field, flux, magnetic moment, magnetisation, magnetic permeability
chemical	humidity, pH level and ions, concentration of gases, vapours and odours, toxic and flammable materials, pollutants
biological	sugars, proteins, hormones, antigens
electrical	charge, current, voltage, resistance, conductance, capacitance, inductance, dielectric, permittivity, polarisation, frequency

Solid-state microsensors

Some microsensors can be made using conventional bipolar or MOS technology, and a whole variety of radiation sensors are available today that can detect visible, near-infrared and infrared radiation using, for example, silicon *p-n* diodes, avalanche photodiodes and pyroelectric devices.

For example, digital thermometers can be engineered using a thermally sensitive device such as a resistor (e.g. an NTC thermistor), diode (a silicon *p-n* thermodiode) or transistor. In the case of a thermotransistor, the temperature-dependent parameter is the voltage between the base and emitter of the transistor, V_{be}. The problem of the control of device geometry can be ameliorated by applying first a high collector current and then a low collector current. Then the difference signal ΔV_{be} becomes directly proportional to the absolute temperature T. This is known as a PTAT device.

Fig. 3 shows the circuit for an integrated silicon thermotransistor based on a number of transistors. The current *i* splits equally down each side of the circuit, as transistors T1 and T2 have the same base-emitter voltage. In the second stage, T3 consists of eight transistors (only one shown), each identical to T4.

Thus the collector current passing through transistor T4 is eight times that passing through transistor T3. The voltage drop across the reference resistor *R* is the difference between the base-emitter voltages, and, as half the current flows through *R*, the current is directly proportional to the absolute temperature. A modified version of this device is the commercially available Analog Devices AD590 temperature sensors, which provide a high-impedance current source with a sensitivity of 1 μA per degree.

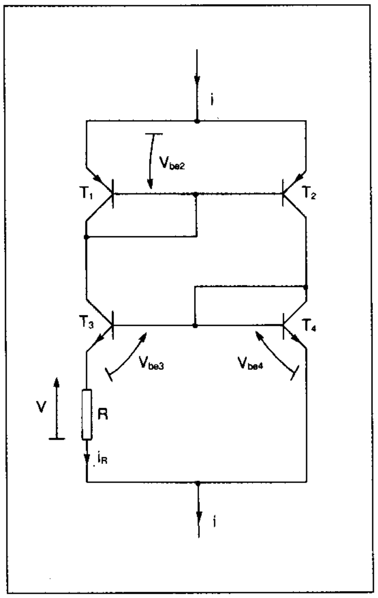
Similarly, a variety of magnetic microsensors are commercially available, such as Hall plate devices, magnetoresistors (e.g. doped InSb/NiSb), magnetodiodes and magnetotransistors (vertical and lateral). In a vertical dual-collector magnetotransistor,[3] for instance, the current flows perpendicular to the silicon surface and so is sensitive to lateral magnetic fields. Such a device can be readily used in a silicon compass watch to detect the earth's magnetic field.

The device consists of two *p-n-p* transistors with the base and emitters common to both devices. A lateral magnetic field deflects the electrons towards one of the n^+ collectors and generates a differential collector current.

Mechanical microsensors

Engineers have built mechanical structures for centuries, and regularly apply static and dynamic codes to design structures ranging from bridges to aircraft engines. Similar design rules have been developed for silicon microstructures, and it is often possible to apply linear elastic equations to micron-sized devices.

Mechanical microsensors form perhaps the largest family of sensors, including displacement, acceleration, strain and pressure sensors. Table 2 shows the physical properties/principles typically used in mechanical microsensors, such as piezoresistivity and capacitive coupling.



3 Circuit for integrated silicon thermotransistor

For example, Fig. 4 shows the basic design of a cantilever silicon microaccelerometer with a simple piezoresistive readout. The proof mass is about 100 μm across and it can move a micron or so in a few milliseconds in response to an external acceleration.

Mechanical micromachined microsensors are now being made in large numbers by companies such as SensoNor and Analog Devices, which make airbag sensors that respond to a collision in under 20 ms, and Druck, which makes precision pressure sensors for the aviation industry. These devices are robust, have a wide dynamic response and are reliable – and yet, when mass produced, they cost only a few tens of dollars each.

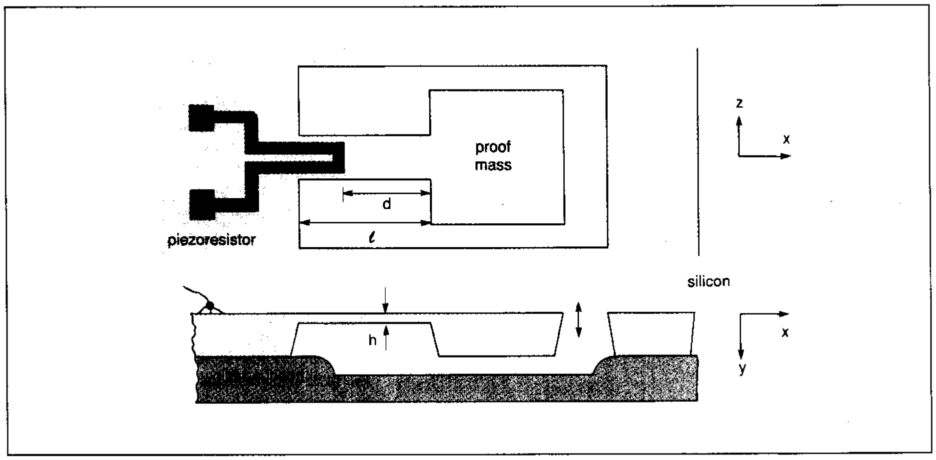
Outlook

Sensors based on the same principles are gradually transforming the way we live through applications in household appliances. Microsensors can be used to measure both the temperature and the load in an intelligent washing machine. We may even see the use of an electronic nose to measure the smell on our clothes, to assess their cleanliness and hence determine the appropriate washing cycle.

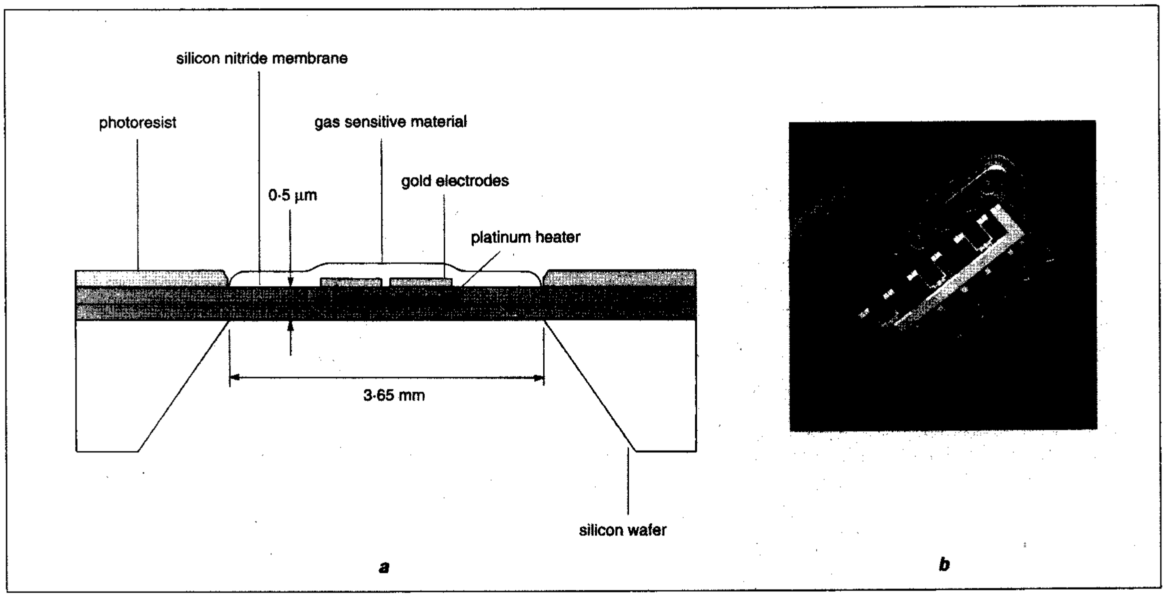
Microsensors are used to control the cooking of foods in a microwave oven, by monitoring the temperature of the food, or the humidity and level of browning gases within the oven. Microsensors are used in video and CD players, lighting and security systems and many other forms of home automation. However, this technology is in its infancy, with minimal feedback to the user and only simple alarm systems. The potential for intelligent instrumentation in the future is enormous.[4]

New markets are opening as our demand for information gathers pace in an increasingly sophisticated world. Two markets that should be of great importance in the future, but are relatively untapped, are environmental monitoring and medicine.

We face increasing health problems caused by the pollution of our air by exhaust emission gases (such as carbon monoxide, hydrocarbons and nitrous oxides) from cars, electricity generating plant, process plant etc., and the pollution of our rivers by industrial, agricultural and domestic waste (e.g. heavy metals, solvents and pesticides).



4 Basic layout of a cantilever silicon microaccelerometer with an integrated piezoresistor



5 (*a*) **Cross-section of one cell in a six-element silicon micromachined array for application within an electronic nose. (*b*) Photograph showing three micro-hotplate cells (9000µm × 3750µm × 0·5µm), each with an addressable integrated platinum heater with a thermal response time of about 60 ms[5]**

Unfortunately, chemical microsensors are the least well developed. There are many reasons for this: for example, it has proved difficult to make stable, sensitive chemical sensors from thin-film electronic materials such as catalytically doped semiconducting oxides. However, recent advances in the design and the synthesis of new conducting polymers and cage compounds make the realisation of high-quality gas microsensors a distinct possibility in the near future. Moreover, by using an array of non-specific chemical sensors and sophisticated pattern-recognition techniques, one can overcome these basic difficulties and develop intelligent sensors.[4]

Second, there is a large potential market in the field of medicine, monitoring, for instance, blood, urine and breath, which contain a wealth of information about our state of health. Applications here include microsensors to monitor the level of anaesthetic gases, as well as blood pressure, heart rate, and levels of various blood salts and sugars *in vivo*.

Only a few such devices exist today: one example is a glucose sensor, made by the million by Medisense Ltd, and ion selective field-effect devices used to measure blood pH. The use of microsensors to gather medical diagnostic information is an attractive proposition, and one day we may even have microsensors to measure hormone levels and even diagnose illness using smell-sensitive microelectronic array devices (see Fig. 5).

Table 2: Properties employed in some typical mechanical microsensors

Nature	Property/principle	Examples
Intrinsic:	resonant (acoustic)	micromass gauge
	resonant (elastic)	microflexural systems
	resistive	strain gauges
	piezoresistive	pressure gauges
	piezoelectric	pressure gauges
	dielectric	strain gauges
Extrinsic:	capacitive	pressure gauges
	inductive	LVDTs
	reluctive	Hall-position sensors
	magnetic coupling	resolvers
	optical coupling	optical encoders

Microsensors are beginning to transform the field of measurement and instrumentation, and the prospects for the future are incredibly exciting. In particular, advances are inevitable at the boundaries of conventional scientific disciplines, where the worlds of electronics, mechanics and chemistry come together.

References

1 From UKSG presentation by Reed International, 225 Washington Street, Newton, MA, USA June 1982
2 Welham, C. J., Gardner, J. W., and Greenwood, J.: 'A laterally driven micromachine resonant pressure sensor', Transducers 9 Stockholm, June 1995
3 Middelhoek, S. and Audet, S.A.: 'Silico sensors' (Academic Press, 1989, p.209)
4 Brignell, J. and White, N.: 'Intelligent senso systems' (IOP Publishing, 1994)
5 Gardner, J.W., Pike, A., de Rooij, N. Koudelka-Hep, M., Clerc, P.A., Hierlemann, and Göpel, W.: 'Integrated chemical sens array for detecting organic solvents', *Sensors Actuators*, 1995, **26**, pp. 135-139

Further reading

This article makes use of the book 'Microsensors: principles and applications' by J. W Gardner (Wiley, 1994, £19·95), which review the field of microsensors. A detailed guide can be found in the six-volume series 'Sensors: a comprehensive survey', edited by W. Göpel, J. Hesse and J. N. Hemel (ACH Publishers, 1989).