Journal of Physics E: Scientific Instruments

Silicon in mechanical sensors

J. Phys. E: Sci. Instrum. 21 (1988) 1114–1128. Printed in the UK

INSTRUMENT SCIENCE AND TECHNOLOGY

Silicon in mechanical sensors

J C Greenwood
STC Technology Ltd, London Road, Harlow, Essex
CM17 9NA, UK

Abstract. This paper describes the application of silicon to sensors in which strain is detected. It discusses the physical properties that make silicon so useful for these applications and the technology specific to the fabrication of sensors.

1. Introduction

Silicon is a uniquely versatile material for sensors because of a combination of four features: it has very respectable mechanical properties, it can be shaped easily with great precision, it can be made sensitive to many physical properties including strain and, thanks to the electronics industry, it is readily available with a remarkable degree of purity and crystalline perfection.

The use of silicon in sensors has received considerable attention recently with a large number of papers and reviews describing a variety of applications. By far the most important of these applications is in pressure sensors, mostly with etched diaphragms and diffused strain gauges. Tables 1 and 2 provide a breakdown of this literature by tabulating the contents of a selection of papers. The second table concentrates specifically on pressure sensors while the first covers more general applications. It is hoped that this mode of presentation provides the reader with an immediate comparison of the relative importance of the various applications of this technology and an efficient route to the relevant source material.

Table 1. Reviews and applications.
A: Accelerometers
B: Pressure sensors
C: Diaphragm design
D: Heat
E: Flow
F: Integral electronic circuits
G: Fabrication
H: Biomedical
I: Automotive
J: Robotic
K: Beams and flexures.

A	B	C	D	E	F	G	H	I	J	K	Reference
*											Roylance and Angell (1979)
*	*	*			*		*	*			Allan (1980)
*	*									*	Whittier (1981)
	*									*	Ai *et al* (1982)
	*				*	*	*			*	Barth (1982)
	*		*						*		Goodenough (1982)
*					*					*	Petersen *et al* (1982)
*										*	Chen *et al* (1982)
*	*	*	*	*	*	*	*				Petersen (1982)
	*						*				Engels and Kuypers (1983)
					*						Holmes (1983)
*	*			*			*				Angell *et al* (1983)
*										*	Rudolf (1983)
								*			Cockshott (1983)
*					*					*	Chen *et al* (1984)
*	*		*		*						Allan (1984)
	*										Teschler (1985)
*	*							*			Mastroianni (1985)
					*						Middelhoek and Hoogerwerf (1985)
	*	*									Everett (1987)
										*	Mallinson and Jerman (1987)
								*			Mallon and Grace (1987)
*	*										Faithi and Reimann (1987)
									*		Yao *et al* (1987)
*											Stewart (1987)
*										*	Seidel (1988)
							*				Shoji *et al* (1988)

0022-3735/88/121114 + 15 $02.50

Table 2. Pressure sensors.
A: Piezoresistive G: Frequency O/P
B: Capacitive H: Packaging
C: Temperature effects I: Non-etched diaphragm
D: Linearity J: Other errors
E: Annular diaphragms K: Differential pressure.
F: Circuits

A	B	C	D	E	F	G	H	I	J	K	Reference
*	*		*						*		Clark and Wise (1979)
	*				*	*					Sander *et al* (1980)
*		*	*	*	*						Nishihara *et al* (1981)
*		*	*	*	*		*			*	Matsuoka *et al* (1981)
*							*				Bose (1981)
*	*	*									Lee and Wise (1981)
*								*			Singh (1981)
*		*			*		*				Shimazoe *et al* (1982)
*								*			Maundrel (1982)
*	*	*	*						*		Lee and Wise (1982a)
	*				*						Ko *et al* (1982)
	*				*						Lee and Wise (1982b)
*			*								Yasukawa *et al* (1982)
*							*		*		Esashi *et al* (1983)
*											Kanda (1983)
*		*	*	*							Greenwood (1983)
*			*		*				*		Gutgesell (1983)
*		*			*		*				Johnson and Wamstad (1983)
*		*							*		Kim and Wise (1983)
	*		*								Huang and Bin (1983)
*						*					French and Dorey (1983)
*									*		Barabash and Cobbold (1983)
	*				*						Ko *et al* (1983)
*		*							*		Bryzek (1983)
*		*			*						Keitel (1984)
			*	*							Voorthuyzen and Bergveld (1984)
*							*				Burns *et al* (1984)
*		*					*				Binder *et al* (1985)
*		*				*					Neumeister *et al* (1985)
			*	*							Liu Rongxun *et al* (1986)
*	*	*	*	*			*		*		Ohlckers and Fung (1986)
*					*				*		Ishihara *et al* (1986)
	*	*		*	*	*					Hanneborg *et al* (1986)
	*		*								Blasquez *et al* (1987)
								*		*	Johnson and Higashi (1987)
*			*								Suzuki *et al* (1987)
*		*	*		*						Ishihara *et al* (1987)
*		*									Frere and Prosser (1987)
*			*								Minhang Bao and Yan Wang (1987)
*				*							Bertioli (1987)
*											Tabata *et al* (1987)
*											Hirata *et al* (1987)

2. Mechanical stability

Mechanical stability is of vital importance in sensing applications where the sensing device is to be free of drift. Silicon shows an absence of plastic behaviour at normal temperatures. A good example of the exploitation of this plastic stability is that silicon is being considered for fabricating the flexures in a new balance for comparisons of the International Prototype Kilogram with substandards. It is believed that the accuracy of the present balance is limited by hysteresis in the present metal flexures (Quinn 1987).

The mechanical losses of single-crystal silicon are extremely low, a fact which is exploited in high-Q resonators (Kleiman *et al* 1985) where Q-factors of up to 10^8 have been measured. The lowest mechanical losses in silicon are obtained in material with high crystal perfection and there is some increase in acoustic loss with increased doping level and dislocation density (Shanker and Tripathi 1978).

A consequence of a lack of plastic flow is of course a proneness to brittle fracture, which means that the practically achievable strength is critically dependent on the state of the surface. However, as the surfaces in micro-machined silicon are chemically etched, strengths close to intrinsic can be obtained. Care must be taken, however, not to introduce stress raisers into the structure. For example, at STL we have found that a potent source of failure by brittle fracture can arise if a layer of oxide or nitride, used to define a beam during etching, is left projecting over the edge. We have seen microscopic cracks in such an overhang which was believed to have caused failure by propagation into the body of the silicon.

The brittleness of silicon can be exploited by providing grooves where a structure needs to be snapped apart, for example between devices on a wafer, which can be broken into single chips like a bar of chocolate. An arrangement of grooves which gives controlled breaking is shown in figure 1. In contrast to this we have found that cantilevers projecting in the (100) plane for a (111) face are strong in spite of the sharp corner at the base.

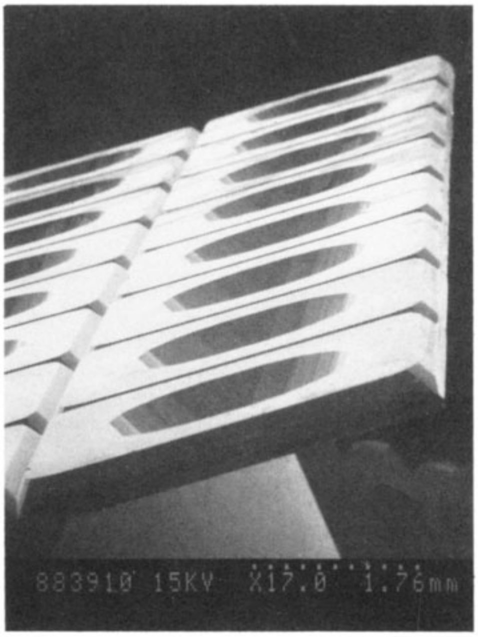


Figure 1. SEM picture of break grooves.

3. Strength and stiffness

The strength of silicon compares favourably with other materials and the specific strength, which is the ratio of strength to density, is markedly higher than most common engineering materials. In figure 2 the strengths and densities of a number

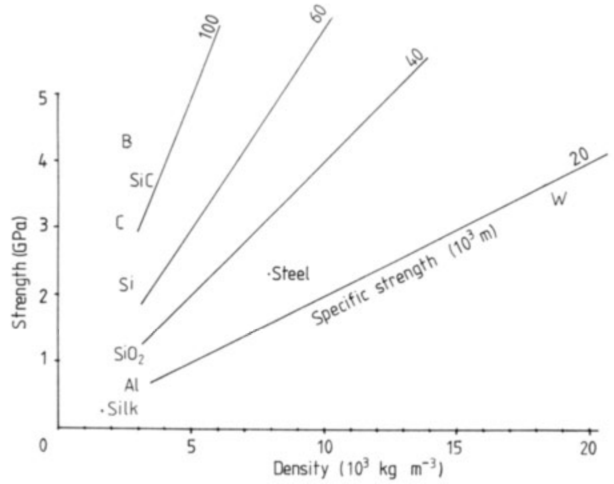


Figure 2. Strength and density of some common engineering materials.

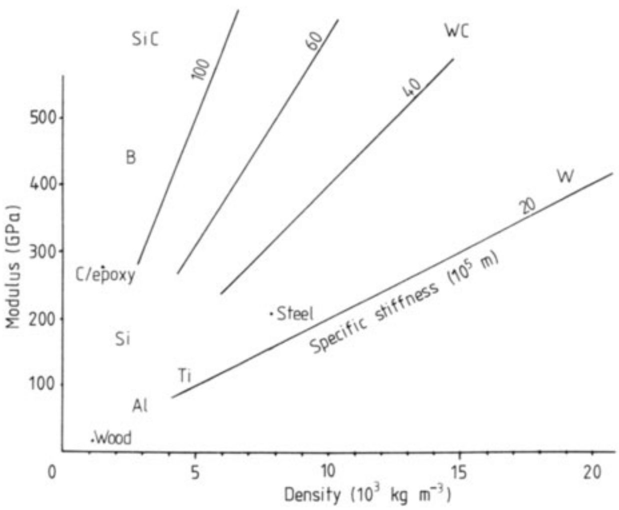


Figure 3. Stiffness and density of some common engineering materials.

of common materials are compared. The sloping lines are contours of constant specific strength. Figure 3 compares the stiffnesses of some common materials in the same way.

The elastic properties of single-crystal silicon are orientation dependent and, because it has cubic symmetry, they can be expressed as a tensor with three independent coefficients. A number of independent determinations of the stiffness coefficients are reviewed by Metzger and Kessler (1970), who give best values, listed in table 3, together with values for the temperature coefficients of the stiffness coefficients.

The modulus of elasticity, the shear modulus and the temperature coefficient of the modulus of elasticity calculated from the above for the three important crystallographic directions are listed in table 4.

Table 3.

Stiffness coefficient (GN m^{-2})	Temperature coefficient of stiffness coefficient (K^{-1})
$C_{11} = 164.8 \pm 0.16$	$(dC_{11}/dT)/C_{11} = -122 \times 10^{-6}$
$C_{12} = 63.5 \pm 0.3$	$(dC_{12}/dT)/C_{12} = -162 \times 10^{-6}$
$C_{44} = 79.0 \pm 0.06$	$(dC_{44}/dT)/C_{44} = -97 \times 10^{-6}$

Table 4.

Crystallographic direction	E (GN m^{-2})	G (GN m^{-2})	$(dE/dT)/E$ (K^{-1})
⟨100⟩	129.5	79.0	−63
⟨110⟩	168.0	61.7	−80.3
⟨111⟩	186.5	57.5	−45.6

The elasticity is also affected by doping level (Shanker and Tripathi 1978), dislocation density (Over *et al* 1982) and hydrostatic pressure (Goncharova *et al* 1983). The elastic properties of amorphous and polycrystalline silicon depend on the preparation and heat treatment. The modulus of amorphous silicon, for example, is considerably lower than that of single-crystal silicon (Zolotukhin *et al* 1983).

4. Thermal properties

Silicon is a good conductor of heat, roughly comparable with aluminium at room temperatures. Like diamond it shows an increase in conductivity at lower temperatures. Figure 4 compares the thermal conductivity of silicon with a number of common materials.

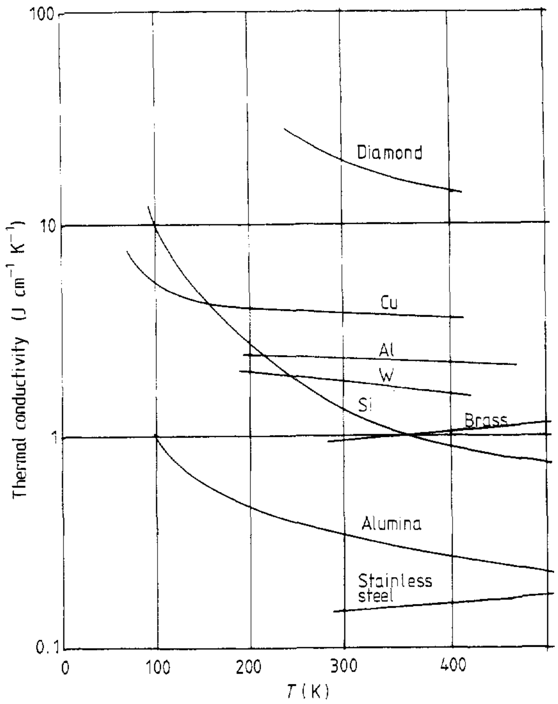


Figure 4. Thermal conductivities of some common materials.

Silicon has a low coefficient of expansion, close to that of Pyrex glass. Again, like diamond it is anomalous (Daniels 1962), which makes it difficult to make structures that are strain-free over a wide temperature range. Figure 5 compares the expansion coefficient of silicon with a number of other materials and figure 6 shows the difference in expansion between silicon and some low-expansion materials, which determines the amount of strain that is incorporated into a structure as a result of heat treatment during fabrication. See Ai *et al* (1982).

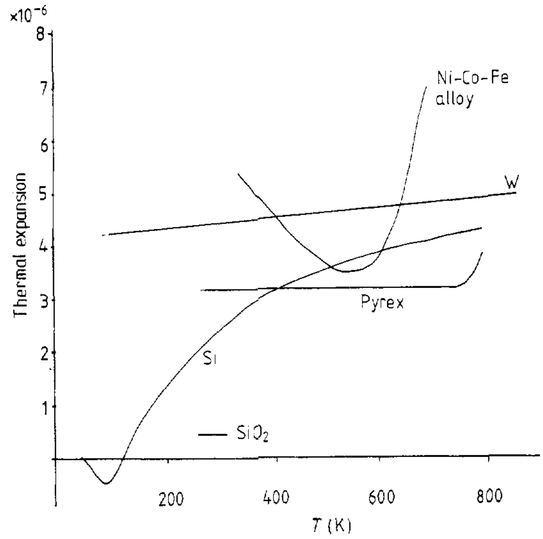


Figure 5. Thermal expansion coefficient of some common low-expansion materials.

5. Fabrication techniques

Silicon is readily shaped by abrasive techniques such as lapping, grinding and sawing. Industry standard wafers, which are the usual starting material for sensors, have been shaped by these means and have a high content of initial precision. This precision is available at low cost provided the requirements are not too far from normal specifications. Thus 100 mm diameter wafers 300–700 μm thick with a thickness tolerance of $\pm 10\,\mu$m and an orientation within 1° of a crystal plane are easily available; beyond such limits the material is increasingly difficult to obtain.

Integrated circuit technology provides many highly developed processes. Photolithography allows the definition of very complex (but planar) structures with submicrometre accuracy, usually as a batch process. Layers can be built up by a variety of deposition and diffusion techniques. The mechanical specification of these layers, such as the intrinsic strains and thicknesses, may not be as well defined as the electronic properties. For example, heavily boron-doped layers tend to be in a state of tension because of lattice shrinkage (Stoneham 1979) but we have found that the amount of strain actually obtained depends on the heat treatment. There is no body of knowledge about how to control this strain, which

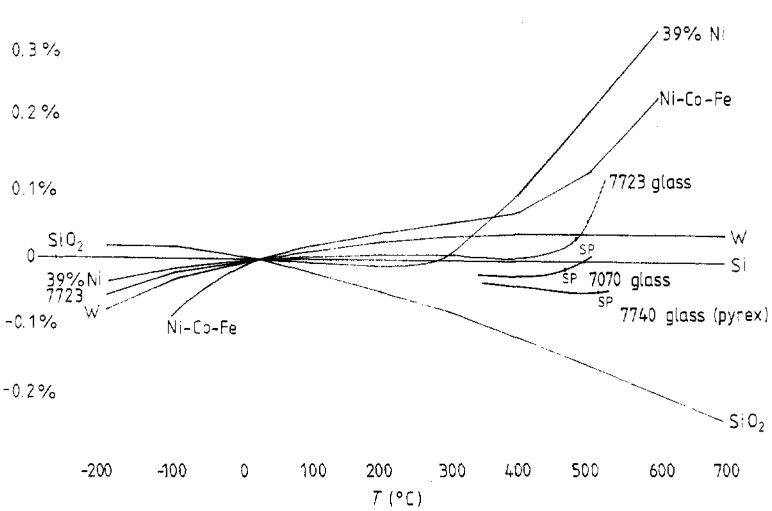
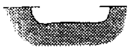


Figure 6. Expansion match to silicon of several materials.

Table 5.

	Acid etch	Alkali etch	Plasma
Typical composition	HNO_3–HF	KOH–IPA	CF_4 gas
Temperature of use (°C)	20	60	20
Etch rate (μm h^{-1})	60	16	10
Control of etch rate	poor	excellent	fair
Orientation dependence	isotropic	anisotropic	directional
Plant cost	low	low	high
Typical shape			

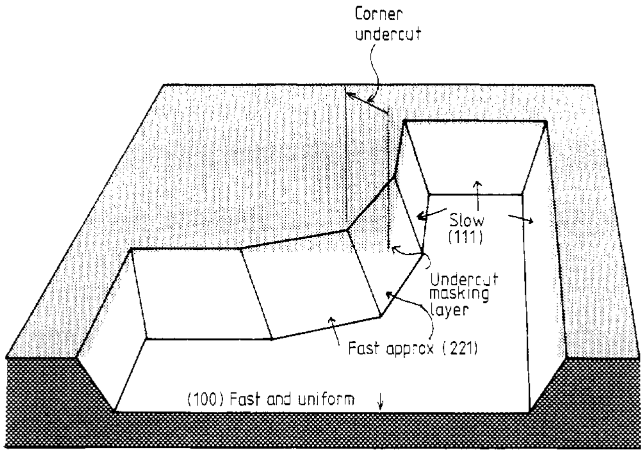


Figure 7. Anisotropic etching of an external corner.

can have a major effect on the mechanical characteristics of diaphragms for example.

Etching is the most important technique for shaping silicon in sensors. There are three main classes of silicon etches: acid (Meek 1971, Bharti *et al* 1984), alkaline and plasma (Hirobe *et al* 1987). The principal differences between them are given in table 5. The alkaline etches are the most versatile and precise and find greatest use in sensor fabrication. Three formulations have been widely used. The choice depends on what materials are available for masking and any other materials that may be needed in the structure, for example metal contacts. These factors are summarised in table 6.

The shape of the etched part can be determined by the anisotropic etching characteristics and by the use of etch stops. There is an extensive literature for which table 7 gives a breakdown of the contents of the more important papers.

6. Anisotropic etching

When using anisotropic etching there are two parameters of importance to the designer, which are illustrated in figure 7. These are the ratio of {100}/{111} etch rates, typically 40:1, and the ratio of {100} etch rate to corner undercut, typically 2:1, although there is considerable dependence on the etch composition and temperature. The smoothness of finish of the etched surface is also important and the factors that determine this are not at all well understood, although there is some correlation between conditions which give high {100}/{111} ratios and the incidence of micro-pyramids on the surface.

The following examples show how various shapes may be obtained. Figure 7 shows how an external corner develops bevels with a (221) orientation. The typical etch rates are shown. The undercutting of such an external corner can be controlled by extending the mask at the corner. A variety of geometries have been proposed. The author prefers a triangular shape as shown in figure 8. The shape of the end of a rectangular mask can be worked out by treating it as two adjacent corners and seeing where all the (221) faces propagate to, as shown in figure 9. Grooves aligned along the ⟨100⟩ direction develop faces at 45° which undercut the mask. Figure 10 shows the cross sections of a variety of grooves in both ⟨100⟩ and ⟨110⟩ directions.

The above examples are in (100) orientation wafers, which are the most commonly used, partly because people are happier with square symmetry. (110) orientation wafers have less symmetry but they have the interesting features that, because there are {111} directions in the (110) plane, there are slow etching planes at right angles to the surface and also the highest values of gauge factor can be obtained. The symmetry and the shapes of recesses in these two orientations are shown in figure 11.

7. Boron-doped etch stop

Silicon doped with more than 4×10^{19} atoms of boron (i.e. about 0.01%) is almost completely insoluble in the alkaline etches. This level of doping is quite easily obtained with IC processing techniques. Figure 12 shows how a bridge or cantilever can be defined by the boron doping and undercut. Great dimensional accuracy can be readily obtained but the high doping level precludes the fabrication of diffused strain gauges or any other electronic component in the etched stopped region. The doping can also introduce strain, which can be exploited in some devices, for example where pre-tensioned struts are required.

8. Electrochemical etch stop

If the silicon is used as the cathode in a cell in which the etch is the electrolyte, etching will only take place over a narrow range of potentials. Figure 13 shows how the etch rate varies

Table 6.

Ingredients (mol%)	10 KOH † isopropanol 90 H_2O	35 $NH_2CH_2CH_2NH_2$ 4 catachol 61 H_2O	50 NH_2NH_2 50 H_2O
Temperature (°C)	60	110	100
Mask materials	SiN_x	SiO_2	SiO_2
Compatible metals	transition metals	transition metals	Al‡
Incompatible metals	Al		transition metals
Toxicity	low	medium	high

† An excess of isopropanol is used so that the solution is saturated.
‡ There is some controversy about the resistance of aluminium to hydrazine etch.

Table 7. Anisotropic etching.
A: KOH F: Wafer orientation
B: EDP G: Micropyramids
C: Hydrazine H: Undercutting
D: Other constituents I: Boron etch stop
E: Etch ratio J: Electrochemistry

A	B	C	D	E	F	G	H	I	J	Reference
	*		*							Finne and Klien (1967)
	*							*		Greenwood (1969)
		*		*		*				Lee (1969)
	*							*		Bohg (1971)
*								*		Rhee and Salitch (1973)
		*				*				Declercq *et al* (1975)
*				*						Kendall (1975)
*	*			*	*					Bean (1978)
	*				*					Bassous (1978)
	*							*		Jolly and Muller (1980)
	*								*	Jackson *et al* (1981)
*									*	Palik *et al* (1982)
*					*					Allen and Routledge (1983)
*					*			*		Seidel and Csepregi (1983)
										Berry and Caviglia (1983)
*										Palik *et al* (1983)
*				*					*	Faust and Palik (1983)
	*							*		Raley *et al* (1984)
	*						*			Abu-Zeid (1984)
*				*						Ogita *et al* (1984)
*	*	*		*						Kaminsky (1985)
*									*	Palik *et al* (1985)
*				*						Petit and Pelletier (1985)
*				*					*	Glembocki and Stahlbush (1985)
*			*			*				Kishi *et al* (1986)
*									*	Sarro and van Herwaarden (1986)
	*		*							Wu *et al* (1986)
							*			Falconer (1987)
*									*	Palik *et al* (1987)
									*	Hirata *et al* (1987)
					*		*			Ciarlo (1987)
		*		*					*	Mehregany and Senturia (1988)
		*							*	Hirata *et al* (1988)

technique where the epitaxial layer has a different doping type to the substrate on which it is grown. In the latter case both hydrofluoric acid and alkaline etches have been used. with potential. Different parts of the silicon can be doped p-type and n-type and effectively insulated from one another by a p–n junction. By holding one part at a potential at which etching is inhibited and the rest at a potential at which it is not, a shape can be made which is defined by the doping. The doping levels used can be low enough to be compatible with the fabrication of diffused electronic components in the etch-stopped region.

Electrochemical etching can be done with either one of the alkaline etches described above or with a hydrofluoric acid solution. In the latter case the current provides the oxidising action. Under certain conditions electrochemical etching with dilute aqueous hydrofluoric acid can produce 'porous' silicon in which a network of fine holes, typically a few micrometres in diameter, is formed, giving the material the appearance of worm-eaten wood (Beale *et al* 1985, Tabata 1986).

Epitaxial layers have been used to define the thickness of diaphragms either by the boron etch-stop using a buried layer of high boron doping or by the electrochemical etch-stop

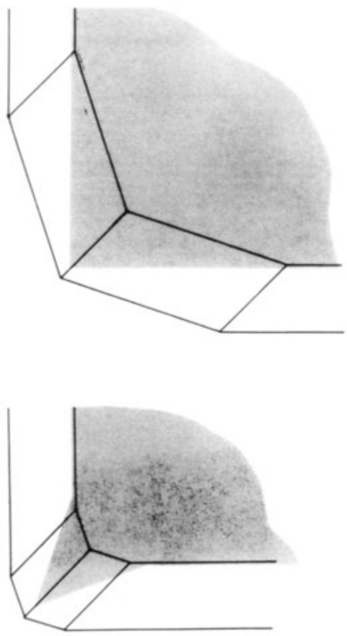


Figure 8. Compensation for corner undercut.

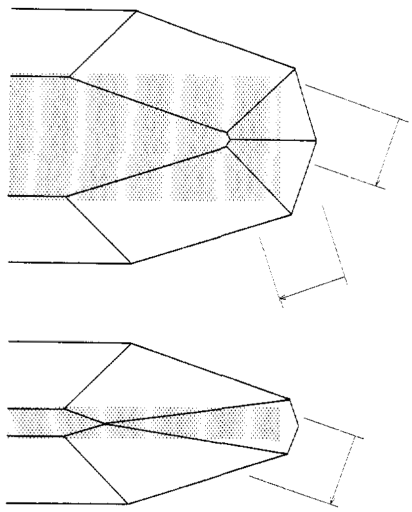


Figure 9. Shape formed by a rectangular mask. Arrows show the advance of the top of a (221) face.

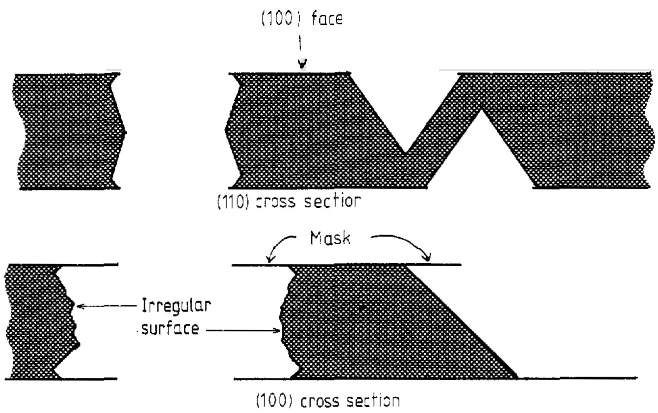


Figure 10. Cross section of grooves in (100) wafer. The grooves are perpendicular to the cross section.

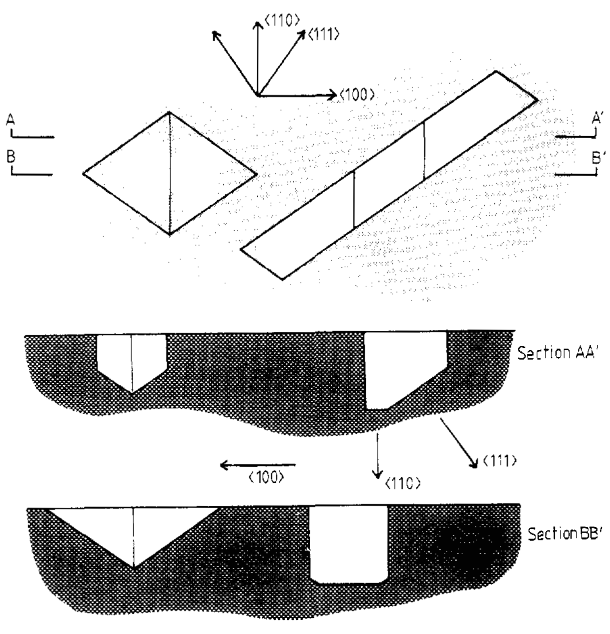


Figure 11. Anisotropic etching of (110) wafers.

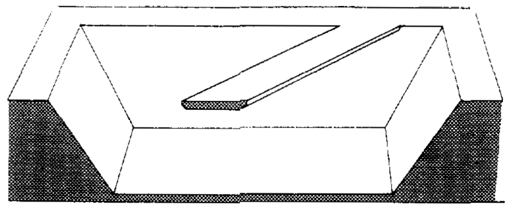


Figure 12. Undercut boron-doped bridge.

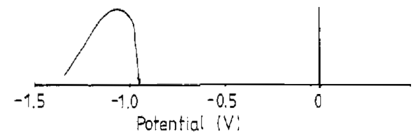


Figure 13. Etch rate as a function of electrochemical potential.

The acid etch gives a smoothly rounded profile to the edge of diaphragms which may have strength advantages.

9. Surface microstructures

As well as structures that use the thickness of the wafer, three-dimensional devices can be built up on the surface of a wafer by a variety of deposition and etching techniques, for example as shown in figure 14. This approach has two advantages: firstly the structures can be smaller because their scale is not related to the thickness of the wafer; secondly the techniques can be more compatible with conventional IC technology, for example the structures are usually flat enough for resist to be spun on. It is more difficult to apply resist to wafers that have deep recesses or holes right through. A disadvantage of this approach is that properties of the layers are less well defined than those of bulk silicon (Onuma *et al* 1988, Guckel *et al* 1988).

Examples of this type of structure are given by Marcus and Sheng (1982), Binder *et al* (1983), Nishida *et al* (1984, 1986), French and Evans (1986), Koike and Kodato (1987) and Naumaan and Boyd (1980).

10. Bonding to silicon

A silicon sensing element, such as a diaphragm, has to be bonded onto a support in order to make a complete sensor, and the stability of this bond and the design of the support can have a large influence on the performance of the resulting sensor. In particular, a bond that yields by plastic flow or cracking can result in irreversible changes in the sensor calibration. To avoid this the bond should use materials that

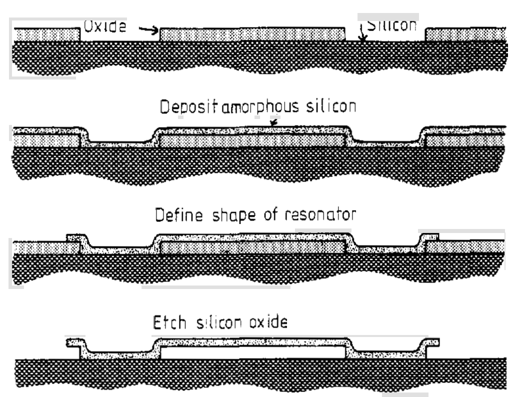


Figure 14. Steps to fabricate a diaphragm or resonator in amorphous silicon.

have a minimum thermal mismatch and should be strong enough to resist what strains there are. Strong bonds can be obtained at temperatures in excess of 700 °C which involve a thin layer of glass, in the form of a thermally grown oxide layer, a screen-printed frit or chemical vapour deposition. These high-temperature bonds are incompatible with standard ohmic contacts, such as aluminium, which is limited to about 450 °C.

Frequently the structure onto which the sensing element is to be bonded has to isolate it from external strains; for example the better pressure sensors are usually mounted on a borosilicate glass tube. An alternative method is to use an elastomer.

Examples of bonds are given in table 8.

11. Measuring strain

In this review I am confining my attention to those sensors in which the quantity being measured causes a mechanical strain, which in turn is transformed into a data signal. Thus chemical, optical, thermal and magnetic sensors are not reviewed although the versatility of silicon is such that these are important applications.

There are three main ways of sensing strain with silicon – piezoresistive, capacitive and resonant – and their features are compared in table 9. Note that the upper temperature limit for the capacitive sensor is set by the detection electronics, which have to be in close proximity in order to avoid errors due to stray capacitances.

The resonant sensor also needs a circuit to maintain it in oscillation but it does not have to be in such close proximity. If optical coupling is used the amplifier can be remote so that the sensor could be used in harsher environments.

Piezoelectric layers can also be used to detect strain. Typically this is an AC effect and has found use in miniature microphones. Almost zero frequency sensing is obtained in piezo-FETs in which a layer of piezoelectric is included in the gate of a metal–oxide field effect transistor (Jolly and Muller 1980, Royer *et al* 1983, Chen *et al* 1984, Kim and Muller 1987, Puers *et al* 1988).

12. Silicon strain gauges

Strain gauges can be fabricated in the form of diffused resistors which, because they are an integral part of the structure, do not have any of the drift caused by creep or aging of bonds which can occur in bonded strain gauges. The gauge factor is defined by $(L/R)\mathrm{d}R/\mathrm{d}L$. In silicon it is about 100 times larger than in metals and varies with doping type, doping level and orientation as shown in figure 15 (Smith 1954, Mason and Thurston 1957, Pfann 1961, Sanchez and Wright 1962, Gross 1967, Bullis *et al* 1968, Rybinski 1970, Norton and Brandt 1978, Yamada *et al* 1982, 1983, Jenschke 1985, Kanda 1987).

The resistance and gauge factor are highly temperature dependent. For the favourite combination, which is with resistors in the ⟨110⟩ direction on a (100) surface, the temperature coefficients vary with doping level as shown in figure 16.

Table 8.

Bond	Bond temperature (°C)	Stability	Comment	References
Epoxy	180	poor		
Elastomer	low	good	provides good isolation but limited temperature and strength	Bose (1981)
Au/Ge eutectic	400	fair	difficult to obtain uniform bond; need flux or ultrasonic	
Anodic	400	good	polished surfaces, one of which must be glass	Barth (1982), Lee and Wise (1982b)
Low MP frit	500	good	e.g. Schott GO17-339	
Glass frit	950	excellent	e.g. Corning 7723	
Oxide	900	good	whole wafers; must be flat	Ohura *et al* (1987), Tenerz and Hok (1986)

Table 9.

	Piezoresistive	Capacitive	Resonant
Normal accuracy (PPM)	10 000	10 000	1000
Maximum accuracy (PPM)	500	100	1
Temperature limit (°C)	120	100	200
Typical power consumption	a few mW	<1 mW	nW
Optical drive	no	no	yes
Output	0–100 mV	voltage or frequency	10–50% change of 100 kHz
Availability	well established	recent	prototype only

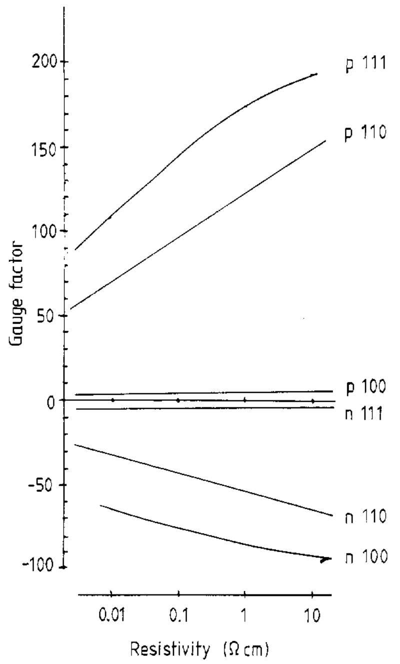


Figure 15. Gauge factor against resistivity for single-crystal silicon.

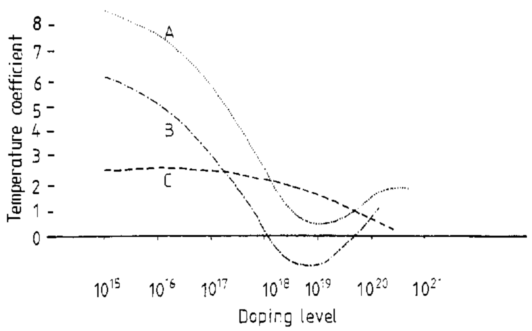


Figure 16. Temperature coefficients of silicon strain gauges: A, resistance; B, sensitivity at constant I; C, sensitivity at constant V.

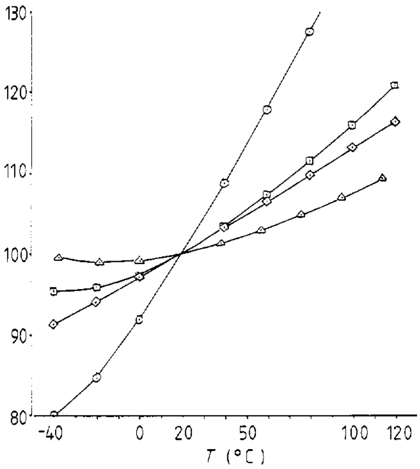


Figure 17. Change of a strain-gauge resistance with temperature for four different doping levels: ○, 1.8×10^{13}; □, 3×10^{14}; △, 1.5×10^{15}; ◇, 2×10^{16}.

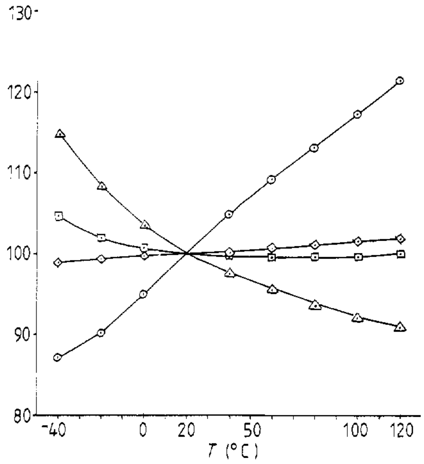


Figure 18. Change of strain-gauge output with temperature. Doping levels as in figure 17.

Note that, if the bridge is supplied by a constant current rather than the more usual constant voltage, there are two doping levels at which the temperature coefficient of the bridge is zero. At the higher doping level the gauge factor is lower but the sensitivity is nearly linear with temperature. At the lower doping level there tends to be a sharp rise in sensitivity at lower temperatures.

The variation of these effects over a wider temperature range is illustrated with some measurements from diffused strain-gauge pressure diaphragms obtained in the author's laboratory. The strain-gauge resistors were doped by ion implantation at four different doses. Figure 17 shows the variation of the whole bridge with temperature and figure 18 shows the variation of bridge output for a constant pressure change input, with the bridge supplied with a constant current. In both cases the variations are shown as a percentage of the value at 20 °C.

The highest temperature at which diffused strain-gauges can be used is limited by junction leakage in the p–n junction which insulates the strain-gauge resistors. The leakage current in a reverse-biased junction increases exponentially with temperature and begins to cause significant errors above about 150 °C. Higher operating temperatures can be obtained by using layers of non-conductor to provide insulation; an example of this is given by Singh (1981).

13. Capacitive sensing

In a typical capacitive sensor the deflection of a flexible part of the sensing device is measured by means of the change of capacitance between it and a counter-electrode in close proximity. For example, in a pressure sensor a sensing chip with an etched diaphragm is bonded onto a substrate with a small clearance between it and the counter-electrode formed on the substrate. The values of capacitance are small and, in order to minimise errors, the capacitance measuring circuit has to be in close proximity. The usual arrangement is to have this circuit integrated into a silicon chip that forms the substrate or into the chip in which the diaphragm has been formed. The latter arrangement is shown in figure 19. The relative merits of capacitive and piezoresistive sensing are discussed by Chau and Wise (1987).

14. Resonant sensors

The principle of the resonant sensor is very old. A strip of flexible material in tension is excited at its resonant frequency. The input force changes this tension, thus providing an output signal frequency which can be easily interfaced with digital electronics. A number of sensors have been around for some time which use this principle but so far they have been confined to applications of high cost requiring high accuracy and low volume. Resonators can be fabricated easily in silicon

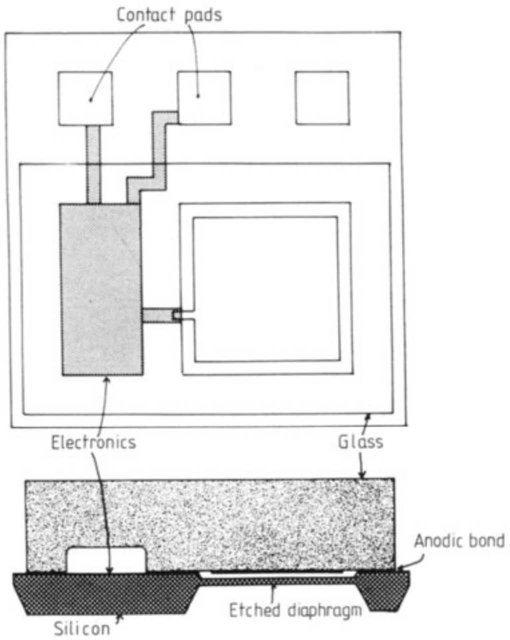


Figure 19. Plan and cross section of a typical capacitive sensor.

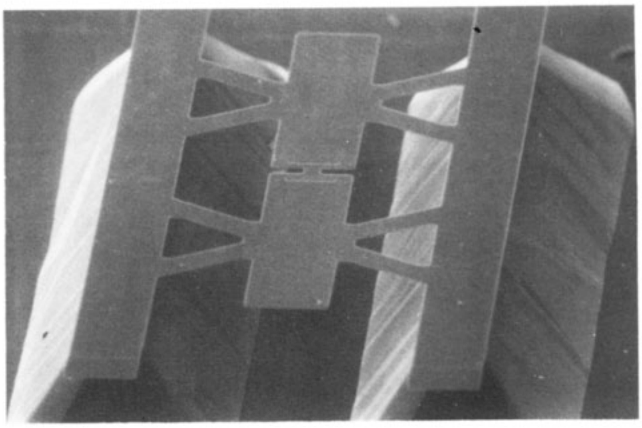


Figure 20. Resonator of the STL resonant sensor.

and promise a range of sensors with high accuracy at low cost; see table 10.

The simplest way of making a resonator is to etch a hole underneath a strip of etch-resistant material, such as silicon dioxide, silicon nitride or boron etch-stopped silicon. The STL pressure sensor (see figure 20) uses the latter system. Very miniature resonators have been fabricated on the surface of a wafer by depositing amorphous silicon over oxide and, after defining the shape of the resonator by etching, the underlying oxide is etched away. An example is shown in figure 21.

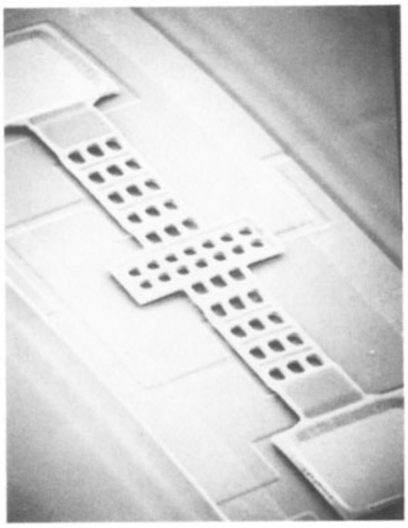


Figure 21. Amorphous silicon resonator. (*Photography courtesy of R Howe, MIT.*)

15. Integral electronics

In principle it is possible to incorporate all sorts of complex integrated circuitry with the sensor (Shimazoe *et al* 1982, French and Dorey 1983, Neumeister *et al* 1985, Ishihara *et al* 1986). In practice this is not as advantageous as it might seem (Middelhoek and Hoogerwerf 1985) and tends to be done only where necessary, for example in capacitive sensors where high-impedance detector circuits need to be physically in close proximity or where the sensor is extremely small. The reasons why it is usually not advantageous are as follows.

(*a*) The total number of process steps is greater than is

Table 10. Resonators.

A: Review
B: Optical
C: Si
D: Oxide or nitride
E: Thermal drive
F: Pressure sensing
G: Piezoelectric drive
H: Electrostatic drive.

A	B	C	D	E	F	G	H	Reference
		*					*	Hribsek and Newcomb (1978)
		*			*		*	Greenwood (1984)
*								Langdon (1985)
	*		*					Culshaw *et al* (1986)
*	*	*						Neat and Hale (1987)
*	*		*					Culshaw (1987)
	*			*				Othman and Brunnschweiler (1987)
	*				*			Uttamchandani and Thornton (1987)
		*				*		Ikeda *et al* (1987)
	*	*						Wolfelschneider *et al* (1987)
		*				*		Wenzel and White (1988)
		*			*		*	Greenwood and Satchell (1988)

needed to make either just the electronics or just the sensor. This will result in lower yields.

(*b*) The processes needed to make the sensor may not be compatible with those needed to make the electronics.

(*c*) The electronic circuits will generate heat which will cause temperature gradients across the sensor unless extreme care is taken in the layout (Steger and Reichl 1983, Crary 1987). These temperature differences would compromise the performance of a strain-gauge bridge for example.

16. Conclusion

In recent years there has been an increasing number of sensors in which the critical sensing element is made from silicon. There is an extraordinary variety of sensor types which includes magnetic, chemical, optical, temperature, pressure and acceleration. This versatility stems from the properties and fabrication techniques for silicon. While those that relate to its use in electronics are well known, those that determine its use in sensors are less well known. In particular the mechanical properties of silicon are outstanding and techniques for shaping it accurately into complex three-dimensional structures are currently being developed.

This paper surveys the properties of silicon that are relevant to its use in mechanical sensors and the fabrication techniques that allow mechanical structures to be made. In particular it describes the elastic, strength and thermal properties of the material, the strain and thermal characteristics of diffused strain-gauges, together with the anisotropic etching and other techniques used to fabricate these sensors. An extensive bibliography is included, in which can be found many examples of silicon sensors.

References

Abu-Zeid M M 1984 Corner undercutting in anisotropically etched isolation contours
J. Electrochem. Soc.: Solid State Sci. Technol. September 2138–42

Ai M, Shimazoe M, Soeno K, Nishihara M, Yasukawa A and Kanda Y 1982 Cantilever type displacement sensor using diffused silicon strain gauges
Sensors and Actuators **2** 297–307

Allan R 1980 New applications open up for silicon sensors: a special report
Electronics November 113–22

Allan R 1984 Sensors in silicon
High Technology September 43–50

Allen D M and Routledge I A 1983 Anisotropic etching of silicon: a model diffusion-controlled reaction
IEE Proc. **130** 49–57

Angell J B, Terry S C and Barth P W 1983 Silicon micromechanical devices
Sci. Am. April 36–47

Barabash P R and Cobbold R S C 1983 Basic limitations of ISFET and silicon pressure transducers: noise theory, models and device scaling
Sensors and Actuators **4** 427–38

Barth P W 1982 Silicon sensors meet integrated circuits
Chemtech November 666–73

Bassous E 1978 Fabrication of novel three dimensional microstructures by the anisotropic etching of (100) and (110) silicon
IEEE Trans. Electron. Devices **ED-25** 1178–84

Beale M I J, Chew N G, Uren M J, Cullis A G and Benjamin J D 1985 Microstructure and formation mechanism of porous silicon
Appl. Phys. Lett. **46** 86–8

Bean K E 1978 Anisotropic etching of silicon
IEEE Trans. Electron. Devices **ED-25** 1185–93

Berry I L and Caviglia A L 1983 High resolution patterning of silicon by selective gallium doping
J. Vac. Sci. Technol. B **1** 1059–61

Bertioli M 1987 Intermediate range pressure measurement
Measurement and Control **20** 33–6

Bharti P L, Sarin S K and Rao M G 1984 Fabrication of deep cavities in silicon using deposited chrome–gold mask
IETE Tech. Rev. (India) **1** (3) 28–9

Binder J, Becker K and Ehrler G 1985 Silicon pressure sensors for the range 2 kPa to 40 MPa
Siemens Components (Engl. edn) **20** (2) 64–7

Binder J, Henning W, Obermeier E, Schaber H and Cutter D 1983 Laser-recrystallised polysilicon resistors for sensing and integrated circuits applications
Sensors and Actuators **4** 527–36

Blasquez G, Naciri Y, Blondel P, Moussa N B and Pons P 1987 Static response of miniature capacitive pressure sensors with square or rectangular silicon diaphragm
Revue Phys. Appl. **22** 505–10

Bohg A 1971 Ethylene diamine–pyrocatechol–water mixture shows etching anomaly in boron-droped silicon
J. Electrochem. Soc.: Electrochem. Technol. **118** 401–2

Bose E 1981 Fluid pressure transducers
Electron. Engng November 169

Bryzek J 1983 Approaching performance limits in silicon piezoresistive pressure sensors
Sensors and Actuators **4** 669–78

Bullis W M, Brewer F H, Kolstad C D and Swartzendruber L J 1968 Temperature coefficient of resistivity of silicon and germanium near room temperature
Solid State Electron. **11** 639–46

Burns B E, Barth P W and Angell J B 1984 Fabrication technology for a chronic *in vivo* pressure sensor
Proc. Conf. IEDM-84 pp 210–12

Chau H L and Wise K D 1987 Scaling limits in batch-fabricated silicon pressure sensors
IEEE Trans. Electron. Devices **ED-34**

Chen P L, Muller R S and Andrews A P 1984 Integrated silicon Pi-FET accelerometer with proof mass
Sensors and Actuators **5** 119–26

Chen P L, Muller R S, Jolly R D, Halac G L, White R M, Andrews A P, Lim T C and Molamedi M E 1982 Integrated silicon microbeam PI-FET accelerometer
IEEE Trans. Electron. Devices **ED-29** 27–33

Ciarlo D R 1987 Corner compensation structures for (110) oriented silicon
Proc. IEEE Micro Robots and Teleoperators Workshop Cat. no 87TH0204-8 6/1–4

Clark S K and Wise K D 1979 Pressure sensitivity in anisotropically etched thin-diaphragm pressure sensors
IEEE Trans. Electron. Devices **ED-26** 1887–96

Cockshott C P 1983 New transducers for automobile electronic systems
Phys. Technol. **14** 10–5

Crary S B 1987 Thermal management of integrated microsensors
Sensors and Actuators **12** 303–12

Culshaw B 1987 Optically excited resonant sensors
IOP Workshop on Fibre Optic Sensors pp 33–44

Culshaw B, Uttam D, Nixon J, Thornton K and Wright A 1986 Micromachined resonant structures
SPIE Fiber Optic and Laser Sensors IV **718** 92–6

Daniels W B 1962 The anomalous thermal expansion of Ge, Si and compounds crystallizing in the zinc blende structure
Proc. Int. Conf. on the Physics of SEM, *Exeter* pp 482–9

Declercq M J, Gerzberg L and Meindl J D 1975 Optimisation of the hydrazine–water solution for anisotropic etching of silicon in integrated circuit technology
J. Electrochem. Soc.: Solid State Sci. Technol. 545–52

Engels J M L and Kuypers M H 1983 Medical applications of silicon sensors
J. Phys. E: Sci. Instrum. **16** 987–94

Esashi M, Komatsu H and Matsuo T 1983 Biomedical pressure sensor using buried piezoresistors
Sensors and Actuators **4** 537–44

Everett C 1987 Smaller, cheaper silicon pressure sensors are starting to appear on vendors' shelves packaging
EDN **32** 83–90

Faithi Y and Reimann H 1987 Accelerometer and sub-psi pressure sensor, a new generation of monolithic silicon sensor chips
Proc. Sensors Expo September 295

Falconer J E 1987 Micromachining of silicon for sensor devices
GEC J. Res. Inc. Marconi Rev. **5** 189–91

Faust J W and Palik E D 1983 Study of the orientation dependent etching and initial anodisation of Si in aqueous KOH
J. Electrochem. Soc. **130** 1413–9

Finne R M and Klien D L 1967 A water-amine-complexing agent system for etching silicon
J. Electrochem. Soc.: Solid State Sci. **114** 965–70

French P J and Dorey A P 1983 Frequency output piezoresistive pressure sensor
Sensors and Actuators **4** 77–83

French P J and Evans A G R 1986 Polycrystalline silicon as a strain gauge material
J. Phys. E: Sci. Instrum. **19** 1055–8

Frere P E M and Prosser S J 1987 Temperature compensation of silicon pressure sensors for automotive applications
6th Int. Conf. on Automotive Electronics 270–4

Glembocki O J and Stahlbush R E 1985 Bias-dependent etching of silicon in aqueous KOH
J. Electrochem. Soc. **132** 145–51

Goncharova V A, Chernysheva E V and Voronov F F 1983 Elastic properties of silicon and germanium single crystals at pressures up to 8 GPa at room temperature
Sov. Phys.-Solid State **25** 2118–21

Goodenough F 1982 IC sensors do the job with greater accuracy and sensitivity, additional circuitry
Electronic Design April 135–40

Greenwood J C 1984 Etched silicon vibrating sensor
J. Phys. E: Sci. Instrum. **17** 650–2

Greenwood J C 1969 Ethylene diamine–catechol–water mixture shows preferential etching of p–n junction
J. Electrochem. Soc. **116**

Greenwood J H 1983 The constraints on the design and use of silicon-diaphragm pressure sensors
Electronics and Power February 170–40

Greenwood J C and Satchell D W 1988 Miniature silicon resonant pressure sensor
Proc. IEE **135D** 369–72

Gross C 1967 Radiation method of improving temperature characteristics *Proc. 22nd Ann. Instrument Soc. Convention* vol. 2 pp 1–12

Guckel H, Burns D W, Visser C C G, Tilmans H A C and Deroo D 1988, Fine-grained polysilicon films with built-in tensile strain
IEEE Trans. Electron. Devices **35** 800–1

Gutgesell H 1983 Basics of pressure transducers
Electronics and Power February 175–7

Hanneborg A, Hansen T E, Ohlckers P A, Carlson E, Dahl B and Holwech O 1986 An integrated capacitive pressure sensor with frequency modulated output
Sensors and Actuators **9** 345–51

Hirata M, Suwazono S and Tanigawa H 1987 Diaphragm thickness control in silicon pressure sensors using an anodic oxidation etch-stop
J. Electrochem. Soc.: Solid State Sci. Technol. **134** 2037–41

Hirata M, Suzuki K and Tanigawa H 1988 Silicon diaphragm pressure sensors fabricated by anodic oxidation etch-stop
Sensors and Actuators **13** 63–70

Hirobe K, Kawamura K and Nojiri K 1987 Formation of deep holes in silicon by reactive ion etching
J. Vac. Sci. Technol B **5** 594–600

Holmes L 1983 Sensors and automotive-engine control
Electronics and Power February 178–80

Hribsek M F and Newcomb R W 1978 High-*Q* selective filters using mechanical resonance of silicon beams
IEEE Trans. Circuits and Systems **CS-25** 215–21

Huang R S and Bin T Y 1983 A silicon capacitive pressure sensor with linear sensitivity *IREECON International, Sydney* Digest of papers pp 136–8

Ikeda K, Tetsuya K and Yasushi H 1987 Vibratory transducer and method of making the same
UK Patent Application 2 180 691 A

Ishihara T, Suzuki K, Suwazono S, Hitala M and Tanigawa H 1987 CMOS integrated silicon pressure sensor circuits
IEEE J. Solid-State Circuits **22** 151–6

Ishihara T, Hirata M, Suzuki K and Tanigawa H 1986 CMOS integrated silicon pressure sensor
IEEE Custom Integrated Circuits Conf. 34–7

Jackson T N, Tischler M A and Wise K D 1981 An electrochemical p–n junction etch-stop for the formation of silicon microstructures
IEEE Electron. Device Lett. **2** 44–5

Jenschke W 1985 Der nichtlineare piezoresistive Effekt in p-leitenden Siliziumplanarwiderstanden
Feingeratetechnik p 710

Johnson R G and Higashi R E 1987 A highly sensitive silicon chip microtransducer for air flow and differential pressure sensing applications
Sensors and Actuators **11** 63–72

Johnson R L and Wamstad D B 1983 An advanced solid state integrated pressure transducer
IEEE 33rd Electronics Components Conf. 568–73

Jolly R D and Muller R S 1980 Miniature cantilever beams fabricated by anisotropic etching of silicon
J. Electrochem. Soc. **127** 2750–4

Kaminsky G 1985 Micromachining of silicon mechanical structures
J. Vac. Sci. Technol. **3** 1015–24

Kanda Y 1983 Optimum design considerations for silicon pressure sensors using a four-terminal gauge
Sensors and Actuators **4** 199–206

Kanda Y 1987 Graphical representation of the piezoresistance coefficients in silicon-shear coefficients in plane
Japan. J. Appl. Phys. part 1 **26** 1031–3

Keitel G 1984 The KP100A monolithic pressure sensor
Electron Components and Appl. **6** 149–54

Kendall D L 1975 On etching very narrow grooves in silicon
Appl. Phys. Lett. **26** 195–8

Kim E S and Muller R S 1987 IC-processed piezoelectric microphone
IEEE Electron. Device Lett. **8** 467–8

Kim S C and Wise K D 1983 Temperature sensitivity in silicon piezoresistive pressure transducers
IEEE Trans. Electron. Devices **ED-30** 802–11

Kishi H, Okada K and Yagawara S 1986 Micropyramid inhibition method in anisotropic etching of silicon
J. Vac. Soc. Japan **29** 85–91

Kleiman R N, Kaminsky G K, Reppy J D, Pindak R and Bishop D J 1985 Single crystal silicon high-*Q* torsional oscillators
Rev. Sci. Instrum. **56** 2088–91

Ko W H, Bao M H and Hong Y D 1982 A high sensitivity integrated circuit capacitive pressure transducer
IEEE Trans. Electron. Devices **ED-29** 48–56

Ko W H, Shao B X, Fung C D, Shen W J and Yeh G J 1983 Capacitive pressure transducers with integrated circuits
Sensors and Actuators **4** 403–11

Koike R and Kodato S 1987 Use of Amorphous Silicon Films as Sensors
Sensors and Actuators **13** 11–27

Langdon R M 1985 Resonator sensors – a review
J. Phys. E: Sci. Instrum. **18** 103–15

Lee D B 1969 Anisotropic etching of silicon
J. Appl. Phys. **40** 4569–74

Lee K W and Wise K D 1981 Accurate simulation of high-performance silicon pressure sensors
IEEE Conf. IEDM81 471–4

Lee K W and Wise K D 1982a SENSIM: a simulation program for solid-state pressure sensors
IEEE Trans. Electron. Devices **ED-29** 34–41

Lee Y S and Wise K D 1982b A batch fabricated silicon capacitive pressure transducer with low temperature sensitivity
IEEE Trans. Electron. Devices **ED-29** 42–8

Liu Rongxun, Fang Jing, Wei Xiangyu, Qin Jichang and Shi Xiaodong 1986 The application of holospeckle–shearing interferometry to displacement and slope analysis of a diaphragm used in silicon pressure sensors
Opt. Engng Management **599** 196–200

Mallinson S R and Jerman J H 1987 Miniature micromachined Fabry–Perot interferometers in silicon
Electron. Lett. **23** 1041–3

Mallon J R and Grace R H 1987 Automotive applications of solid state sensors and silicon microstructures
Proc. Sensors Expo September 385–99

Marcus R B and Sheng T T 1982 The oxidation of shaped silicon surfaces
J. Electrochem. Soc. 1278–82

Mason W P and Thurston R N 1957 Use of piezoresistive materials in the measurement of displacement force, and torque
J. Acoust. Soc. Am. **29** 1096–101

Mastroianni J 1985 Automotive applications of silicon-based sensors *Proc. 5th Int. Conf. on Automotive Electronics, Birmingham* (London: Institute of Mechanical Engineers) pp 317–23

Matsuoka Y, Nishihara M, Sakamoto T and Ikegami A 1981 Transmitter using diffused semiconductor strain gauges
Hitachi Rev. **3** 290–6

Maundrel D 1982 Silicon semiconductor pressure sensors – beams or diaphragms
Transducer Technol. March 28–9

Meek R L 1971 Electrochemically thinned N/N+ epitaxial silicon – method and applications
J. Electrochem. Soc. **118** 1240–6

Mehregany M and Senturia S D 1988 Anisotropic etching of silicon in hydrazine
Sensors and Actuators **13** 375–90

Metzger H and Kessler F R 1970 Der Debye–Sears-Effect zur Bestimmung de elastischen konstanten von Silicium
Z. Naturf. A **25** 904–6

Middelhoek S and Hoogerwerf A C 1985 Smart sensors: when and where?
Sensors and Actuators **8** 39–48

Minhang Bao and Yan Wang 1987 Analysis and design of a four-terminal silicon pressure sensor at the centre of a diaphragm
Sensors and Actuators **12** 49–56

Naumaan A and Boyd J T 1980 Phosphosilicate glass bridge structures
J. Electrochem. Soc. **127** 1414–5

Neat R C and Hale P G 1987 Micromachined silicon sensors
IEE Colloq. No 31 3/1–3

Neumeister J, Schuster G and Von Munch W 1985 A silicon pressure sensor using MOS ring oscillators
Sensors and Actuators **7** 167–76

Nishida S, Konagai M and Takahashi K 1984 Seebeck and piezoresistance effects in amorphous–microcrystalline mixed-phase silicon films and applications to power sensors and strain gauges
Thin Solid Films **112** 7–16

Nishida S, Konagai M and Takahashi K 1986 Piezoresistive effect of hydrogenated microcrystalline silicon prepared by plasma and photo-chemical vapor deposition
Japan. J. Appl. Phys. part 1 **25** 17–21

Nishihara M, Yamada K and Matsuoka Y 1981 Recent semiconductor pressure sensors
Hitachi Rev. **30** 285–9

Norton P and Brandt J 1978 Temperature coefficient of resistance for p- and n-type silicon
Solid State Electron. **21** 969–74

Ogita M, Carroll T, Wei J, Van der Spiegel J and Zemel J N 1984 Use of gold films as masks for a KOH preferential etch
Thin Solid Films **120** L79–81

Ohlckers P and Fung C 1986 Design rules for minimising signal errors in silicon pressure sensors induced by packaging strains *Proc. 12th Nordic Semiconductor Meeting, Jevnaker, Norway* pp 275–8

Ohura J, Tsukakoshi T, Fukuda K, Shimbo M and Ohashi H 1987 A dielectrically isolated photodiode array by silicon-wafer direct bonding
IEEE Electron. Device Lett. **8** 454–6

Onuma Y, Kamimura K and Homma Y 1988 Piezoresistive elements of polycrystalline semiconductor thin films
Sensors and Actuators **13** 71–7

Othman M B and Brunnschweiler A 1987 Electrothermally excited silicon beam mechanical resonators
Electron. Lett. **23** 728–30

Over H H, Knotek O and Lugscheider 1982 The elastic properties of single crystal silicon as a function of temperature and dislocation density
Z. Metallk. **73** 552–7

Palik E D, Bermudez, V M and Glembocki O J 1985 Ellipsometric study of the etch-stop mechanism in heavily doped silicon
J. Electrochem. Soc. 135–41

Palik E D, Faust J W, Gray H F and Greene R F 1982 Study of the etch-stop mechanism in silicon
J. Electrochem. Soc.: Solid State Sci. Technol. **129** 2051–8

Palik E D, Glembocki O J and Heard I 1987 Study of bias-dependent etching of Si in aqueous KOH
J. Electrochem. Soc. 404–9

Palik E D, Gray H F and Klein P B 1983 A Raman study of etching silicon in aqueous KOH
J. Electrochem. Soc. **130** 956–9

Petersen K E 1982 Silicon as a mechanical material
Proc. IEEE **70** 420–55

Petersen K E, Shartel A and Raley N F 1982 Micromechanical accelerometer integrated with MOS detection circuitry
IEEE Trans. Electron. Devices **ED-29** 23–7

Petit B and Pelletier J 1985 A novel processing technique for the fabrication of thick silicon grids by anisotropic etching
J. Electrochem. Soc. **132** 982–4

Pfann W G 1961 Improvement of semiconducting devices by elastic strain
Solid State Electron. **3** 261–7

Price J B 1973 Anisotropic etching of silicon with KOH–H_2O–isopropyl alcohol
Semiconductor Silicon 1973 Symposium Series (Princeton, NJ: The Electrochemical Society)

Puers B, Reynaert L, Snoeys W and Sansen W M C 1988 A new uniaxial accelerometer in silicon based on the piezojunction effect
IEEE Trans. Electron. Devices **ED-35** 764–70

Quinn T R 1987 Private communication

Raley N F, Sugiyama Y and Van Duzer T 1984 (100) silicon etch-rate dependence on boron concentration in ethylenediamine–pyrocatechol–water solutions
J. Electrochem. Soc.: Solid State Sci. Technol. 161–71

Rhee C J and Salitch J 1973 Integral heat sink IMPATT diodes fabricated using p+ etch stop
Proc. IEEE Lett. 385–6

Royer M, Holmen J O, Wurm M A, Aadland O S and Glenn M 1983 ZnO on Si integrated acoustic sensor
Sensors and Actuators **4** 357–62

Roylance L M and Angell J B 1979 A batch-fabricated silicon accelerometer
IEEE Trans. Electron. Devices **ED-26** 1911–7

Rudolf F 1983 A micromechanical capacitive accelerometer with a two-point inertial-mass suspension
Sensors and Actuators **4** 191–8

Rybinski J 1979 Piezoresistance tensor coefficients of phosphorus implanted silicon thin films
Electron Technol. **12** 59–65

Sanchez J C and Wright W V 1962 Recent developments in flexible silicon strain gauges
Semiconductor and Conventional Strain Gauges (New York: Academic) p 309

Sander C S, Knutti J W and Meindl J D 1980 A monolithic capacitive pressure sensor with pulse-period output
IEEE Trans. Electron. Devices **ED-27** 927–30

Sarro P M and van Herwaarden A W 1986 Silicon cantilever beams fabricated by electrochemically controlled etching for sensor applications
J. Electrochem. Soc. **133** 1724–9

Seidel H 1988 Capacitive acceleration sensors
UK Patent Application 2194341

Seidel H and Csepregi L 1983 Three dimensional structuring of silicon for sensor applications
Sensors and Actuators **4** 455–63

Shanker K and Tripathi N D 1978 Acoustical investigations in pure and doped n-type germanium and silicon
J. Acoust. Soc. India **VI** no 3 62–3

Shimazoe M, Matsuoka Y, Yasukawa A and Tanabe M 1982 A special silicon diaphragm pressure sensor with high output and high accuracy
Sensors and Actuators **2** 275–82

Shoji S, Esashi M and Matsuo T 1988 Prototype miniature blood gas analyser fabricated on a silicon wafer
Sensors and Actuators **14** 101–7

Singh G 1981 A feasibility study of a low cost junctionless silicon sensor for high temperature applications
Instrum. Aerospace Industry **18** 431–42

Smith C S 1954 Piezoresistance effect in germanium and silicon
Phys. Rev. **94** 42–9

Steger U and Reichl H 1983 Thermal simulation of integrated digital transducers
Sensors and Actuators **4** 621–7

Stewart R E 1987 Integrated force balanced accelerometer
UK Patent 2178856

Stoneham A M 1979 Lattice dilatation of boron in silicon
Phys. Lett. **70A** 55–6

Suzuki K, Ishihara T, Hirata M and Tanigawa H 1987 Nonlinear analysis of a CMOS integrated silicon pressure sensor non-linearity
IEEE Trans. Electron. Devices **ED-34** 1360–7

Tabata O 1986 Fast-response silicon flow sensor with an on-chip fluid temperature sensing element *IEEE Trans. Electron. Devices* **ED-33** 361–5

Tabata O, Inagaki H and Ingarashi I 1987 Monolithic pressure-flow sensor *IEEE Trans. Electron. Devices* **ED-34** 2456–62

Tenerz L and Hok B 1986 Silicon microcavities fabricated with a new technique *Electron. Lett.* **22** 615–6

Teschler L E 1985 The push into silicon for pressure sensing *Mach. Des.* **57** 71–6

Uttamchandani D, Thornton K E B and Culshaw B 1987 Optically excited resonant beam pressure sensor *Electron. Lett.* **23** 1333–4

Voorthuyzen J A and Bergveld P 1984 The influence of tensile forces on the deflection of circular diaphragms in pressure sensors *Sensors and Actuators* **6** 201–13

Wenzel S W and White R M 1988 A multisensor employing an ultrasonic Lamb-wave oscillator *IEEE Trans. Electron. Devices* **ED-35** 735–43

Whittier R M 1981 Silicon strain gauge technology in aerospace applications *Electron. Engng* **53** 151–4

Wolfelschneider H, Kist R, Knoll G, Ramakrishnan S and Hofflin H 1987 Optically excited and interrogated micromechanical silicon cantilever structure *SPIE* **798** 61–6

Wu Xian-Ping, Wu Quing-Hai and Ko Wen H 1986 A study on deep etching of silicon using ethylene-diamine–pyrocatechol–water *Sensors and Actuators* **9** 333–43

Yamada K, Nishihara M, Shimada S, Tanabe M, Shimazoe M and Matsuoka Y 1982 Nonlinearity of the piezoresistance effect of p-type silicon diffused layers *IEEE Trans. Electron. Devices* **ED-29** 71–7

Yamada K, Nishihara M, Shimada S, Tanabe M and Shimazoe M 1983 Temperature dependence of the piezoresistance effects of p-type silicon diffused layers *Elec. Engng Japan* **103** 8–17

Yao C T, Peckerar M C, Wasilik J H, Amazeen C and Bishop S 1987 A novel three-dimensional microstructure fabrication technique for a triaxial tactile sensor array *Proc. IEEE Micro Robots and Teleoperators Workshop* Cat. no 87TH0204-8 4/1-6

Yasukawa A, Shimada S, Matsuoka Y and Kanda Y 1982 Design considerations for silicon circular diaphragm pressure sensors *Japan. J. Appl. Phys.* **21** 1049–52

Zolotukhin I V, Barmin Y V and Sitnikov A V 1983 Elastic and inelastic properties of amorphous silicon *Sov. Phys.–Solid State* **25** 1988–9

John Greenwood has been working for STC Technology Ltd at the Harlow laboratories for over 22 years. Much of this time has been devoted to the development of silicon sensors and included the discovery of the boron etch-stop phenomenon in 1969. He was awarded a BSc in chemistry in 1965 and holds a number of patents related to silicon mechanical devices.