Miniature pressure transducers with a silicon diaphragm

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Readers of this journal will probably now be familiar with the many advantages of the planar technology in modern electronics. It may however come as something of a surprise to learn of an application of this technology to a purely mechanical device. This is a miniature pressure transducer, whose submillimetre dimensions enable measurements to be made in situations previously considered to be completely inaccessible.

Silicon, strain gauges and pressure meters

A pressure measurement amounts to a determination of a mechanical load. When a structure is subjected to a mechanical load, a strain is produced. It therefore follows that a pressure can be detected with a strain gauge mechanically coupled to an elastic wall (such as a diaphragm) on which the pressure to be measured is exerted. The deformation of the strain gauge caused by the pressure affects the electrical resistance of the gauge. If the relation between deformation and pressure is known the unknown pressure can be determined by measuring the change in resistance.

Strain gauges used to be made — and to some extent still are — of alloy metals of high resistivity. Later it was found that single-crystal silicon is a much more suitable material for this purpose because of certain of its elastic properties, which will be dealt with presently.

In this article we shall discuss pressure transducers in which the elastic part is a minute circular diaphragm, of single-crystal N-type silicon. The diaphragm has a diameter of about 1 mm and is an integral part of a substrate acting as a clamp ring (fig. 1). This ring can be mounted in a simple encapsulation that also connects the transducer to the space in which the pressure is to be measured. For measuring the deformation or flexure of the diaphragm — and hence the pressure — the diaphragm contains four small strain gauges, which together form a complete Wheatstone bridge. The unbalance of the bridge is a sensitive measure of the pressure, provided that the gauges are located to take the best advantage of the mechanical strains in the diaphragm. In their basic design, therefore, the new pressure transducers are extremely simple.

An advantage of the monolithic construction is that it dispenses with the difficult and expensive process of mounting and tensioning an extremely thin diaphragm on a separate clamp ring. Another advantage is that the strain gauges are an integral part of the diaphragm. The gauges are made by the planar technology used for integrated circuits; in fact they are simply P-type zones of high conductivity diffused into the N-type diaphragm. A separate connecting layer is therefore not needed. Such a layer could lead to troublesome creep effects, which would of course impair the stability of a transducer.

Fig. 1. The diaphragm of a miniature pressure transducer, seen from above (a) and in cross-section (b). The cross-section shows the clamp ring C and the circular diaphragm (typical thickness 15 µm, diameter 1 mm). Both are parts of a monolithic structure of single-crystal silicon. Diffused into the diaphragm (red circle, plan view) is an uninterrupted and electrically conducting four-active-arm pattern. The four (grey) aluminium contacts enable the diffusion pattern to be used as a Wheatstone bridge of four pressure-sensitive resistors.
The miniaturization of pressure transducers offers various advantages in measurement techniques. The first is an improved frequency characteristic, since the frequency response of a pressure transducer improves with decreasing mass and dimensions. We have made transducers that faithfully follow periodic pressure variations up to about 100 kHz. This represents a bandwidth about a hundred times greater than that of conventional pressure transducers. A miniaturized transducer also interferes less with the pressure to be measured. Another associated advantage is that temperature differences across the surface of the diaphragms are small.

Miniaturization has allowed many measurements to be made that were previously thought to be almost impossible, and this is of course also partly due to the useful properties of the single-crystal silicon incorporated in the transducers. Pressure measurements on scale models in wind tunnels, measurements in fast hydraulic control systems, ultrasonic measurements of certain types, and local blood-pressure measurements (for example inside a blood vessel in cardiovascular examinations) are four examples of cases where the new transducers can prove to be of great value.

Why is single-crystal silicon a more attractive material for diaphragms and for strain gauges than the alloy metals? One of the reasons is the fact that pure single-crystal material obeys Hooke’s law over a wider range of strain values, the resulting stress being proportional to the strain in a given direction up to an elongation of about 1%. With the alloy metals, on the other hand, the elastic limit is exceeded at a ten times smaller strain; permanent deformation then occurs, and the reproducibility deteriorates as a result of hysteresis effects.

In structural terms, the single-crystal material is clearly superior in ruggedness and strength, and is free from hysteresis. It can withstand high temperatures, remaining perfectly elastic up to about 500 °C, and it is chemically not very reactive.

However, it is not because of any of these features that single-crystal material is used. It has been chosen because of another elastic effect: the piezoresistance effect. This is the change in the resistivity of the material caused by a mechanical stress.

From the expression \( \rho / D \) for the resistance \( R \) of a conductor of a cross-section \( D \), length \( l \) and resistivity \( \rho \), it can be shown that the change in resistance in a deformed strain gauge is composed of two terms:

\[
\Delta R = \rho \Delta (l/D) + (l/D) \Delta \rho.
\]

The first term on the right-hand side of this equation describes the change of resistance directly caused by the deformation of the conductor. The second term is the contribution of the piezoresistance effect, as the deformation is accompanied by a mechanical stress that changes the resistivity.

The alloy metals also give the piezoresistance effect, but the change it brings about in the resistance is generally considerably less than that caused by the ordinary deformation effect, i.e. by the change of length and cross-section under strain.

Since 1954 it has been known that the piezoresistance effect is very much larger than the ordinary deformation effect in single-crystal silicon [31]. In this material the same stress causes a change in resistance that is a hundred times greater than in the alloy metals, resulting in a proportionately larger output signal from a transducer using such a strain gauge. A disadvantage of silicon strain gauges is that their resistance is rather temperature-dependent.

We shall now take a closer look at the piezoresistance effect in strain gauges located in a diaphragm of single-crystal semiconducting material of cubic structure, and we shall then discuss the new pressure transducers with their characteristics and fabrication processes.

The piezoresistance effect

Let us first of all examine the physical background of the piezoresistance effect in silicon.

In a P-type single-crystal silicon chip the normal single valence band is not found, but a more complicated structure, described as a degenerate valence band. The holes are therefore of two kinds. They differ in effective mass, which has the result that the contributions to the conductivity measured in a particular direction are different. Nevertheless, the conductivity of non-deformed chips is independent of direction; this is referred to as the ‘normal’ conductivity. If, however, there is deformation in a particular direction, for example along a crystallographic axis, the value of the effective masses—and also the ratio between the number of ‘light’ and ‘heavy’ holes—may change considerably. Both effects are strongly dependent on the direction. The deformation is associated with a mechanical stress in the same direction. The resistivity for currents in the direction of the mechanical stress changes in that direction. The magnitude of this piezoresistance effect therefore depends closely on the direction chosen.

In the case of N-type silicon the explanation of the effect is rather different. The conduction electrons are


in a multi-valley conduction band, which implies that the electrons are distributed in a number of groups (e.g. six) which make different contributions to the conductivity measured in a particular direction. In this type of material the conductivity is also independent of direction as long as the material is not deformed. On deformation there may be a marked direction-dependent redistribution of the electrons among the valleys.

In order to examine the effect in a strain gauge we must know the mechanical stresses in the gauge. In our case we want to know the stress distribution in a diaphragm clamped at the edge, which is flexed by the application of pressure. The thickness of the diaphragm is much smaller than the diameter. For flexures that are small compared with the thickness the stress distribution is then very nearly circularly symmetrical in the plane of the diaphragm. The curves of the radial and tangential components of this stress distribution, illustrated in fig. 2, show for example that gauges near the edge and near the centre are subjected to stresses of opposite sign, which can increase the output signal of a bridge circuit and thus increase the sensitivity of the pressure transducer.

The stress distributions deviate from pure circular symmetry because the elastic properties of single-crystal material are direction-dependent [5]. For example, in single-crystal silicon with a cubic structure the proportionality constant in Hooke’s law is about 40% greater in the [111] direction than in the [100] direction, at least in extremely pure material. Such material is therefore much more rigid on the main diagonal than along a crystallographic axis.

The relation between the state of stress in a strain gauge that forms part of a single-crystal silicon diaphragm and the piezoresistance effect in the gauge can be described by the general expression

\[
\Delta \rho = (\sigma_|| + \sigma_\perp) \rho,
\]

where \(\Delta \rho\) is the change in resistivity encountered by an electric current in the longitudinal axis of the strain gauge, and \(\sigma_||\) and \(\sigma_\perp\) are the components of the stress in the diaphragm parallel to the long axis and perpendicular to it. (Any stress perpendicular to the plane of the diaphragm is neglected here.) The longitudinal and transverse piezoresistance coefficients \(\pi_{||}\) and \(\pi_{\perp}\) can be expressed in fundamental piezoresistance coefficients (material constants) and in geometrical factors for the orientation of the normal stresses in the gauge \((\sigma_||\) and \(\sigma_\perp)) with respect to the crystallographic axes [6].

There are in total 36 fundamental \(\pi_{ij}\) coefficients \((i, j = 1, 2, \ldots, 6)\) in a crystal of cubic structure only three of them are important: \(\pi_{11}, \pi_{12}\) and \(\pi_{44}\) [11, 17]. The values of each of these three coefficients differ considerably in \(N\)-type semiconductors from the values in \(P\)-type semiconductors.

The values also depend slightly on the resistivity itself and on temperature. The coefficient \(\pi_{14}\) is found in situations where shear stresses occur; \(\pi_{13}\) and \(\pi_{12}\) are connected with normal stresses.

For doped silicon of resistivity no greater than a few tens of \(\Omega \cdot \text{cm}\) and no less than about one thousandth of an \(\Omega \cdot \text{cm}\), the relations between the fundamental coefficients given in the first line of Table 1 are approximately correct. The expressions given in the table are found by inserting these relations in the general expressions [6] for \(\pi_{13}\) and \(\pi_{14}\). The geometrical factors \(F_{13}\) and \(F_{12}\) are respectively \(l_1^2 m_2^2 + l_2^2 m_1^2 + m_1^2 m_2^2\) and \(l_1^2 l_2^2 + m_1^2 m_2^2 + m_1^2 m_2^2\), where \(l_1, m_1\) and \(n_1\) are the direction cosines of \(\sigma_||\) (i.e. of the longitudinal axis of the gauge) with respect to the three crystallographic axes, and likewise \(l_2, m_2, n_2\) are the direction cosines of \(\sigma_\perp\).

The behaviour of these geometrical factors, to which the anisotropy of the ‘ordinary’ elastic properties also relates, explains why it is possible to influence the piezoresistance effect by the choice of orientation. In our investigations the choice was limited to two orientations and to \(P\)-type silicon.

\[
\sigma_\perp = \frac{3h(p_1 - p_2)R^2}{8h^2} \left[\frac{(3\nu + 1)c^2 - (1 - \nu)}{R^2} \right]
\]

\[
\sigma_\parallel = \frac{3h(p_1 - p_2)R^2}{8h^2} \left[\frac{3\nu c^2}{R^2} - (1 + \nu)\right]
\]

Fig. 2. The radial component \(\sigma_r\) and the tangential component \(\sigma_\theta\) of the stress distribution, assumed to possess circular symmetry, in a clamped circular diaphragm that flexes slightly under a uniform compressive load, plotted against the distance \(r\) between the points where these stress components occur and the centre of the diaphragm. \(R\) the radius of the diaphragm, \(h\) its thickness, \(p_1 - p_2\) the pressure difference across the diaphragm, \(\nu\) Poisson’s ratio.
In the first case we choose the diaphragm plane parallel to the plane determined by a main diagonal and an edge of the cubic crystal, for example the (110) plane. For gauges in this diaphragm with a direction perpendicular to the cube edge, we then have:

\[ \Delta \rho = \frac{1}{2} \pi_{44} \sigma \rho, \]

where \( \pi_{44} \) is one of the fundamental coefficients. In this case the longitudinal coefficient \( \pi_i \) is equal to half the fundamental coefficient \( \pi_{44} \), and the transverse coefficient \( \pi_1 \) is equal to zero. For gauges parallel to the edge the whole effect disappears because \( \pi_{i} \) is then zero as well as \( \pi_{1} \).

In the second case, where the diaphragm plane is taken parallel to a plane determined by three side diagonals, we find on the contrary a certain isotropy. In such a plane, for example the (111) plane, the change of resistivity is given by

\[ \Delta \rho = \frac{1}{2} \pi_{44}(\sigma_{i} - \frac{1}{3} \sigma_{1}) \rho, \]

irrespective of the orientation of the gauge. Although in this case the piezoresistance effect is smaller than in the first case, there are definite technological advantages if the orientation of a gauge is not too critical.

There are graphs from which the fundamental coefficient \( \pi_{44} \) can be determined for, say, a diffusion zone in single-crystal silicon as a function of the surface doping concentration and the temperature \([8]\). The maximum value of this coefficient (about \( 140 \times 10^{-11} \text{ m}^2/\text{N} \) at room temperature) is found for resistivities greater than about 1 \( \Omega \text{cm} \). Unfortunately the resistivity is most dependent on temperature in this region. A good compromise is a choice in the region of 0.015 \( \Omega \text{cm} \), which reduces the temperature dependence by a factor of five, while reducing \( \pi_{44} \) itself by only about 30%. Finally, there is the preference for gauges of \( P \)-type material. There are various reasons for this. One is that the fundamental piezoresistance coefficient \( \pi_{44} \) is about 35% greater than the coefficient \( \pi_{31} \) that would have to be used for \( N \)-type silicon. Another is that the relation between change of resistance and strain is more linear in \( P \)-type silicon and the temperature dependence is less.

### Location of the strain gauges

The free choice in the location of the four strain gauges on the diaphragm makes it possible to give a transducer a choice of desirable features, such as high sensitivity or temperature independence. It is of course then necessary to know the orientation of the crystallographic axes with respect to the diaphragm.

Out of the many possible locations we have only adopted the two mentioned in the previous section.

Our aim with the first location was to obtain a pressure transducer with the simplest possible bridge arrangement on the diaphragm and with the least temperature dependence. The diaphragm lies parallel to the (110) plane. The bridge consists of two gauges in the [001] direction and two in the [110] direction, and all four are located close to the centre (fig. 3). The piezoresistance effect does not then arise in the first pair. The second pair, on the other hand, is subject to a reasonably strong effect. Because they are all close together the four gauges encounter very nearly identical temperature changes. A change in temperature hardly affects the balance of the bridge at all, since the four resistances then change by the same amount. The bridge does however go out of balance if the pressure changes.

Although this arrangement looks promising, it has not in practice come up to expectations, for two main reasons. The first, which is apparently related to the fairly high anisotropy of the elasticity in the (110) plane, is the presence of strongly direction-dependent mechanical stresses in the diaphragm at zero pressure. The second is that the measurements are not sufficiently reproducible, owing to variations in the junction resistances between the aluminium and the \( P \)-type silicon of the gauges.

These difficulties do not arise in the transducers in which the second choice of location is adopted (fig. 4). The diaphragms in this case are parallel to the (111) plane. The internal stresses at zero pressure are now found to be negligibly small, and the orientation of the gauges with respect to the crystallographic axes is not particularly critical. The gauges form one continuous diffusion path, and all junction resistances from alumi-
nium to P-type silicon are kept 'outside' the current-carrying branches of the bridge circuit. This helps to prevent interference with the pressure measurements. In this configuration the four resistances are identical, and the gauges therefore have the same number of right-angle bends. The changes in resistance are of the same magnitude but of opposite sign, which increases the sensitivity of the bridge and facilitates measurements. The active parts of the gauges $S_1$ and $S_3$ are arranged radially because at the edge of the diaphragm the radial component of the stress is several times greater than the tangential component (fig. 2). Another attractive feature of the pressure transducers based on the configuration in fig. 4 is that fabrication is straightforward with few rejects.

Features of the transducers

The measuring range of the pressure transducers with the configuration of strain gauges and connections illustrated in fig. 4 on the diaphragm can be varied extensively by selecting the ratio between the thickness and diameter of the diaphragms. The limits of the measuring range lie at about 1 atm and 100 atm. These values correspond to thickness/diameter ratios of 0.015 and 0.15. Within these limits the sensitivity is the same, i.e. a full-scale deflection of 20 millivolts per volt applied to the bridge. The sensitivity is satisfactorily linear with the pressure being measured, deviations remaining below 1% of maximum unbalance. If a little greater deviation from linearity is permissible, or a slightly lower sensitivity, the pressure range can be extended to 0.2 atm full scale. The linearity is worse because the flexure in the middle of the diaphragm is no longer small compared with the thickness. The diaphragm bulges out in the middle (the 'balloon effect' \cite{4}). The transducers can safely be overloaded, and an overload of ten times full scale causes no damage. The zero shift is at the most 0.02% of full scale per degree Celsius. The adverse effect of temperature on the signal sensitivity of the circuit can be kept below about the same level by means of a compensating device, such as an NTC resistor connected in series.

The reproducibility of the measurements is excellent; the differences are no more than 0.05%, which shows that the transducers are free from hysteresis effects and creep.

Technology

The main technological problem to be solved was to find the right combination of planar silicon technologies with two advanced finishing processes to enable the transducer with all its composite parts to be made in a single monolithic device of the required miniature...
Material Growth Diffusion Vacuum evaporation Spark machining Electrochemical etching

<table>
<thead>
<tr>
<th>Material</th>
<th>Process</th>
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<tbody>
<tr>
<td>N-Si</td>
<td>1</td>
</tr>
<tr>
<td>N+-Si</td>
<td>2, 3, 4</td>
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<td>B</td>
<td>2</td>
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Table II. Survey of the technology used for the simultaneous production of 200 miniature pressure transducers. There are five steps (horizontal axis) and four materials (vertical axis). The starting material, N+ silicon, is defined in block 1. The blocks 2, 3 and 4 give the results of the processing of the materials (planar technology). Blocks 5 and 6 refer to the finishing techniques, limited to the N+ silicon substrate. Each process step takes place simultaneously for the 200 transducers, with the exception of the machining process (4 → 5).

dimensions. For quantity production it was also necessary to meet the requirement of satisfactory reproducibility.

A survey of the production technology is given in Table II. Three conventional planar processes are used [9]. The bridge circuit can easily be kept so small that a complete signal amplifier and the bridge can be mounted on a diaphragm with a diameter of 0.5 mm.

The other techniques used, spark machining [10] and electrochemical (or anodic) etching [11], are less conventional. The first is used for removing material in the N+ silicon substrate at the locations where the diaphragms are to be formed, and the second is used for fine finishing. The relatively high conductivity of the N+ silicon, which has a resistivity of only 10 to 20 mΩcm, facilitates the application of spark machining. The inside diameter of the clamp ring is accurately defined by the diameter of the cylindrical electrodes. The dimensions produced so far range from about 0.3 to 2 mm, but smaller inside diameters can be produced if required. Spark machining is a relatively crude process; the lower surface of the recesses may be pitted to depths of about 3 μm, and the centre of the recess is somewhat deeper than at the edge. Since the diaphragm (the epitaxial N layer) is usually required to be extremely thin, the spark machining is stopped when the bottom of the recess is within about 15 μm of the epitaxial layer. The remaining substrate material (the shielding layer) on the diaphragm is subsequently removed by electrochemical etching, an anodic oxidation in which the silicon-oxide layer produced is removed by a dilute HF solution. The N+ silicon acts as the anode, and the cathode is of platinum. At an appropriate current density the N+ silicon then


dissolves away at a rate of about 2 μm per minute, but the epitaxial layer is unaffected, because N-type silicon has a much higher resistivity and is not etched away under these conditions. The substrate layer dissolves away completely in a few minutes. At the same time the inside diameter of the clamp ring has become 20 to 30 μm larger, but this is no disadvantage as there is some rounding off at the edge between the ring and the diaphragm. The gradual transition in thickness here ensures good clamping of the diaphragm.

In this way perfectly smooth and flat diaphragms are obtained whose thickness is exactly equal to that of the epitaxial layer, and which are integral with the clamp rings. The completed transducers can easily be separated from each other, either by breaking along a pattern of scribed lines on the silicon slice, or by spark machining with a tubular electrode.

The reproducibility of the method of fabrication can be judged from the signal sensitivity of the transducers. Even with batches of several hundred transducers the variation in signal sensitivity can be kept within 10%.

The mounting of a pressure transducer is another matter. The encapsulation for such a transducer must of course be as small as possible. The encapsulation must also be designed to permit firm mechanical bonding of the four electrical leads to the bridge circuit.

Fig. 5 shows a way of meeting these requirements that is eminently suitable for applications such as blood-pressure measurements. It consists essentially of a thick-walled glass tube, with an outside diameter of about 1.5 mm and a length of 6 mm. Four thin channels are recessed in the wall for the electrical leads. The clamp ring of the transducer can be located at the front of the tube in such a way that the ends of the leads just touch the four contact strips of the transducer. These strips are located on the clamp ring (fig. 4) so that they do not load the diaphragm, and are tinned with a layer of solder. The contacts are soldered by heating the whole assembly in a non-oxidizing atmosphere, and a nickel layer along the circumference strengthens the joint and ensures a good seal. The glass tube can easily be mounted in the tip of a catheter, so that measurements can be made inside a blood vessel. What the catheter measures is of course the difference between the blood pressure and the pressure — usually atmospheric — which appears on the other side of the diaphragm via the central opening in the glass tube.

The technology described above is clearly applicable for making other types of transducer. In one such example we were able to produce an accelerometer by making a pressure transducer in which the central part of the diaphragm had a relatively large mass.