

## Section 2 – Kulite Sensing Technology

### 2.1 Pressure Transducers

A pressure transducer produces an electrical output proportional to the pressure applied. The frequency of pressure fluctuation should be lower than the resonance frequency of the transducer and the electrical output is essentially independent of frequency below one-fifth the resonance frequency (flat frequency response).

When pressure is applied, the force on the sensing element due to the pressure results in a deformation of the sensing element. This deformation changes the electrical properties of the element and the electrical output of the transducer. In a well-designed transducer, the deformation and electrical output are directly proportional to pressure over a wide range of frequencies.

### 2.2 Theory of Operation

Pressure is defined as force per unit area. The most common measurements are made in gaseous or liquid media. All pressure gages and transducers use a force-summing device to convert the pressure into a stress or displacement proportional to the pressure. In transducers, the stress or displacement is then applied to an electrical transduction element to generate the required signal. Kulite piezoresistive pressure transducers combine the force summing device and the transduction element into a micromachined, dielectrically isolated silicon diaphragm. The high stiffness, small size, and low mass of the transduction system provide an ideal combination of wide frequency response, high sensitivity, and immunity to acceleration and strain inputs.

### 2.3 Transducer Types

Pressure transducers are available with four reference pressure options. These are (a) Absolute – (psia); (b) Gauge - (psig); (c) Differential - (psid) and (d) Differential Sealed Reference – (psid).

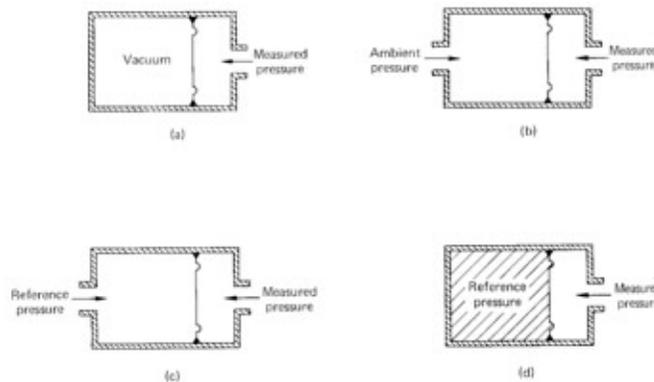


Figure 2-1: Pressure Reference Configurations

All pressure transducers use a force-summing device to convert pressure to displacement, but that displacement is then converted to an electrical output by a variety of transduction methods. Kulite specialises in piezoresistive strain sensing technology in silicon and, most recently, in silicon carbide for ultra high temperature applications.

### 2.4 The Piezoresistive Effect

During his experiments with temperature measurements, Lord Kelvin discovered that the resistance of a conductor increased when it was in tension. In his work, this phenomenon was a annoying error source. In the 1930's it was recognised as a useful measurement tool, the metal strain gage.

When a conductor is strained, its length and thickness change (related by Poisson's Ratio). Since electric current is forced to travel a longer path of smaller area when the conductor is stretched by tension, the resistance of the conductor increases.

The resistance change, compared to the original resistance divided by the fractional change in length, is called the gage factor,  $K$ .

Different types of gages exhibit different gage factors:

<u>Type of Gauge</u>	<u>Gauge Factor</u>
Unbonded Wire	4
Bonded Foil	2
Thin Film	2
Bonded Discrete Semiconductor	50 to 200
Integral Diffused or Isolated Semiconductor	50 to 200

Higher gage factor means higher output for the same strain, or higher sensitivity relative to the stiffness and natural frequency of the structure. Semiconductor gages have much higher gage factors than metal because, in addition to the lengthening and narrowing of the conductor, the resistance of doped silicon changes under strain. The change in electrical resistance of a strain gauge with the application of a physical stress is referred to as the piezoelectric effect.

For the measurement of strain in an object, the strain gauge is bonded to the object, which in the case of a pressure transducer, is usually a diaphragm. When a load (pressure) is applied, the diaphragm and the strain gauge both deform, causing the resistance of the strain gauge to change. This resistance can be calculated as follows. The resistance of a wire is:-

$$R = \rho L / O \quad (2.1)$$

where  $L$  = the length of the wire,  $\rho$  = resistivity of the wire material and  $O$  = cross-section.

Differentiating equation (2.1), we obtain:-

$$(dR/R) = (d\rho/\rho) + (dL/L) - (dO/O) \quad (2.2)$$

The ratio of the relative increase in the length  $\epsilon_L$  to the relative decrease in the diameter  $\epsilon_D$  is defined as Poisson's ratio  $\mu$  and this depends upon the material.

$$\mu = -\epsilon_L / \epsilon_D = -(dD/D) / (dL/L) \quad (2.3)$$

For the relation between the relative change in the cross section and the relative change in the diameter we find:-

$$dO/O = 2 dD/D \quad (2.4)$$

Combining equations (2.2) and (2.4) we obtain:-

$$dR/R = \epsilon_L (1 + 2\mu) + d\rho/\rho \quad (2.5)$$

The gauge factor (K) of a strain gauge is defined as:-

$$K = \left( \frac{dR}{R} \right) \epsilon_L \quad (2.6)$$

so that we obtain the general expression:-

$$K = 1 + 2\mu + (d\rho/\rho) \epsilon_L \quad (2.7)$$

For metals, the resistivity does not vary with strain so the last term in equation (2.7) can be ignored. The change in the resistance of metals with strain is due solely to geometric effects.

However, in semiconductor materials the strain dependency of the last term of equation (2.7), the specific resistivity  $\rho$ , is significantly larger than the geometrical piezoresistive effect and results in semiconductor strain gauges having large gauge factors.

## 2.5 The Piezoresistive Effect in Silicon

Kulite generally specifies the use of *p*-type silicon which possesses a very large gauge factor of up to 200, in comparison with *n*-type silicon which also has a large, though negative, gauge factor down to -140.

Equation (2.7) in section 2.4, shows that a change in resistance is generally dependent on a term which has to do with the geometrical piezoresistive effect and a term originating from the strain dependency of the specific resistivity  $\rho$ . In metals this latter term is zero. If a semiconductor bar is stressed, geometrical changes also occur leading to resistance changes according to the geometrical effect. It can be expected that the contribution of this to the gauge factor will be comparable to that measured in metals. Therefore, the large gauge factor in semiconductors can only be due to the strain sensitivity of the specific resistivity in semiconductors. An explanation involves the theory of the electronic energy-band structure of semiconductors.

In classical as well as quantum mechanics the energy  $E$  of a particle can be expressed in terms of the mass  $m$  and the momentum  $p$ . For a cannon ball the kinetic energy is given by

$$E = mv^2/2 \quad (2.8)$$

where  $m$  is the mass and  $v$  is the velocity. The momentum is given by

$$p = mv \quad (2.9)$$

When the energy  $E$  is expressed in terms of momentum  $p$  we obtain

$$E = p^2/2m \quad (2.10)$$

The plot of  $E$  as a function of  $p$  is a parabola, as shown in Figure 2-2 (a).

This curve also applies for free-moving electrons as for example, those in a CRT.

When an electron moves in a solid, an interaction of the electron with the periodic lattice can be expected. This interaction leads to the important result that the energy curve shows discontinuities at

certain values of momentum. The graph describing the relation between  $E$  and  $p$  is shown in Figure 2-2 (a) as a solid line. This result is obtained for a very simple, one dimensional lattice case.

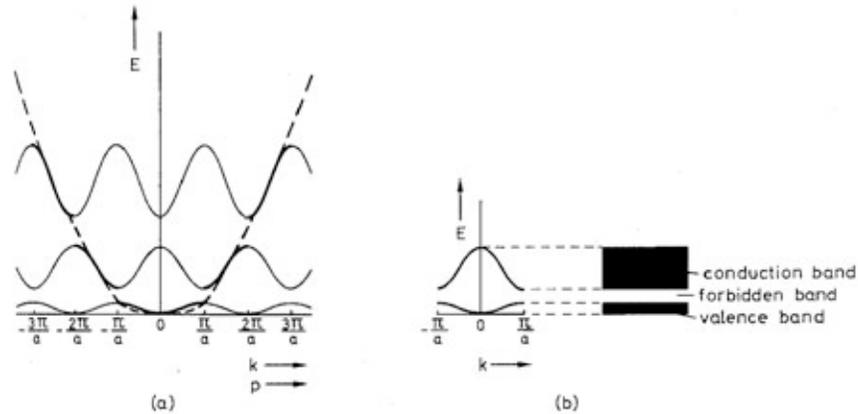


Figure 2-2: (a) Energy  $E$  as a function of the momentum  $p$  for a classical particle (dashed line) & as a function of the wave number  $k$  for a particle with wave-like nature in interaction with a periodic crystal lattice (solid lines); (b) Part of the possible solutions indicating the conduction, the forbidden and the valence band.

It is usual in quantum mechanics to replace the momentum by the wave-number  $k$ . The relation is

$$p = \hbar k / 2\pi \quad (2.11)$$

where  $\hbar$  is Planck's constant. As indicated in Figure 2-2 (a), the discontinuities in the energy occur at

$$k = n\pi/a, \quad n = -1, -2, \dots \text{ and } n = +1, +2, \dots \quad (2.12)$$

where  $a$  is the lattice spacing. For values far from the values given by (2.12), the dashed and solid lines coincide, which means that the electrons behave as free electrons. However, when  $k$  is close to  $n\pi/a$ , certain energy levels are forbidden, which is due to the strong interaction of the electrons with the lattice.

The periodic occurrence of forbidden energy gaps has to do with the wave-like nature of electrons moving in a lattice. At the specified  $k$  values, the electron is scattered by the periodic lattice and can even be totally reflected.

Figure 2-2 (b) focuses on the central range. For all  $k$  values, we obtain two energy levels. Two bands of allowed energy levels occur. Between these a band is obtained of energy levels that are forbidden for the electrons. In a semiconductor the lower allowed energy band could be the almost empty conduction band. The relationship between  $E$  and  $k$  as depicted in Figure 2-2 (b) only applies for the very simple case of a one-dimensional lattice. For real three-dimensional semiconductors like silicon the situation is much more complex.

Detailed band-structure calculations are rather difficult, so use is made of the fact that the crystal lattice is often highly symmetric. For certain directions of symmetry, solutions can be found and for silicon the band structure has been calculated for the [100] and [111] directions.

In Figure 2-3 (a) and (b) those parts of the band structure of silicon that are relevant for explaining the piezoresistive effect in silicon are shown.

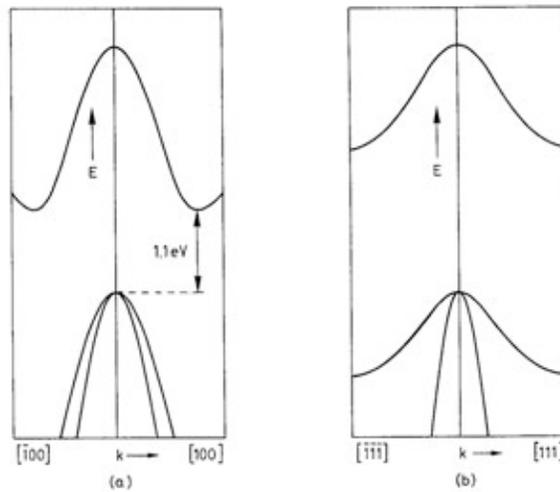


Figure 2-3: Energy Band Structures of Silicon for (a) the [100] and (b) the [111] Direction

In order to understand the piezoresistive effect in *p*-type silicon, we have to study how the band structure is affected by the application of a stress. The forbidden energy bands are the result of the interaction of the moving electrons with the periodic lattice. When an anisotropic stress is applied, in one direction the lattice spacing increases and in the direction perpendicular to this direction the lattice spacing decreases. As one might expect, the interaction of the electrons with the lattice are also affected.

As can be seen from Figure 2-3, in the valence band two relations between the energy  $E$  and the wave-number  $k$  exist. The maxima are at  $k = 0$  and equally high (properly stated, equally low) for holes. In fact there is even a third relation (not shown in Fig. 3.3), but that has a maximum little bit lower than the other two and plays only a minor role in the piezoresistive effect. The valence band can be described by the so-called two-and-one band model. The two bands have different flatnesses and consequently different effective masses and mobilities. The difference for the [100] directions is rather small, whereas for the [111] directions the difference is greatest. When a stress is applied the two bands split and redistribution of holes takes place. When the mobilities of the two bands do not differ very much, the effect of the redistribution on the resistivity is small. This is the case for the [100] directions. However, for the [111] directions the effect is maximum. The gauge factor of *p*-type silicon is positive. This means that a positive strain (elongation) causes the band with the lowest mass and highest mobility to lower with respect to the low mobility band, so that the holes move to the low mobility band. When, as a result more holes have a lower mobility, the resistivity increases, which leads to the experimentally observed positive piezoresistive effect.

Figure 2-4 Shows how the gauge factor  $k$  depends on the temperature and the impurity concentration equation (2.7). Similar to *n*-type material, the gauge factor decreases for increasing impurity concentration and higher temperature. Both effects can again be explained by the fact that when fewer holes distribute themselves over the two bands the relative change is larger.

To summarise; the piezoresistive gauge factor  $k$  in silicon increases when the impurity concentration decreases. Additionally the gauge factor is a strong function of temperature with the lowest doping levels producing the highest temperature sensitivity. For these two reasons, Kulite generally processes the silicon to produce degenerative (highly) doped piezoresistive sensors which have a significantly more stable gauge factor with temperature than sensors which may have higher sensitivities at the expense of stability with temperature change.

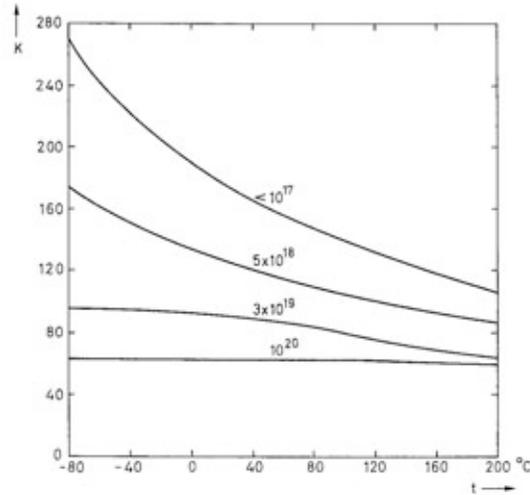


Figure 2-4: Gauge Factor of *p*-Type Silicon as a Function of Temperature & Impurity Concentration

## 2.6 Sensing Elements

The sensing elements are the electromechanical conversion devices which convert the displacement of the force summing device into an electrical signal. They must be designed and fabricated so that the conversion is accurate, linear, stable, and exhibits minimum hysteresis. The more intimate the relationship between the sensing elements and the force-summing device, the better these characteristics will be. Sensing elements may be discrete gages which are applied to some part of the force-summing device, or they may be an integral part of it.

### 2.6.1. Discrete Gages

Bonded strain gauges are separate strain gauges applied to the diaphragm, or to some other mechanical element, which is strained by the application of pressure. Silicon semiconductor strain gauges were used in bonded strain gauge transducers before the development of the Integrated Silicon Sensor by Kulite in the early 1960s. The primary advantage of the semiconductor strain gauge over the metal wire or foil strain gauge is higher sensitivity at the expense of its greater thermal sensitivity and zero shift. Application of a bonded discrete strain gauge involves finding the best location, properly aligning the gauge, and bonding the strain gauge to the structure with an adhesive. The silicon strain gauge is still used in a small number of pressure transducer designs today, but has largely been superseded by the Integrated Sensor design which is described later.

### 2.6.2. Integral Gages

The diffused piezoresistive transducer uses a silicon element for the mechanical structure, and the strain gauge is an integral part of the silicon element instead of the strain sensitive elements being bonded to the diaphragm as in the past. The silicon integrated chip is itself the diaphragm. Applied pressure presents a distributed load to the diaphragm, which in turn provides bending stresses and resultant strains, to which the strain gages react. This stress creates a strain proportional to the applied pressure, which results in a bridge unbalance. With an applied voltage, this unbalance typically produces a 100 millivolt deviation at the bridge output, which is proportional to the net difference in pressure acting upon the diaphragm for a supply voltage of 10 volts.

The piezoresistors are formed within the silicon diaphragm by either diffusion or implantation of atoms from the third atomic group (e.g. phosphorus which produces an *n*-type semiconductor) or the fifth atomic group (e.g. boron which produces a *p*-type semiconductor). By the use of photolithographic techniques, typically four elongated piezoresistors are created. Two of these resistors are positioned on the silicon diaphragm such that they experience a compressive strain and two positioned where they experience a tensile strain. They are then connected together electrically to form a fully active Wheatstone bridge. Figure 3 is an enlarged view of a silicon diaphragm which illustrates the four piezoresistors and the electrical interconnections.

Kulite later developed and patented a variation to the integrated diffused sensor design in which the four piezoresistive gages are molecularly bonded to a micromachined silicon diaphragm with an insulating layer of silicon dioxide between. This technology is referred to as either “silicon on silicon”, “silicon on insulator” or “dielectrically isolated silicon strain gauges”. This single development resulted in the extension of the maximum operating temperature capability from 150°C up to 540°C, an incredible improvement in performance in one step. Kulite’s capability to design, manufacture and package ultra high temperature piezoresistive pressure transducers is still unmatched even two decades after its first implementation.

### 2.6.3. The Wheatstone Bridge

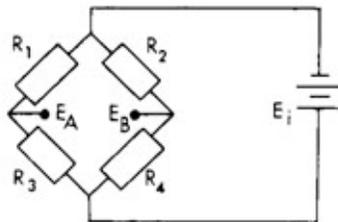
The most popular circuit for use with all types of strain gages is the Wheatstone Bridge. Bridge

$$\rho = \frac{1}{eN_i \mu_{ave}}$$

circuits can be made using from 1 to 4 strain gages, at least one of which is active (changes resistance with strain). The popularity of the bridge circuit is due to the fact that it converts the strain-induced resistance change of the gauge to voltage changes which can be measured more directly and accurately with conventional instruments.

The Wheatstone bridge is normally energised by applying a regulated voltage across two opposite corners. A voltage output proportional to the product of the excitation voltage and the resistance changes of the strain gages appears across the signal terminals. For conventional wire and foil gages, the signal level is measured in terms of a few tens of millivolts whereas semiconductor strain gauges typically produce signals of several hundreds of millivolts.

The sensitivity of a constant voltage strain gage bridge circuit is generally discussed in terms of the ratio of the change of signal voltage to excitation voltage for some fixed strain change.



For a four-arm bridge, as shown above, this can be shown to be:

$$\frac{\Delta(E_A - E_B)}{E_i} = \frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_3 + \Delta R_3}{R_3 + \Delta R_3 + R_4 + \Delta R_4} - \left[ \frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4} \right]$$

Good circuit design dictates that whenever possible, the two adjacent arms of the bridge should change equally but in opposite directions under strain. This will eliminate temperature induced changes from the output voltage. This condition is achieved, for example, in the special case of a fully active Wheatstone bridge circuit where  $R_1$  and  $R_4$ , the tension gages and  $R_2$  and  $R_3$ , the compression gages, are equal.

For this special case

$$\frac{E_A - E_B}{E_I} = \frac{\Delta R}{R} = \text{Gauge Factor}$$

Thus the bridge output voltage is linear with applied strain for any gauge which exhibits a characteristic of

$$\Delta R / R \text{ versus } \epsilon = \text{constant}$$

A Wheatstone bridge is relatively easy to signal condition, since it is excited by a constant voltage (or current) and produces a low output impedance (a few hundred to a few thousand ohms) millivolt output signal.

All strain gauges, semiconductor and metal, exhibit two temperature-dependent characteristics:

- (1) Their resistance changes with temperature, and
- (2) Their gauge factor changes with temperature.

These variations are generally larger for semiconductor gauges than for metal gauges. In addition, for semiconductor gauges, another factor must be considered. The thermal expansion of semiconductor materials is much lower than those of metals to which the gauges are usually bonded. Thus, as the temperature changes from that at which the gauges were bonded, the gauges are subjected to a thermal strain in addition to load produced strains. Proper circuitry can do much to isolate wanted from unwanted effects to obtain accurate measurements.

Apparent strain is defined as that strain calculated from resistance changes produced by factors other than load induced strains. Principally, it is the combination of the temperature coefficient of resistivity of the semiconductor plus differential thermal expansion effects. It is given by:

$$\epsilon_A = (C_M - C_K) + TCR / k$$

Where  $\epsilon_A$  - apparent strain / degree F

$k$  = gauge factor

$C_M$  = Coefficient of thermal expansion of material to which gauge is bonded (ins /in/ degree F)

$C_K$  = Coefficient of Thermal Expansion of gauge =  $1.4 \times 10^{-6}$  inches/ inch/ degree F.

TCR = Temperature coefficient of Resistance (ohms per ohm / degree F.

The simplest technique for eliminating apparent strain effects is the Wheatstone bridge circuit. Either two strain gauges or four may be used. This techniques utilises the fact that the resistance changes of two gauges in adjacent arms of a bridge will subtract if of the same polarity and add if opposite. Thus, if the two gages are subjected to the same temperature, their apparent strain

contributions will cancel. Of course, it is necessary that one of the gages be unstrained or both gages be strained in opposite directions to obtain a load responsive signal.

#### **2.6.4. Key Characteristics of Kulite Piezoresistive Technology**

The dielectrically isolated piezoresistive technology of Kulite's pressure sensor has the following strengths which are summarised below:-

Increased reliability – the piezoresistive gauges are molecularly bonded to the diaphragm.

High gage factor.

High frequency response – the natural frequencies of the diaphragms is 150 kHz minimum.

No hysteresis – the silicon diaphragm has a single crystal structure.

Not susceptible to electromagnetic interference (EMI) as there are no P-N junctions (unlike the diffused design of piezoresistive technology)

Not electrostatic discharge (ESD) sensitive.

Capable of operation up to 1000°F/ 540°C & down to cryogenic temperatures.

Mature sensor technology with a track record of reliable performance

The active area of the pressure- sensing surface, which is made of silicon, is less than 0.3 mm square. Key to the performance and ruggedness is Kulite's unique sensor design which incorporates a four-arm Wheatstone bridge molecularly bonded to, but electrically isolated from, the silicon diaphragm. Over many years, Kulite has developed computer aided design tools to design micromachining patterns in the silicon diaphragm which concentrates the stress at the locations of the resistive elements and produces a very linear electrical output against applied pressure characteristic. Additionally, the micro-machining of the silicon diaphragm produces a higher sensitivity for a given diaphragm resonant frequency as well as increasing the robustness of the sensor. The micro-machining process also enables the dimensions of the central boss to be adjusted so as to contact the supporting Pyrex glass pedestal at a predetermined pressure and provide a dramatic increase in over pressure protection (typically from x3 without stopping to x30 with stopping).

In the 1960s and 1970s, Kulite silicon diaphragm pressure transducers were mostly known as dynamic-only pressure measuring devices. They have now gained full acceptance as static pressure measuring devices and typical static error bands (nonlinearity, hysteresis and nonrepeatability) are 0.25% of full scale output, and better than 0.15% when using digital compensation techniques. Kulite piezoresistive silicon on insulator (SOI) technology pressure transducers are currently used in applications where high reliability and high accuracy at an affordable price are required in the aerospace, industrial, automotive and oil industries.

Because of the extremely small size of the sensing element (1.6mm x1.6 mm x 0.5 mm), Kulite pressure transducers offer more flexibility in packaging than any other technology. Typical aerospace applications are model and full-scale wind tunnel tests, flight tests, brake and hydraulic system tests, jet engine fuel system tests, and other measurements of turbulent flow. Automotive applications include engine air, oil, cooling and fuel systems, brake systems, transmissions and general laboratory pressure measurements. Kulite amplified pressure transducers are used by the majority of the Formula 1 racing teams in Europe both on the engines and the chassis. Ultra miniature Kulite pressure transducers are used in the wind tunnel testing of the chassis.

## **2.7. Microphones**

Microphones are very sensitive pressure transducers which are calibrated in terms of Sound Pressure Level (SPL) rather than common pressure units. Kulite models MIC-062, MIC-093, MIC-152 and MIC-190 are designed as microphones for high-intensity sound measurements.

SPL is expressed in dB or decibel notation. "Decibel" for pressure levels, voltages, accelerations, and similar measurements is defined by:-

$$\text{dB} = 20 \log_{10} P_1 / P_0$$

Where  $P_1$  is the pressure being characterised and  $P_0$  is the reference pressure. By international agreement, reference pressure for SPL is 0.000 02 N/m<sup>2</sup> (pascal) or  $2.9 \times 10^{-9}$  psi. Note also that pressures for SPL are always rms pressure levels.