

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 gauges 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) Sealed Reference – (psig).

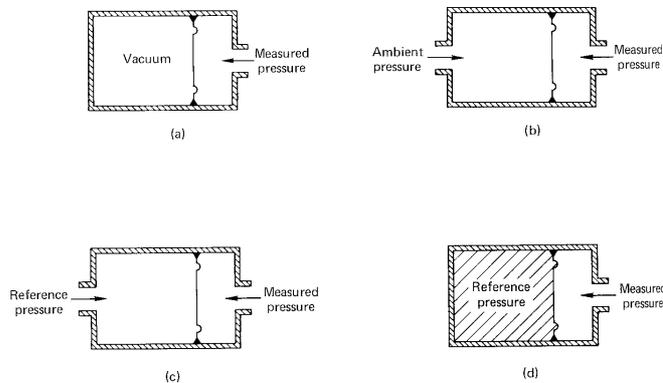


Figure 2-1: Pressure Reference Configurations

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 an annoying error source. In the 1930's it was recognised as a useful measurement tool, the metal strain gauge.

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 gauge factor, G .

Different types of gauges exhibit different gauge 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 gauge factor means higher output for the same strain, or higher sensitivity relative to the stiffness and natural frequency of the structure. Semiconductor gauges have much higher gauge factors than metal because, in addition to the lengthening and narrowing of the conductor, the resistivity 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 piezoresistive 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

$$R = \rho L / A, \quad (2.1)$$

where L is the length of the wire, ρ is resistivity of the wire material and A is the wire's cross-sectional area.

Differentiating Equation 2.1, we obtain

$$(dR/R) = (d\rho/\rho) + (dL/L) - (dA/A). \quad (2.2)$$

The relative change of the length dL/L of the strain gauge is known as the axial strain, ε_a , and similarly the relative change of the diameter dD/D of the strain gauge is known as the lateral strain, ε_L . The ratio of these strains for a particular material is given by its Poisson ratio, ν .

$$\nu = -\varepsilon_l / \varepsilon_a = -\frac{dD/D}{dL/L}. \quad (2.3)$$

For the relation between the relative change in the cross-sectional area and the relative change in the diameter we find

$$dA/A = 2dD/D. \quad (2.4)$$

Combining Equations 2.2 and 2.4 we obtain

$$dR/R = \varepsilon_L (1 + 2\nu) + d\rho/\rho. \quad (2.5)$$

The gauge factor, G , of a strain gauge is defined as

$$G = (dR/R) / \varepsilon_A, \quad (2.6)$$

so that we obtain the general expression

$$G = 1 + 2\nu + (d\rho/\rho) / \varepsilon_A. \quad (2.7)$$

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 resistivity ρ , 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 resistivity ρ . 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 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 of atoms in the crystal can be expected. This interaction leads to the important result that the energy curve is no longer continuous as for the free electrons, but rather it 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. However, actual three dimensional lattices show similar discontinuities in the energy-momentum relations.

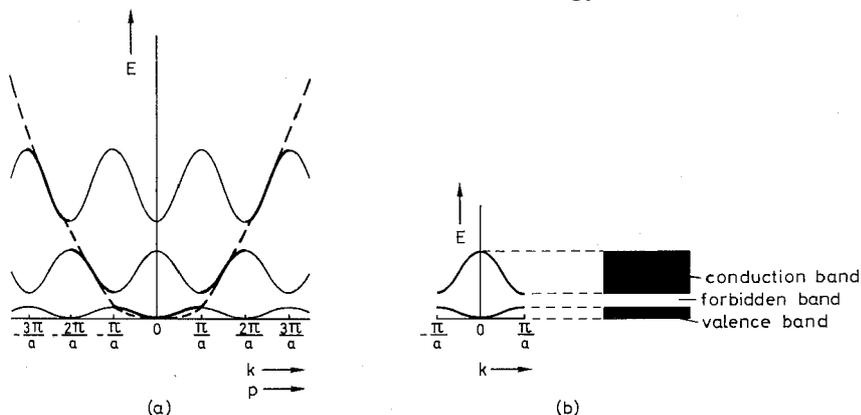


Figure 2-2: (a) Energy E as a function of the momentum p for a classical particle (dashed line) and as a function of the wave number k for a particle with wave-like nature in interaction with a periodic crystal lattice (solid lines);
 (b) Part of the possible solutions indicating the conduction, the 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 h 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 of k far from the discontinuity points given by Equation 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 periodic lattice. 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 in the three-dimensional case, so use is made of the fact that the crystal lattice is often highly symmetric. Solutions are often found for directions of high crystalline symmetry such as the [100] and [111] directions shown in Figure 2-3. In Figure 2-3 those parts of the band structure of silicon that are relevant for explaining the piezoresistive effect in silicon are shown.

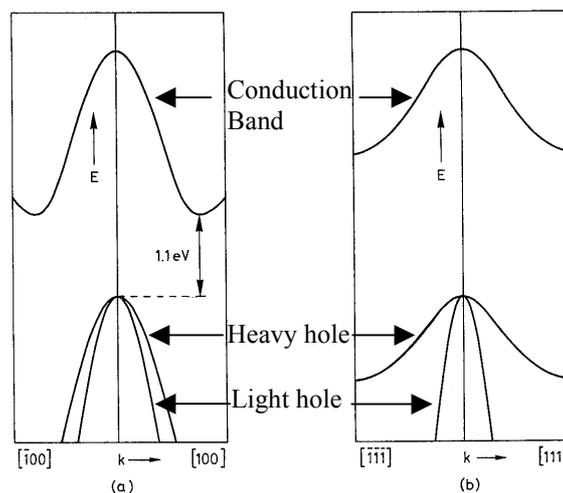


Figure 2-3: Energy Band Structures of Silicon for (a) the [100] and (b) the [111] directions.

In order to understand the piezoresistive effect in p -type silicon, we first must understand the concepts of carrier effective mass and mobility. Figure 2-3 shows that near the maxima, the hole bands (lower two bands) in both the [100] and [111] directions are parabolic in shape. This can be directly compared with the case of a free electron (Equation 2.10) which is also parabolic. The hole band parabola is upside down because the hole charge is opposite that of an electron. By making

comparison with Equation 2.10, we define an effective hole mass which corresponds to the curvature of the parabola in the energy band diagram: the tighter the parabola, the lower the effective mass.

When an electric field is applied across a semiconductor, the charged carriers, which are holes in the case of p-type silicon, move in the direction of the field. When the electric field is increased the holes move faster. The ratio between the speed of the holes and the electric field is known as the mobility. In a semiconductor with a high mobility, hole moves faster for the same applied electric field. The mobility is related to the hole effective mass just as if the holes were actually heavier: holes with a larger effective mass move more slowly, and therefore have lower mobilities. Thus, the higher the mobility of the charge carriers, the higher the current resulting from the same applied electric field, and therefore the lower the resistivity.

So holes in a p-type semiconductor behave similarly to free electrons with the exception that their effective mass is different. Inspection of Figure 2-3 reveals that silicon has two types of holes with different effective masses, known as the heavy holes and the light holes, and it is this variation in effective mass (and hence mobility) which leads directly to the piezoresistive effect. Actually the silicon bandstructure has a third hole band, known as the split-off hole band, which is not pictured in Figure 2-3 because it does not play a significant role in piezoresistance.

The average mobility of the p-type silicon is the average mobility of the individual holes in the silicon and therefore is determined by the proportion of heavy holes to light holes. Piezoresistance in semiconductor works by altering this proportion with the application of stress. When an anisotropic stress is applied, the lattice spacing increases in one direction, while the lattice spacing decreases in the perpendicular direction. As one might expect, the interaction of the charged carriers with the lattice is also affected. The stress causes the holes to move from the heavy-hole band to the light-hole band or vice versa, depending on the direction the stress is applied. Since the ratio of heavy-hole to light-holes is altered, the average effective mass of all the holes changes, and therefore the mobility and the resistivity changes. This is the piezoresistive effect in silicon.

Recall that the tightness of the band parabola is directly related to the hole effective mass. As is apparent in Figure 2-3, the difference in curvature and therefore the difference in effective mass is much larger in the [111] direction than in the [100] direction. Therefore, when stress is applied to the silicon and the holes redistribute themselves among the heavy-hole and light-hole bands, the effect of the redistribution on the resistivity is small in the case of the [100] directions but quite large for the [111] directions. Therefore piezoresistors in p-type silicon are aligned in the [111] directions.

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 G depends on the temperature and the doping level. Similar to n-type material, the gauge factor decreases for increasing doping concentration and higher temperature. Both effects can be explained by the fact that when fewer holes distribute themselves over the two bands, the relative change is larger. As can be seen in Figure 2-4, the gauge factor is significantly smaller in more heavily doped material, but it is much more stable with temperature. Therefore, Kulite generally processes the silicon to produce degenerative (highly) doped piezoresistive sensors. A little sensitivity in the magnitude of the output of the sensor is lost in order to create a sensor whose output is much more temperature stable. The loss of sensitivity can be made up by carefully designing the diaphragm under the piezoresistance to maximize output.

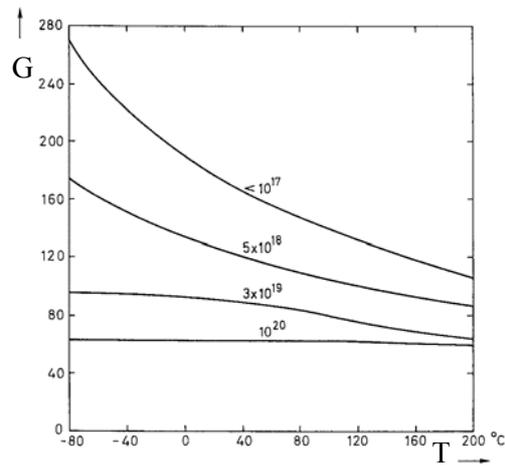


Figure 2-4: Gauge Factor of *p*-Type Silicon as a Function of Temperature & Doping Concentration

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 gauges which are applied to some part of the force-summing device, or they may be an integral part of it.

2.6.1. Discrete Gauges

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 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 Gauges

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 gauges 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.

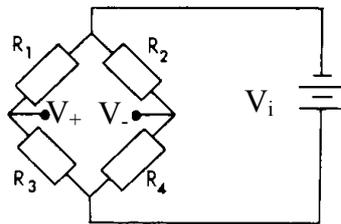
Kulite later developed and patented a variation to the integrated diffused sensor design in which the four piezoresistive gauges are molecularly bonded to a micromachined silicon diaphragm with an insulating layer of silicon dioxide between. This technology is referred to as either “silicon on silicon”, “silicon on insulator” or “dielectrically isolated silicon strain gauges”. In diffused silicon sensors, the piezoresistors are electrically isolated from one another and the substrate by reverse-biased p-n junctions which leak current at high temperatures. Dielectric isolation, however, allows for operation at much higher temperatures. 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 gauges is the Wheatstone bridge. Bridge circuits can be made using from 1 to 4 strain gauges, 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 gauges appears across the signal terminals. For conventional wire and foil gauges, 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 gauge 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

$$\frac{\Delta(V_+ - V_-)}{V_i} = \frac{R_1 + \Delta R_1}{R_1 + \Delta R_1 + R_2 + \Delta R_2} - \frac{R_3 + \Delta R_3}{R_3 + \Delta R_3 + R_4 + \Delta R_4} - \left[\frac{R_1}{R_1 + R_2} - \frac{R_3}{R_3 + R_4} \right] \quad (2.13)$$

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 gauges and R_2 and R_3 , the compression gauges, are equal. For this special case

$$\frac{V_+ - V_-}{V_i} = \frac{\Delta R}{R} = \varepsilon G \quad (2.14)$$

where ε is the strain and G is the gauge factor.

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

$$\frac{\Delta R}{R} \text{ versus } \varepsilon = \text{constant} \quad (2.15)$$

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.
- (3) 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

$$\varepsilon_A = (C_M - C_K) + \text{TCR} / G, \quad (2.16)$$

where ε_A is the apparent strain/°F, G is the gauge factor, C_M is the coefficient of thermal expansion of material to which gauge is bonded (inches/inch/°F), C_K is the coefficient of thermal expansion of gauge (1.4×10^{-6} inches/inch/°F), and TCR is the temperature coefficient of resistance (ohms/ohm/°F).

The simplest technique for eliminating apparent strain effects is the Wheatstone bridge circuit. Either two strain gauges or four may be used. This technique utilizes 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 gauges are subjected to the same temperature, their apparent strain contributions will cancel. Of course, it is necessary that one of the gauges be unstrained or both gauges 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 gauge 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

$$\text{dB} = 20 \log_{10} P_1 / P_0 \quad (2.17)$$

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/m² (pascal) or 2.9Qx 10⁻⁹ psi.

Note also that pressures for SPL are always rms pressure levels.

2.8. Integrated Sensor Design

The integrated sensor design uses a silicon diaphragm, as the description suggests, as the basic force-collecting and sensing mechanism. The diaphragms for the integrated sensors are fabricated either by the techniques of solid state diffusion and oxide masking, epitaxial growth or, more recently, Diffusion Enhanced Fusion (DEF) bonding of two discrete wafers (pattern and carrier) to produce a strain sensing network that is electrically isolated from the silicon substrate that forms the force collector.

Each diaphragm contains a fully active four-arm bridge with the gauge positions chosen to provide; tension and compression. Details of the basic fabrication processes including diffusion, oxide masking, photolithography, contact metallisation and lead attachment as well as the fabrication processes for DEF bonded units are not described in detail in this handbook but are generally available in previously published Kulite technical papers.

These devices represented a state of the art advance in the field of miniature pressure transducers when they were first developed by Kulite in the 1960s and have found wide application in such fields as jet engine testing, wind tunnel testing and flight testing for the measurement of high frequency pressure fluctuations.

The design of a successful silicon diaphragm pressure transducer requires a detailed understanding of the physics of piezoresistivity and also the relationship between the change in resistivity and the stress inducing the change. Factors such as the type of material to use for a particular application (P or N-

type), the physical form of silicon (monocrystalline, polycrystalline or amorphous silicon), the dopant to be used and the concentration required to fabricate the piezoresistors in the silicon and the orientation of the crystal planes relative to the transducer diaphragm all need to be considered by the designer.

In order to construct a pressure transducer from the silicon diaphragm as discussed in the preceding sections, it is necessary to support the silicon diaphragm on a pedestal in such a manner as to enable a pressure differential to be applied across the diaphragm without introducing a mounting strain in the diaphragm. To complete the manufacture of the pressure capsule, a Pyrex glass or silicon pedestal is electrostatically bonded to the silicon sensor. The purpose of the pedestal is to:-

- Mechanically support the silicon sensor
- Isolate the sensor from stress
- Provide an overload stop when required
- To configure the sensor reference pressure (absolute, gauge, differential)

The figure below is a schematic diagram of an absolute pressure capsule diffused integrated sensor.

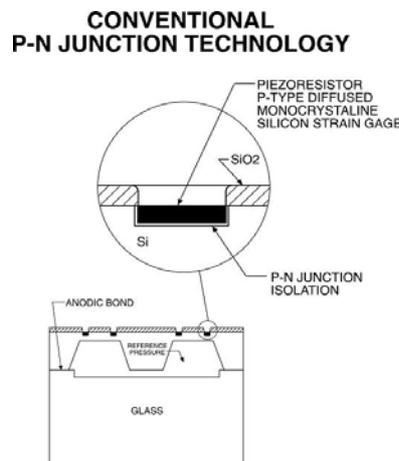


Figure 2-7: The Diffused Integrated Sensor

The use of silicon based components throughout the construction of the pressure capsule i.e. n-type silicon diaphragm, p-type silicon piezoresistors, low expansion “Pyrex” glass results in a mechanical assembly in which the coefficients of expansion of all the components are very closely matched. This aspect of the design ensures minimum internal stresses are generated when the temperature of the pressure capsule is changed and leads to enhanced long term stability.

The construction of the pressure capsule also enables semiconductor manufacturing techniques to be employed which produces a very small sensor with a diaphragm which has a very high natural frequency. This enables the sensor to measure both static and dynamic pressures with high accuracy. A dramatic comparison between the relative sizes of an integrated silicon diaphragm capsule (left) and a strain gauged metal diaphragm (right) is shown below.



Figure 2-8: Integrated Silicon Diaphragm v Bonded Strain Gauge Design

2.8.1. Dielectrically Isolated Design (Silicon on Silicon)

The diffused integrated sensor design described in section 2.7 was incorporated into the majority of Kulite pressure transducers and enabled the manufacture of ultra miniature pressure transducers with exceptionally high natural frequencies. However, the diffused design of integrated sensor has two major drawbacks.

The p-n junction between the p-type piezoresistors and the n-type silicon diaphragm has a resistance characteristic which falls rapidly with temperature. Above temperatures of 150°C to 200°C, the leakage currents within the Wheatstone bridge circuit have effectively bypassed the piezoresistors and the bridge is no longer measuring pressure accurately. In addition, the p-n junctions display a photosensitivity i.e. they are light sensitive. For applications where dynamic pressures are required to be measured in the presence of a detonation or other luminous events, the transducer will generate an electrical output due to the light and which is totally separate from the pressure changes.

Many applications to measure pressures within the aerospace, oil and automotive industries require transducers to operate in a temperature environment in excess of 150°C. In order to overcome these limitations of the original p-n junction type sensor, the dielectrically isolated (or silicon on silicon) sensor has been developed by Kulite in which the piezoresistors are electrically insulated from the n-type diaphragm material by the interposition of a layer of silicon dioxide alone or, more recently, in combination with a second layer of glass. A schematic diagram of a dielectrically isolated fusion bonded sensor together with a photograph of a processed diaphragm is shown below.

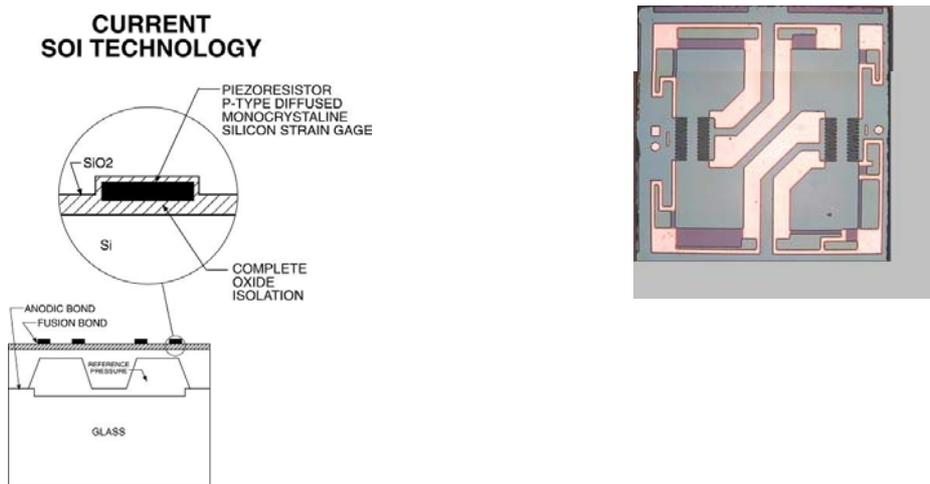


Figure 2-9: Schematic Diagram & Photograph of Silicon on Insulator Sensor

2.8.2. Diaphragm Characteristics

In order to fabricate integral silicon diaphragms containing a four-active arm Wheatstone bridge and to ensure that both tension and compression gages are fully active, careful attention must be given to the stress distribution across the diaphragm and its effect on gauge placement as shown in Figure 2-10.

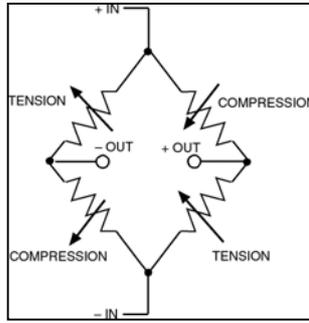


Figure 2-10: Connection of Resistors in Wheatstone Bridge

Figure 2-11 shows a classical clamped-edge flat diaphragm with the resulting normal and surface stress distributions shown in Figure 2-12. Use of a diaphragm with this stress distribution would result in a pressure transducer with a very non-linear electrical output with respect to applied pressure. The addition of a specially designed thickened area in the centre of the diaphragm, as shown in Figure 2-13 which Kulite refers to as a “boss”, produces the stress distributions shown in Figure 2-14. The stresses in the surface of the diaphragm are designed to vary equally in the compressive and tensile directions which results in an ideal characteristic for the measurement of pressure.

The sensing network is located, in the thin (active) portion of the diaphragm. When the diaphragm deflects under pressure, the surface stress in the region nearest the unetched clamp region is of one sign and the stress next to the boss is of the opposite sign: Therefore, if a sensor network is disposed such that one sensing gauge is adjacent to the clamped edge and the other, sensing gauge is disposed adjacent to the boss by connecting the two gauges together one gauge will increase in resistance and the other will decrease. If the same technique is used on the other side and the gauges are interconnected properly a fully active Wheatstone bridge circuit will result.

If a gauge or differential pressure is to be measured, a vent hole is drilled through the pedestal to enable barometric or a reference pressure respectively to be applied to the back of the diaphragm.

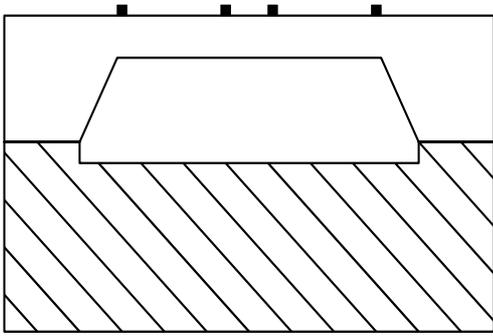


Figure 2-11: Clamped-Edge Diaphragm

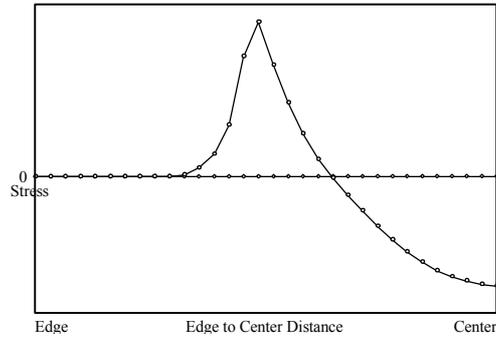


Figure 2-12: Stress Distribution for Clamped-Edge Diaphragm

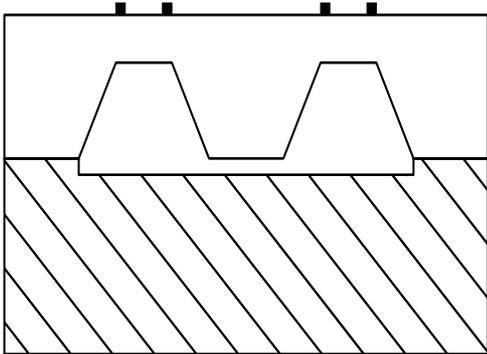


Figure 2-13: Bossed Diaphragm

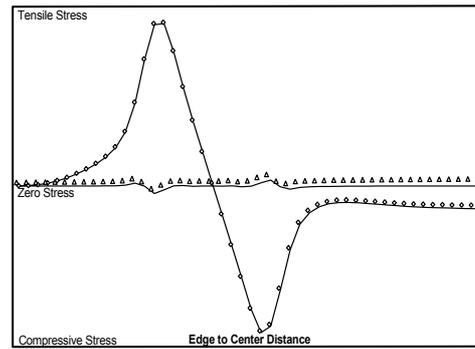


Figure 2-14: Stress Distribution for Bossed Diaphragm

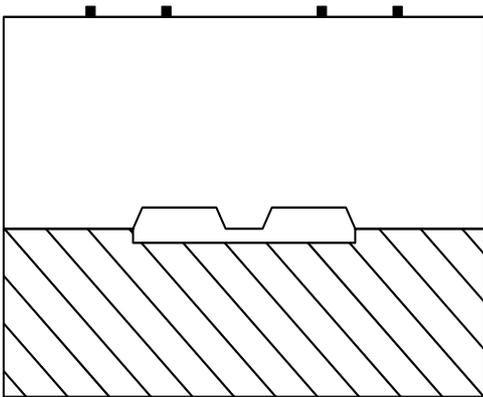


Figure 2-15: High Pressure Diaphragm

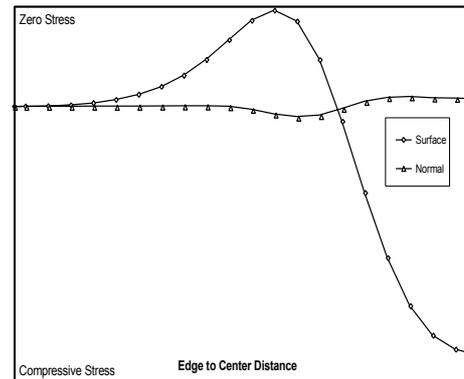


Figure 2-16: Stress Distribution for High Pressure Diaphragm

The pressure range of a diaphragm is determined by the thickness of the silicon between the central boss area and the clamping area at the edge of the diaphragm. For diaphragms which are designed to operate at high pressures, the diaphragm thickness can approach the radius of a circular diaphragm as shown in Figure 2-15. The resultant stress distributions are shown in Figure 2-16. If the surface stresses are measured as in the lower pressure designs, it can be seen that there is no point on the diaphragm where there is a positive (tensile) stress. This inability to generate negative and positive going gauges for inclusion into a Wheatstone bridge circuit will produce a severely non-linear response to applied pressure.

By careful analysis of the stress distributions within a high pressure diaphragm design and by exploiting the surface stresses normal to the diaphragm by the appropriate selection of gauge material and crystallographic orientation, it is possible to produce a gauge which has a positive resistance change. The reference to a detailed report on high pressure transducer designs is to be found in Section 9.3.1.

To ensure optimal performance the etched regions must be very narrow (in the order of 0.010 inches) and the individual gauges must be very short (in the order of 0.001 to 0.002 inches) and extremely narrow (in the order of 0.0001 inches). For low and medium pressure range diaphragms, the gauges are best made such that the gauge length is in a longitudinal direction i.e. perpendicular to the wall of the edge of the clamped region and of the boss. The longitudinal crystallographic direction being in the <110> direction and the transverse in the <100> direction.

Use of the Kulite developed DEF bonding technique has produced a group of transducers which can operate up to temperatures well in excess of 1000°F with excellent linearity and thermal characteristics.

2.8.3. Isolated Capsule Design

Frequently it is a requirement of airworthiness organisations that pressure transducers which are to be used on board aircraft should have some form of secondary pressure containment incorporated within the basic transducer design. Secondary pressure containment is defined as the ability to contain the pressure media if, for some reason, the primary pressure containment (the silicon diaphragm in the case of silicon based transducers) fails. This is achieved typically by mounting the silicon sensor capsule on a 304 stainless steel header with high-pressure glass-to-metal sealed pins. An isolation diaphragm of 304 stainless steel is electron-beam welded to the front surface of the header and the cavity between the isolation diaphragm and the sensor capsule is filled with silicone oil which acts as a pressure transfer medium. This form of construction is shown schematically in Figure 2-17.

The use of the header-silicon capsule-isolation diaphragm design combines the advantages of a metal diaphragm and an all welded construction with the advantages of an inorganically bonded silicon sensor for excellent repeatability and long term stability. The header assembly is frequently welded into an outer case which incorporates the electrical connector. This outer case provides tertiary containment and ensures that the transducer is totally hermetically sealed, which considerably enhances the reliability and survivability of the transducer in humid and contaminated environments.

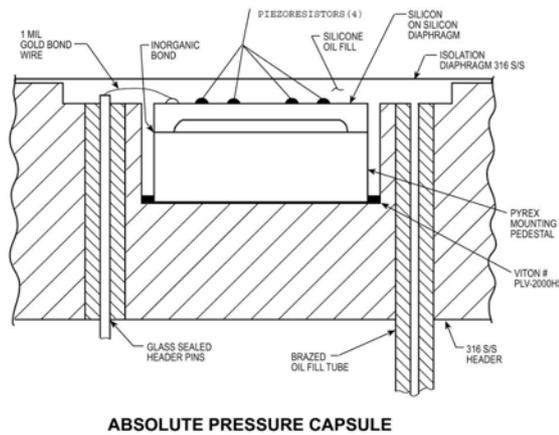


Figure 2-17: Isolated Pressure Capsule Design

2.8.4. Dual Diaphragm Technology

For the measurement of gauge or differential pressures, Kulite has patented a design of pressure transducer which uses two separate, oil filled, absolute pressure capsules (Kulite Patent #4,695,817). This method was developed to eliminate the historical problems of having gauge pressure transducers which were typically vented either through the case, which exposed the internal electronics and components to environmental contamination and frequently resulted in a very short life, or via small pressure tubes which tended to become clogged or filled with water which could freeze. These advantages are also relevant to differential pressure transducers using two pressure capsules. To maintain acceptable levels of accuracy for the two pressure capsule design of differential pressure

transducer, a line pressure limitation of a maximum of 4 times the differential pressure range is generally applicable.

This design of gauge or differential pressure transducer produces a transducer, the internals of which are totally hermetically sealed from the external environment leading to exceptional levels of reliability, stability and operational life. Each pressure port of a two capsule differential pressure transducer is associated with a separate measuring element. In the case of a gauge unit, one pressure port is vented to atmosphere to provide the reference pressure.

One measuring element is a half bridge array and monitors the main pressure applied to the positive port. The second element is also a half bridge array and monitors the pressure applied to the other port, which is the negative, or reference port. A fully active Wheatstone bridge is formed by two piezoresistors associated with the positive port and two piezoresistors associated with the negative port. By selecting the magnitudes of the resistors associated with each port it is possible to generate one electrical signal which is an analogue of the differential pressure.

The preferred circuit is shown below.

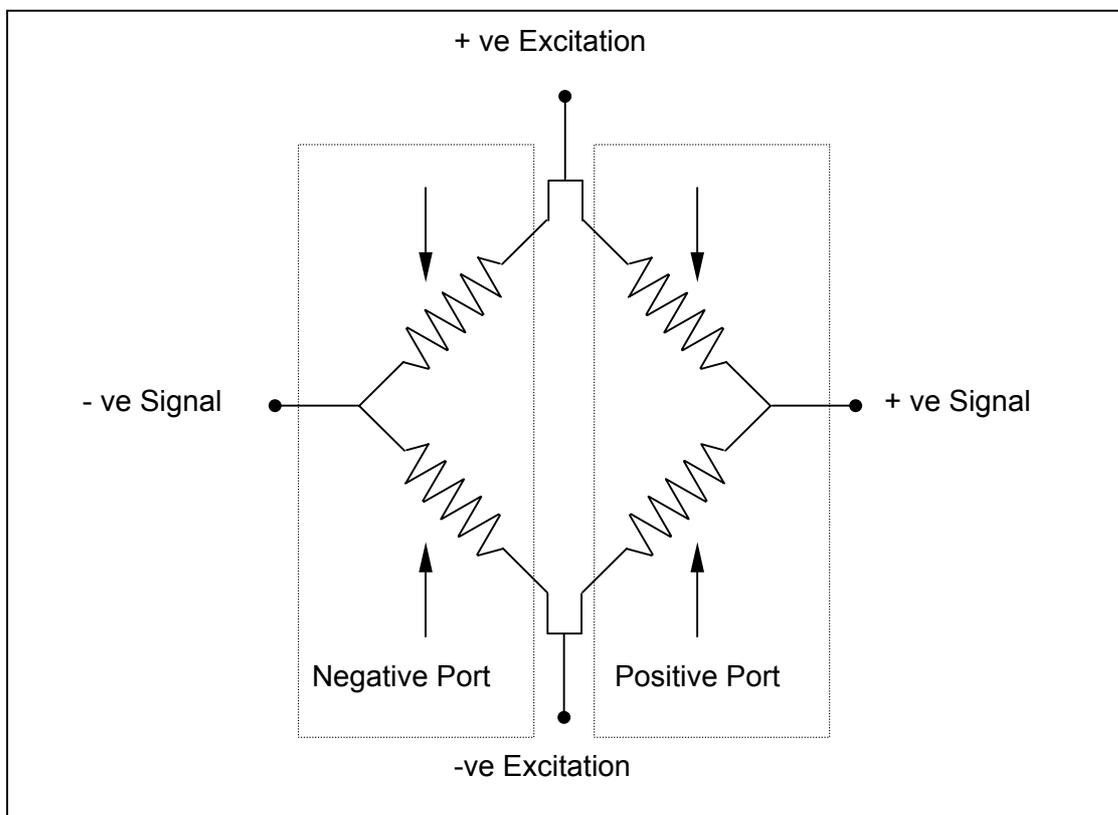


Figure 2-18: Schematic Circuit Diagram of Dual Capsule Design

2.8.5. Combination Pressure/ Temperature Transducers.

As a result of the small size of the isolated pressure capsule design, which is due in large part to the incorporation of Kulite's ultra miniature pressure capsule design, pressure transducers can be designed and manufactured which may have two or three pressure sensing capsules inside. Kulite pressure transducers can also be supplied with one or more resistance temperature sensors included within the housing.

Such pressure transducers are referred to as "Combination Pressure or Pressure/ Temperature Sensors". Combination sensors may also be used to provide a redundant capability where two totally independent transducers, with separate electrical connectors within one body, are used to measure the same pressure, an example being the engine oil feed pressure which is critical for the health of a gas turbine. Combination sensors are designed and built for high reliability/ availability and extreme

service environments and feature small size and minimum weight, critical features in aircraft and many other applications. Combined pressure and temperature measurement will give a better indication of process status or fluid health. Redundant sensors give an extra measure of reliability, and maintain process control in the event of a single sensor failure. The installation of redundant or multiple sensors in a single penetration or package makes engineering and installation easier and significantly reduces the weight of the installation. Reducing sensor penetrations and wiring harnesses also decreases installation and life cycle costs.

Combination sensors have been developed exclusively by Kulite and are finding many applications in both the Aerospace and Autosport Industries. References to a paper which describes Combination Pressure /Temperature sensors in more detail are given in section 9.3.5.

2.8.6. Kulite Leadless Design

Electrical connection is made to the Wheatstone bridge on the silicon diaphragm using four or five 0.024mm (0.001 inch) diameter gold bond wires which are ultrasonically ball bonded to the diaphragm metallisation. The pressure media is in direct contact with the stress-sensing network, leadouts and interconnects which, at high temperatures, in the presence of aggressive chemicals and after prolonged exposure, can deteriorate and fail. The key elements in the design of a ruggedised pressure sensor are the elimination of the gold bond wires and the protection of the sensing elements from corrosive environments at high temperatures, hence the reference to the new sensor capsule as the “leadless” design.

The leadless sensor capsule is comprised of two main components, the sensor chip and the cover as shown below in Figure 2-18.

The sensor chip and the cover wafer are assembled using an electrostatic bond to form the sensor capsule. Once the two wafers have been bonded, only the metallised leadout pads are exposed whilst all the gauges and electrical interconnections on the sensing side of the silicon chip are sealed by the cover. Thus the active portion of the pressure sensor is hermetically isolated as shown in Figure 2-19.

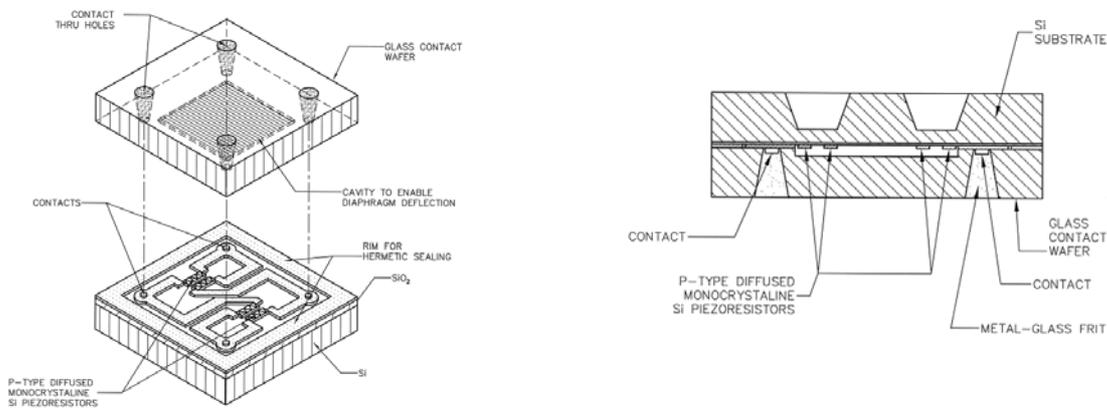


Figure 2-18: Sensor Chip & Cover Before Bonding Figure 2-19: Sensor Chip Bonded to Cover

To avoid the use of gold ball bonds and fine gold wires, a high temperature conductive glass is used to provide the electrical connection between the sensing chip and a specially designed header. The pressure capsule is bonded to the header at a high temperature using a non conductive glass, during which process the conductive glass in the cover wafer holes melts and creates low resistance electrical connections between the header pins and the metal contact pads on the sensor chip as shown in Figure 2-20.

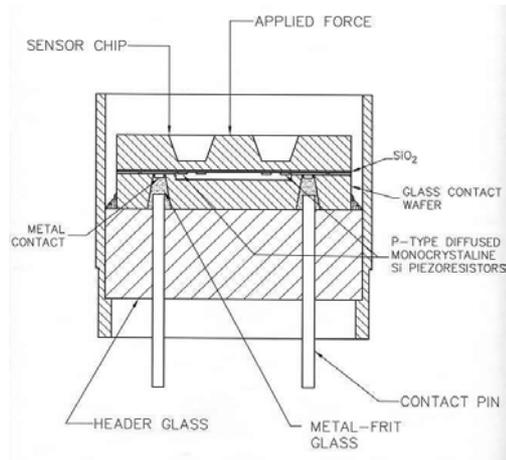


Figure 2-20: Pressure Capsule Bonded to Header

After this firing process, only the non-active side of the diaphragm is exposed to the pressure medium. The small ball bonded gold leads have been eliminated and the entire sensor network and contact areas are hermetically sealed from the environment and the pressure media.

2.8.6.1 Leadless/ Acceleration Compensated Design

There are many environments which are very harsh in which to attempt fast response measurements of static pressure, particularly on rotating components. Because of the high rotational speed of most turbomachines, pressure sensors can be exposed to high levels of centrifugal and vibrational acceleration.

As has been described, semiconductor pressure sensors function by determining the deflection of a small silicon diaphragm under exposure to a normal stress (pressure), using a Wheatstone bridge network of strain gauges to measure this movement. However, the diaphragm will also deflect under the influence of centrifugal and vibrational accelerations which will generate both offset errors and dynamic errors.

Kulite has designed an acceleration insensitive semiconductor pressure sensor which compensates for these deleterious effects and is shown below:-

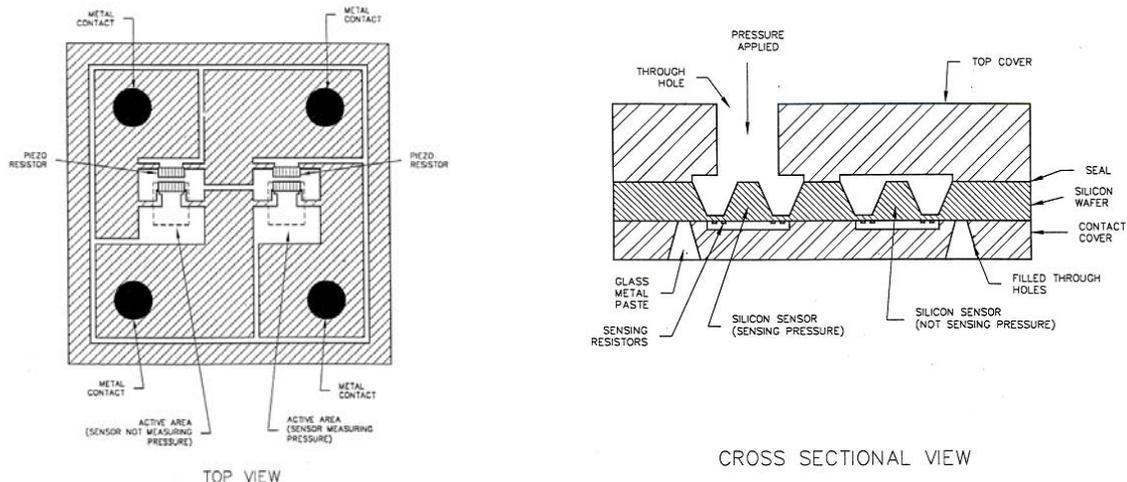


Figure 2-21: Acceleration Insensitive Pressure Sensor

The device is based upon the leadless technology described in section 2.8.5 and comprises two pressure sensing diaphragms which are manufactured on one silicon chip. On each diaphragm, a half Wheatstone bridge is formed using two piezoresistors in series. The two diaphragms are both exposed to the inertial stresses (vibration and centrifugal acceleration), but only one is exposed to the pressure

to be measured. The two half bridges from each diaphragm are electrically connected to form a full bridge such that for a positive stress applied substantially normal to the diaphragm, the bridge output from one half-bridge will subtract from the other. Thus the signal output is responsive to the pressure as applied to one diaphragm while the signal response to inertial stresses (or any other stress other than that due to pressure) applied to both diaphragms is cancelled out. Reference to a comprehensive report on the acceleration insensitive pressure sensor is given in section 9.3.11.

2.8.7 Temperature Compensation

Semiconductor strain gauge characteristics are temperature dependent. In particular, the resistance of an semiconductor strain gauge increases with temperature by typically +10% per 100 degrees F rise in temperature i.e. the Temperature Coefficient of Resistance (TCR) is +10%/100°F. The strain sensitivity, or gauge factor, decreases with temperature by typically -2% per 100 degrees F increase in temperature i.e. the Temperature Coefficient of Gauge Factor or Sensitivity (TCGF or TCS) is -2%/100°F.

To properly utilise semiconductor gauges for accurate measurements of mechanical strain, it is necessary to compensate the gauge output signals against these undesirable temperature effects. Compensation can generally be accomplished with simple circuit techniques using passive shunt or series resistor elements whose resistance is temperature independent. Piezoresistive strain gauge bridges must be compensated for zero and zero shift with temperature and for the decrease in sensitivity by means of adjustment of the bridge excitation voltage. Relations are derived for calculating the values of the compensation resistors from a knowledge of the strain gage parameters and the measured effects of temperature on signal output.

2.8.7.1 Bridge Zero and Zero Shift Compensation

Placing a near zero temperature coefficient of resistance (TCR) resistor in series or shunt with a piezoresistive gauge changes the magnitude of the resistance and TCR of the gauge.

| Element Position | Magnitude | TCR |
|------------------|-----------|-----|
| Series | ↑ | ↓ |
| Shunt | ↓ | ↓ |
| Both | ↑ or ↓ | ↓ |

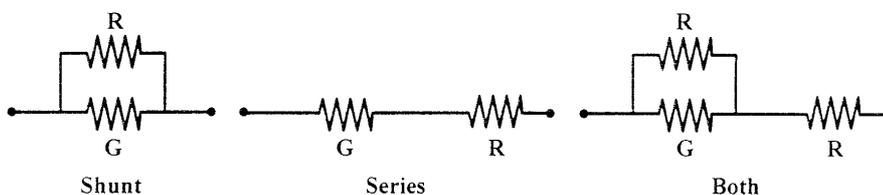


Figure 2-22: Effect of Zero Compensation Resistor Placement

Kulite has developed computer based models to calculate the magnitude and location of compensation resistors to nullify the effects of temperature changes on both zero and zero offset values for half bridges, 4-wire and 5-wire full bridges.

2.8.7.2 Bridge Sensitivity Compensation

Bridge sensitivity compensation is achieved by the insertion of a span resistor connected in series with the bridge supply voltage.

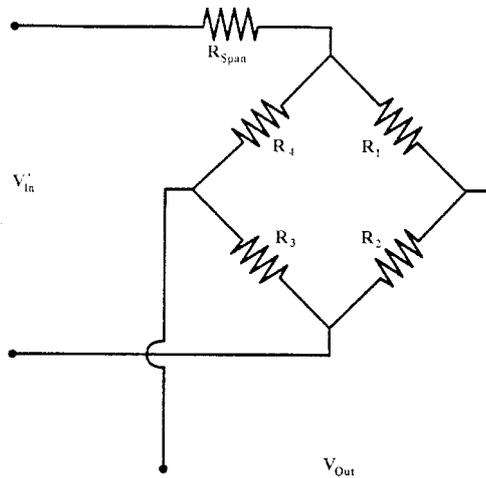


Figure 2-23: Wheatstone Bridge with Span compensation

$$V_{Out} = V'_{In} \left(\frac{R_{Bridge}(T)}{R_{Bridge}(T) + R_{Span}} \right) \{S(T)P\} \quad (2.19)$$

The equation for the output voltage from a Wheatstone bridge equipped with a span resistor is:
 The bridge input resistance, $R_{bridge}(T)$, increases with temperature at its TCR value. The bridge sensitivity, $S(T)$, decreases with temperature at its TCS value.
 By observing the above equation it can be noted that a correct choice of R_{span} can compensate the sensitivity of the transducer over temperature.

A simple qualitative explanation as to how the span compensation process works is that as the temperature of the bridge increases, the resistance of the bridge also increases. However, the resistance of the span compensation resistor R_{span} does not change with change in bridge temperature. Thus as the temperature of the bridge increases, an increasing proportion of the supply voltage will be applied to the bridge which will proportionally increase the bridge output. The resistance of R_{span} is chosen such that the increase in bridge output with temperature is exactly offset by the decrease in sensitivity of the bridge with temperature.

Because of variations in material properties, processes, and dimensions, the performance of a population of pressure transducers of a given design will scatter about the typical. To provide the lowest effect of temperature, the performance is measured for each transducer during the manufacturing process, and resistance values are chosen to compensate for the changes with temperature. The resistance R_{span} in series with the bridge supply is used to reduce the sensitivity variation with temperature. The resistances in series and parallel with one arm of the bridge correct for bridge zero and changes in zero (zero shift) with temperature.

The temperature compensation resistors are mounted within the transducer case for the majority of Kulite pressure transducers. Only when the pressure capsules are used without any external casings (chip-on applications) or with ultra high temperature pressure transducers (temperatures in excess of 400°C) are the compensation resistors located remotely from the sensor. This arrangement is possible due to the fact that Kulite pressure transducers only require zero temperature coefficient resistors in their temperature compensation networks, unlike many other manufacturers who also use temperature dependent resistors (thermistors) in their “active” temperature compensation networks. In order to achieve accurate temperature compensation, the temperature of the thermistor must be the same as the temperature of the sensor. Temperature gradients within an actively temperature compensated pressure transducer can significantly degrade the accuracy of pressure measurement, errors of up to 10% full

scale being possible during thermal transients. Each pressure transducer is tested in the manufacturing process and the resistors are selected to optimise performance.

2.8.8. Mechanical Design

Kulite's unique range of sensors are packaged in stainless steel cases of an infinite variety of sizes and shapes. The pressure capsules are mounted in headers which isolate the silicon diaphragms from strains in the casings which may effect the measurement accuracy. Popular designs of miniature pressure transducers include those with threads from sizes M5 to M10 and those with no external threads in diameters ranging from 1.7mm to 3.8mm. The cases for transducers for aerospace applications are frequently designed to meet a specified space envelope. Transducers may incorporate power supplies, regulators and amplifiers with voltage, current or frequency outputs. Cases may be made from titanium, Inconel or Hastelloy in place of stainless steel and are frequently hermetically sealed to protect the unit from external contamination.

Kulite's pressure transducers will operate from -200°C to over 530°C.

The silicon diaphragm of many of Kulite's miniature pressure transducers is mounted at the end of the transducer which enables them to be used in flush diaphragm applications. A protective "B" or "M" screen is usually specified for these units and is designed to have a minimum effect on frequency response.

At the front end, the sensing module is isolated from strains in the case, yet it is mounted at the extreme front of the transducer making it equivalent to a flush-mounted diaphragm. Most models include a standard protective screen, designed and tested to minimise effects on frequency response, while providing maximum protection to the silicon diaphragm.

At the rear of Kulite's pressure transducers, the cable is securely anchored inside the case, and sealed with a strain-relieving boot. The vent tube (on gage pressure models) is securely anchored and may be cut, bent or adjusted for specific applications. It may be connected to a reference source for differential pressure measurements. Alternatively, a multi-pin electrical connector may be welded to the case in place of a cable exit and strain relief.

For the reference port of Kulite's miniature differential pressure transducers, the pressure media must generally be clean, non-conductive and non-corrosive. In the case of Kulite's larger aircraft or industrial pressure transducers which either use Kulite's patented two sensor design or a true differential "wet- wet" design, virtually all pressure media which are compatible with stainless steel may be safely used.

The reference port is the low pressure side in all differential measurements. Differential transducers are designed for specified maximum line pressure. Maximum reference pressure, and maximum case pressure *should be* (!) specified on the data sheets.

2.8.9 Silicon Carbide

Increased performance requirements for pressure transducers for aircraft and for spacecraft demand sensing capabilities at high temperatures. The pressure environments to be measured in these applications require sensing capabilities down to 25 psi. To meet the high temperature requirements, silicon carbide (SiC) has been selected by Kulite as a semiconductor material to be used in fabrication of the sensor chip. SiC material, because of its wide bandgap (3eV), high breakdown electrical field ($2.5 \times 10^6 \text{Vcm}^{-1}$) and large piezoresistive coefficients, exhibits excellent thermal, mechanical and electrical characteristics as a sensing material. Kulite have reported on the fabrication, packaging, and testing of a low-pressure 6H-SiC piezoresistive pressure sensor (25 psi range) operational at 600°C. Sensor fabrication was done using a combination of electrochemical etching and Deep Reactive Ion Etching (DRIE). The sensor is similar in structure with a 1000 psi pressure sensor that was previously reported. The 1000 psi sensor had a diaphragm of about 60 μm thickness, while the 25 psi range required a significantly thinner diaphragm. The sensor reported has a diaphragm of about 20 μm thickness. Fabrication of thin 6H-SiC diaphragms is difficult, because of challenging control of SiC etch depth, and because of the presence of 6H-SiC micropipe defects. These defects are inherent to

currently commercially available 6H-SiC wafers, and their detrimental effect on device yield is increased for thinner diaphragms. As opposed to alternative devices the sensor described has the piezoresistors and diaphragm fabricated from SiC. The utilization of a SiC diaphragm makes the sensor suitable for higher temperature applications (due to excellent mechanical properties of SiC at very high temperatures) and for harsh environments (due to SiC chemical inertness). References to this paper are given in section 9.3.2.

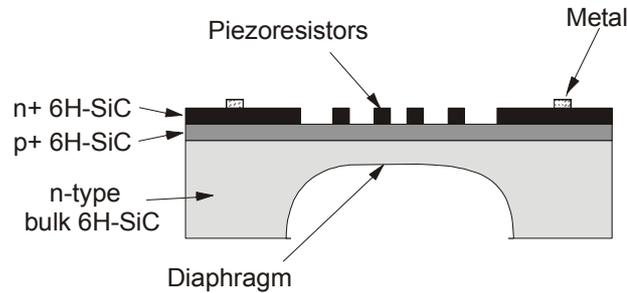


Figure 2-24: Section of SiC Sensor Chip

In a departure from Kulite's preferred use of piezoresistive technology, a paper has been written which describes a silicon carbide dual-resonant-beam pressure sensor capable of operating at ultra-high temperature. Silicon begins to plastically deform above approximately 600°C. However, many applications, such as those associated with combustion in gas turbine engines, require transducers capable of operation at much higher temperatures. At such high temperatures, silicon carbide is the material of choice due to its high temperature of plasticity, large bandwidth and chemical inertness. The device is composed of two pressure-sensing diaphragms each spanned by a beam that is caused to vibrate at its respective resonant frequency. One diaphragm is exposed to the applied pressure, which induces stress in the beam that spans it and therefore alters the beam's resonant frequency. The other diaphragm is not exposed to pressure; thus its beam's resonant frequency remains unchanged. The difference in the frequencies of the two beams is then directly proportional to the pressure that is to be measured. As the output of sensor is a frequency, interfacing the signal with a digital system is simple. Because of the close physical proximity of the two diaphragms and beams, any measurement errors induced by such external variables as temperature or acceleration are cancelled out when taking the difference frequency.

A sectioned view of the dual resonating SiC beam pressure sensing structure with beat frequency output is shown in Figure 2-25.

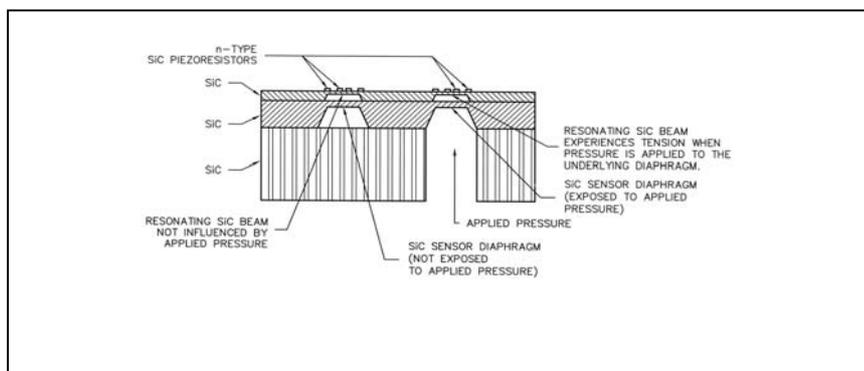


Figure 2-25: Cross-Section of a Dual Resonating SiC Beam Structure With Beat Frequency Output

References to this paper are given in section 9.3.3.