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.

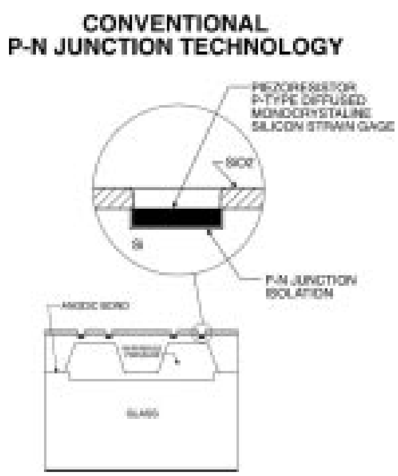


Figure 2.7: The Diffused Integrated Sensor

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.

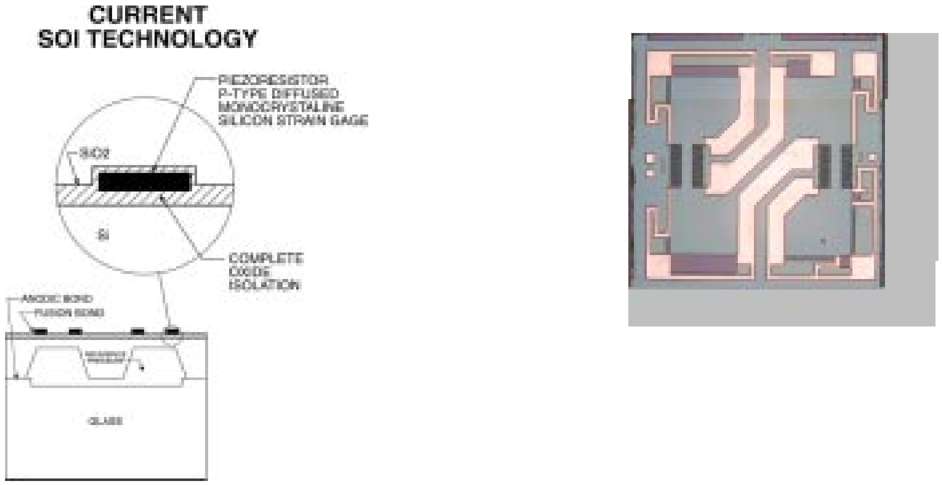


Figure 2-9: Schematic Diagram & Photograph of Silicon on Insulator Sensor

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.

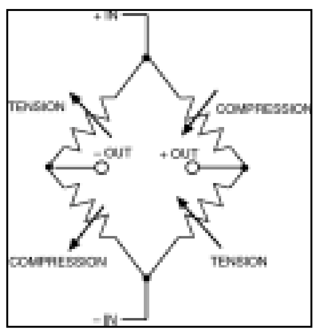


Figure 2-10: Connection of Resistors in Wheatstone Bridge

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.

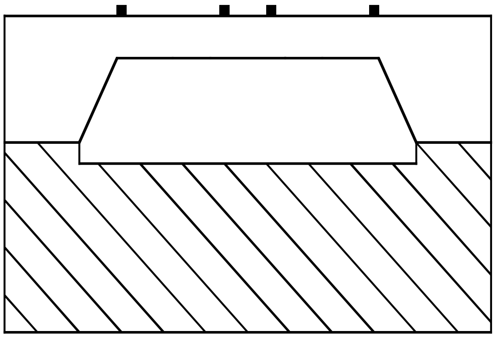


Figure 2-11: Clamped-Edge Diaphragm

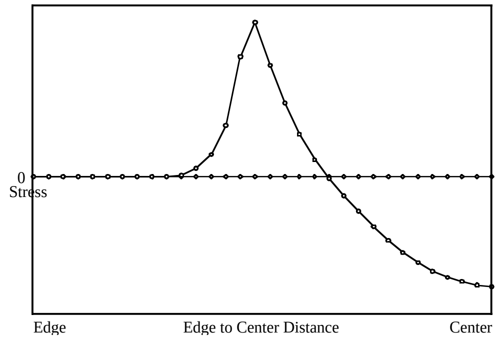


Figure 2-12: Stress Distribution for Clamped-Edge Diaphragm

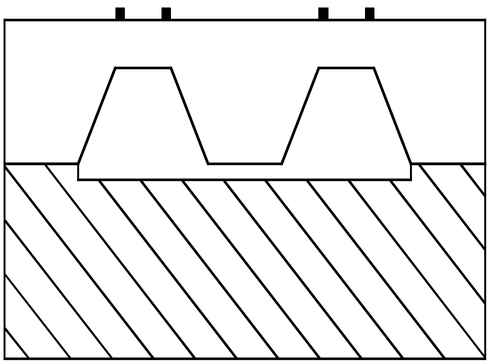


Figure 2-13: Bossed Diaphragm

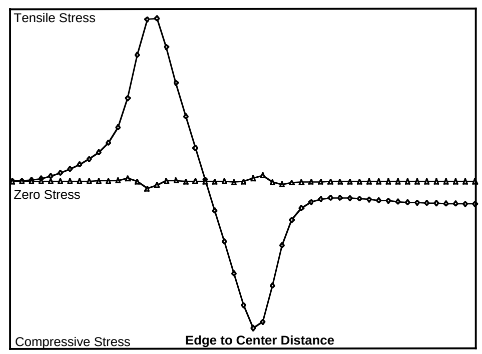


Figure 2-14: Stress Distribution for Bossed Diaphragm

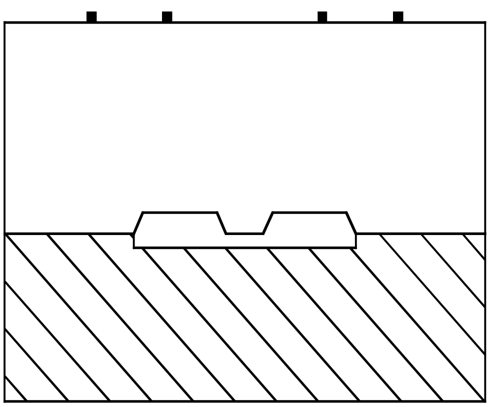


Figure 2-15: High Pressure Diaphragm

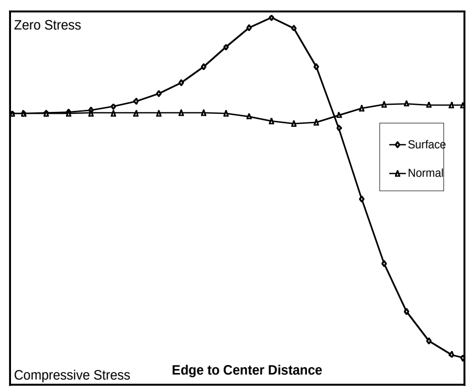


Figure 2-16: Stress Distribution for High Pressure Diaphragm

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 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 silicon 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.

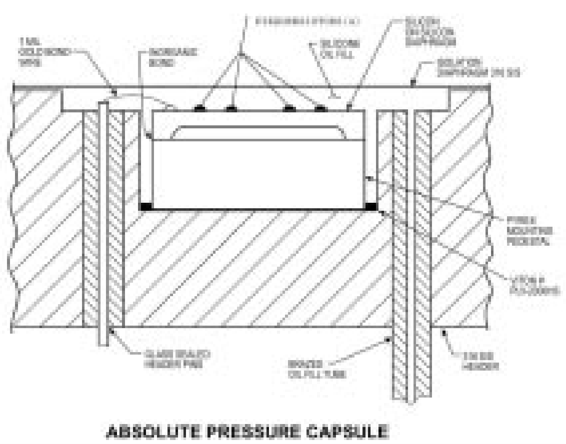


Figure 2-17: Isolated Pressure Capsule Design

2.8.4. 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 included within the housing. Such pressure transducers are referred to as “Combination Pressure or Pressure/ Temperature Sensors”. Combination sensors possess a redundant capability and are designed and built for high reliability/ availability and extreme service environments. These sensors feature small size and minimum weight, critical features in aircraft and 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. Reducing sensor penetrations and wiring harnesses also decreases installation and life cycle costs.

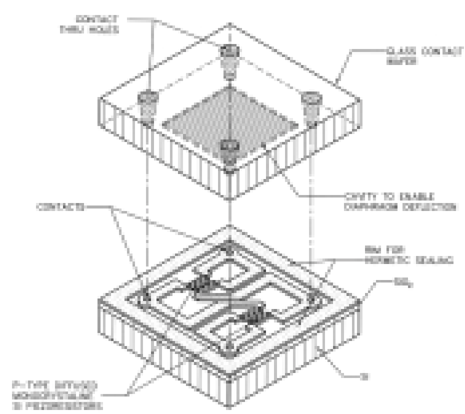
Combination sensors have been developed exclusively by Kulite and are finding many applications in both the Aerospace and Autosport Industries. References to a paper which describes Combination Pressure /Temperature sensors in more detail are given in section 9.3.5.

2.8.5. 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.



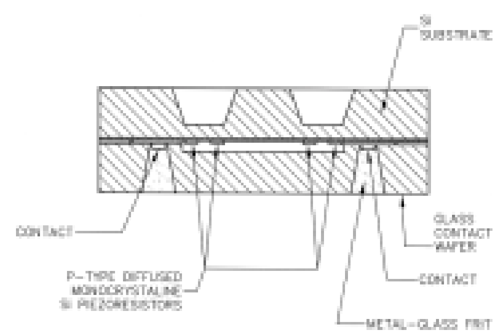


Figure 2-18: Sensor Chip & Cover Before Bonding   Figure 2-19: Sensor Chip Bonded to Cover

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 creates low resistance electrical connections between the header pins and the metal contact pads on the sensor chip as shown in Figure 2-20.

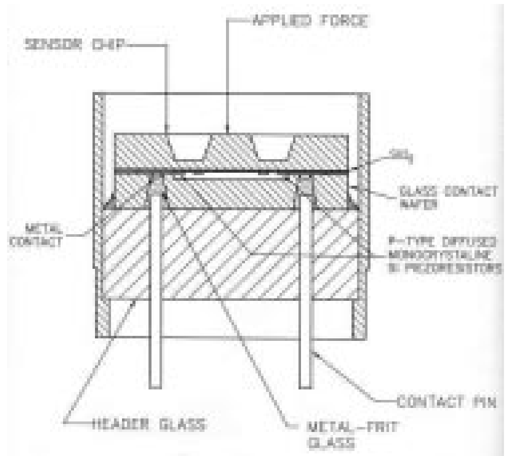


Figure 2-20: Pressure Capsule Bonded to Header

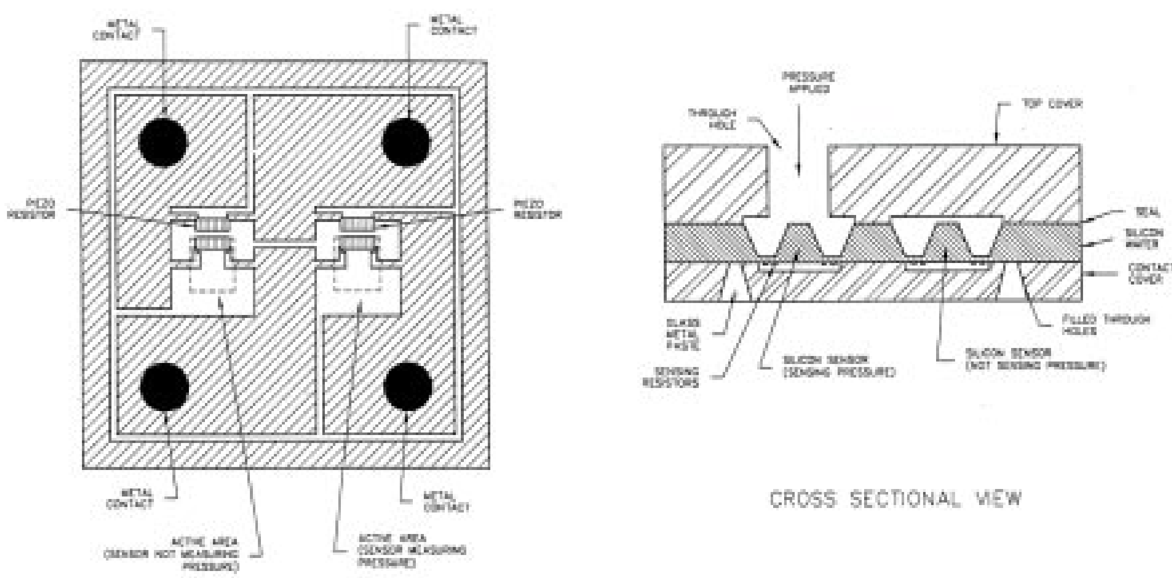
After this firing process, only the non-active side of the diaphragm is exposed to the pressure medium. The small ball bonded gold leads have been eliminated and the entire sensor network and contact areas are hermetically sealed from the environment and the pressure media.

2.8.5.1 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:-



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 in given in section 9.3.11.

2.8.6 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.

2.8.6.1 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 ↓	↓

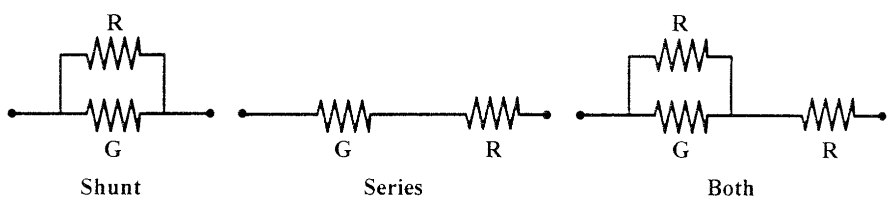


Figure 2-22: Effect of Zero Compensation Resistor Placement

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.

2.8.6.2 Bridge Sensitivity Compensation

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

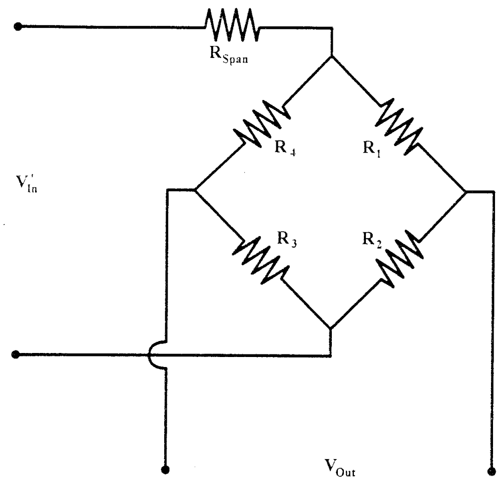


Figure 2-23: Wheatstone Bridge with Span compensation

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

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 it's TCR value. the bridge sensitivity, S(T), decreases with temperature at it's 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.

2.8.7. 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 an 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.

2.8.8 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 x $10^6 Vcm^{-1}$) 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 600ºC. 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 _m thickness, while the 25 psi range required a significantly thinner diaphragm. The sensor reported has a diaphragm of about 20 _m 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).

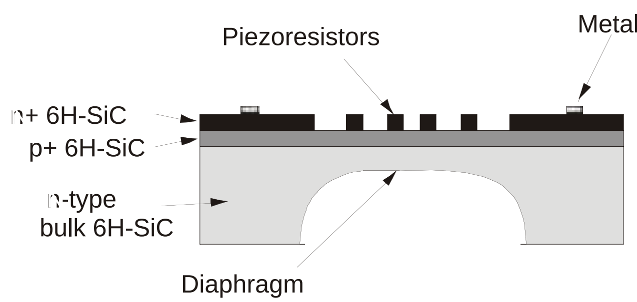


Figure 2-24: Section of SiC Sensor Chip

References to this paper are given in section 9.3.2.

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 600^0C. 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.

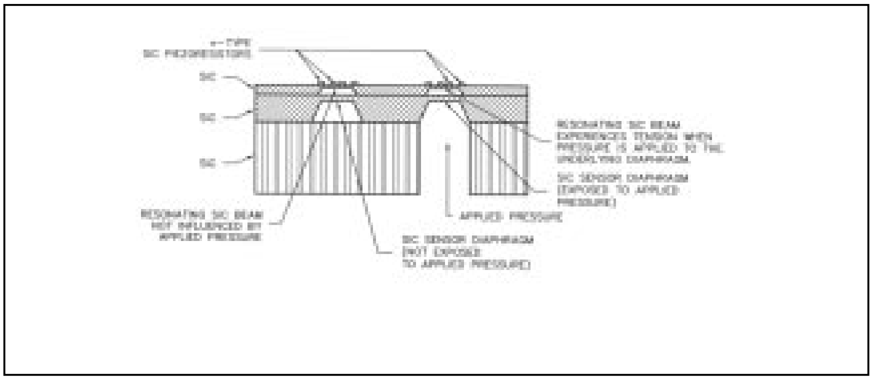


Figure 2-25: Cross-Section of a Dual Resonating SiC Beam Structure With Beat Frequency Output

References to this paper are given in section 9.3.3.