IMPROVED RUGGEDISED HIGH TEMPERATURE PRESSURE TRANSDUCERS FOR GAS TURBINE ENGINE & COMPONENT RIG RESEARCH & DEVELOPMENT

Dr. A. D. Kurtz[1], Dr. J. W. H. Chivers[1], A. A. Ned[1], Scott Goodman[1]
Professor R. W. Ainsworth[2], S. J. Thorpe[2]
Professor A. H. Epstein[3]

1
Kulite Semiconductor Products, Inc.
One Willow Tree Road,
Leonia, NJ 07605
USA

2
Department of Engineering Science,
The University of Oxford
Parks Road
Oxford
UK

3
MIT
Massachusetts,
Cambridge, MA
01239, USA

ABSTRACT

The need for semiconductor pressure transducers that can be used in applications requiring operation in harsh environments which are corrosive, oxidizing, experiencing high vibration, and involving high temperatures continues to increase.

This paper reports on the latest developments of Silicon-On-Insulator (SOI) piezoresistive pressure sensors for extreme environments. Challenges which can arise from use of these sensors in ultra harsh environments are reviewed and the design of the latest "leadless", miniature, dynamic pressure transducers capable of operating reliably under extreme environmental conditions (temperatures in excess of 600°C and accelerations greater than 200g) – is described in detail. The performance of such "leadless" pressure transducers is presented and indicates that ruggedised, high frequency, miniature, piezoresistive transducers with improved performance characteristics are now feasible for use in extremely harsh, high temperature environments.

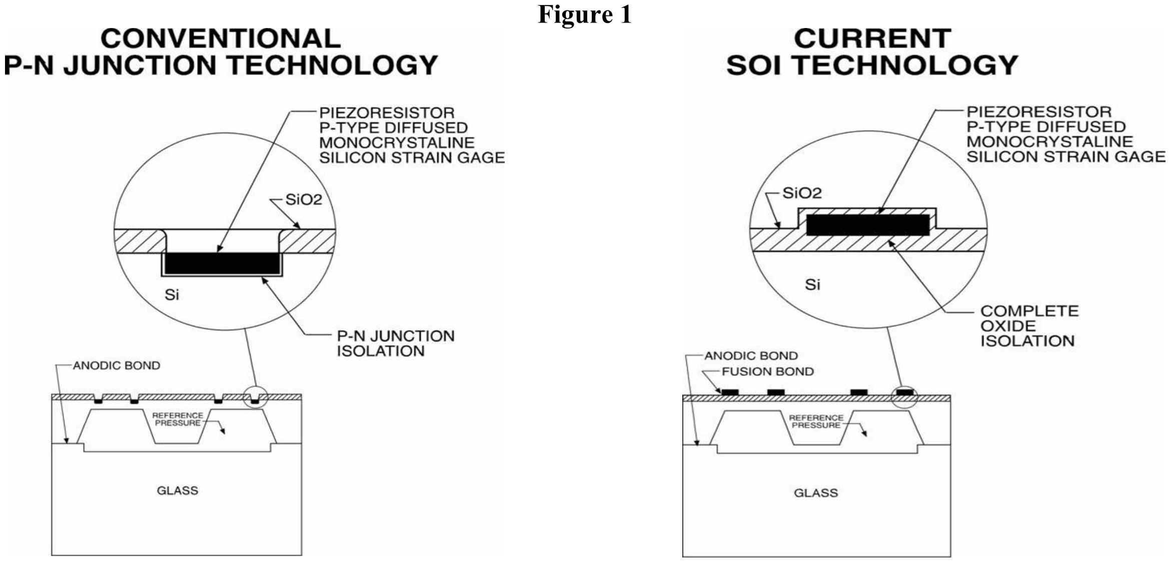
The "leadless" technology has been further developed to produce a true acceleration insensitive pressure transducer which is also described.

INTRODUCTION

The sensor design for this latest generation of transducers utilizes the state-of-the-art MEMS technologies. In this design the front end of the sensor is intended to withstand both the high temperatures and the extreme environments throughout its lifetime, with an opportunity to locate the electronics (if needed) some distance away. This approach enables the sensor to achieve high reliability under extreme operating conditions. There is no maintainability associated with this design approach since everything, including the entire sensing network, is enclosed and hermetically sealed within the transducer assembly. The leadless modular design, together with the use of the SOI technology for the fabrication of piezoresistive sensors, is intended to enhance transducer performance characteristics and to keep the cost of these transducers down.

Significant improvements to gas turbines require better instrumentation for both development and operation. In particular, the ability to measure steady state and time varying pressures at high temperatures in the operational engine environment is an enabling technology for: 1) afterburners free from acoustic screech and rumble, 2) improvement in stability of compressors through the anticipation and suppression of surge and rotating stall, and 3) improvement in stability of the combustion process, especially for low emissions combustors. One example is that the natural aerodynamic instabilities of turbomachines often limit their performance, but increased stability potentially leads to lighter more efficient compressors with fewer stages and shorter airfoil chords, reduced fan noise from lower tip speeds, faster engine acceleration as the surge constraints have been removed, and greater operating flexibility. The piezoresistive sensing approach adopted by Kulite is extremely well suited in terms of device performance, component utility, and systems integration to all the mentioned applications. The DC and low frequency components are ideal for use by conventional engine control logic, while the high frequency information is needed for stall avoidance and control, and aeromechanical diagnostics. Of course, operational capability at these extreme temperatures and high vibration

Figure 1



levels implies that this technology is also well suited for a variety of additional applications across many industries.

Piezoresistive transducers are generally considered to be superior to alternative approaches for several reasons. First, unlike piezoelectric transducers, low noise and controlled impedance wiring plus bulky and expensive charge amplifiers are not required. Also, unlike the piezoelectric devices, which can only be used for dynamic measurements, the piezoresistive devices can be used for both static and dynamic measurements. The new technology described in this paper offers the system level advantages of complete freedom from transducer cooling and thus more freedom for transducer placement, multifunction transducers, reduced transducer electronics, and reduced volume. Overall, this improves the cost, weight, and reliability penalties associated with the additional control functionality desired for advanced engine concepts.

THE SILICON-ON-INSULATOR (SOI) SENSOR

For the last 40 years, Kulite has supplied high performance pressure transducers to the aerospace industries for both research and development and for production applications. These transducers are based upon the piezoresistive silicon technology, which Kulite pioneered [1] and developed to its current high levels of performance and reliability. The latest evolution of sensors at Kulite, including the leadless sensor, uses silicon on insulator (SOI) technology [2,3].

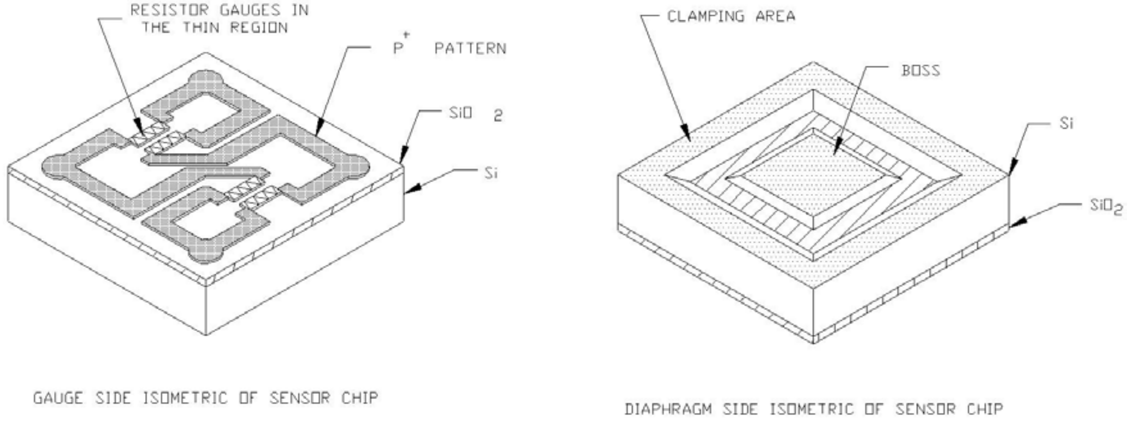
Piezoresistive silicon strain gauges are integrated within the silicon diaphragm structure but are electrically isolated from the silicon diaphragm as shown schematically in **Figure 1**. The piezoresistors measure the stress in the silicon diaphragm, which deflects as a direct function of the applied pressure.

There are two core elements of the current generation of devices which will be considered in turn: the production of a suitable deflecting diaphragm to convert applied pressure into displacement, and the addition of piezoresistive strain gauge elements to the diaphragm to measure the displacement.

The latest evolution of the patented Silicon on Insulator (SOI) technology enables the piezoresistive sensing elements to be dielectrically isolated from, while being molecularly attached to a silicon diaphragm (**Figure 2**).

The process for fabricating the composite dielectrically isolated SOI sensor structure requires the use of two separate wafers. The first “Pattern” wafer is specifically selected to optimize the piezoresistive performance characteristics of the sensor chip, while the second “Substrate” wafer is specifically selected to optimize the capabilities of micromachining the sensing diaphragm. A layer of high quality thermally grown oxide is then grown on the surface of the substrate, while the piezoresistive patterns are introduced into the pattern wafer. The piezoresistive patterns are diffused to the highest concentration level (solid solubility) in order to achieve the most stable, long-term electrical performance characteristics of the sensing

Figure 2



network. Once the pattern and the substrate wafers are appropriately processed, the two wafers are fusion bonded together using a specifically developed and patented diffusion enhanced fusion bonding technique [2]. The resulting molecular bond between the two wafers is as strong as the silicon itself, and since both the sensing elements and the diaphragm are comprised of the same silicon material, there is no thermal mismatch between the two, thus resulting in very stable and accurate performance characteristics with temperature. The presence of dielectric isolation enables the sensor to function at very high temperatures without any current leakage effects associated with the p-n junction type devices. Since the device is capable of operating at high temperatures, a high temperature metallisation scheme is introduced to enable the device to interface with the header at these high temperatures as well.

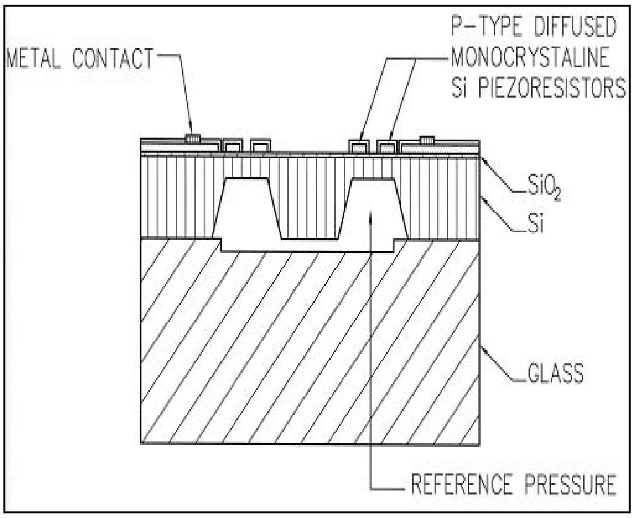


Figure 3

The micromachining is performed using a combination of different wet (Isotropic and Anisotropic) chemical etch processes. The shape and performance characteristics of the micromachined sensing diaphragm are modeled using finite element analysis at the initial design stage. The composite silicon sensor is attached to a Pyrex pedestal, by an anodic bonding process, to form a pressure-sensing capsule as shown in **Figure 3**. The pedestal material is selected to thermally match the physical characteristics of the silicon sensor.

The sensing circuit is electrically isolated from the metallic housing by virtue of the non-conductive pedestal in the pressure capsule. The isolation resistance and the dielectric strength are inherently very high. The reference pressure is contained within the cavity between the diaphragm and pedestal, which has a true hermetic seal.

THE LEADLESS SENSOR DESIGN

In the semiconductor sensor industry, the standard method of providing electrical connections between a sensor chip and the package is wire bonding. The ultrasonic agitation used to form the wire bonds causes abrasion to take place during the welding process and allows microscopic holes to develop in the metallisation through which, at high operating temperatures, the gold can migrate and form a gold-silicon eutectic which causes the leads to fail. In addition, the pressure media is in direct contact with the stress-sensing network, leadouts and interconnects, which can fail at high temperatures and in the presence of aggressive chemicals. The key elements in the design of a ruggedised pressure sensor is the elimination of 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 [4,5,6].

The leadless sensor uses high temperature metal-glass mixtures for providing electrical connections between the sensor chip and the package. The leadless sensor capsule is comprised of two main components, the sensor chip and the cover wafer, which are eventually assembled to form the pressure capsule.

Figure 4
Leadless (SOI) Sensor with Cover Glass Attached

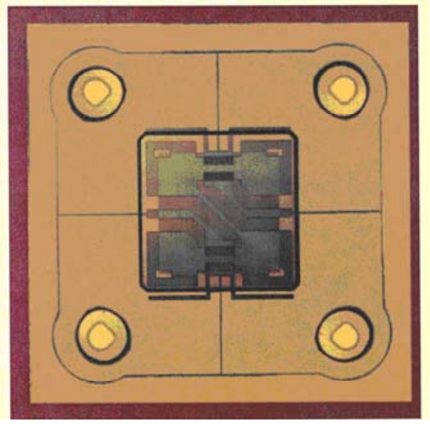


Figure 4 shows a photograph of the sensor chip with the four-piezoresistive gauges strategically positioned inside the sensing diaphragm region and connected in a Wheatstone bridge. The entire sensing network is P^+ Silicon and there are separations between the contact regions of the bridge. Metal is deposited to form ohmic contacts to the P+ regions located inside the large contact regions. There is also a rim of P+ material around the periphery of the sensor chip. When the cover wafer is assembled to the sensor chip, an hermetic seal is formed between the cover and this rim area of P+ material, thus protecting the stress sensing network and all the electrical interconnections from the harsh environmental conditions. The cover wafer is manufactured from a Pyrex glass to the same dimensions as the silicon wafer. Four holes are micromachined in the cover, one in each corner, which align with the metallised contact pad areas. A cavity is also created in the centre of the cover wafer to allow the diaphragm to deflect freely when assembled. The sensor chip and the cover wafer are then assembled using anodic bonding.

Figure 5 shows a top isometric view of the components just prior to sealing. Once the two wafers are bonded, only the metallised leadout pads are effectively exposed, while 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.

SENSOR IMPROVEMENTS

Kulite is continuing to develop and optimise the sensor chip design and the associated packaging techniques. The latest generation of the optimised sensors includes:

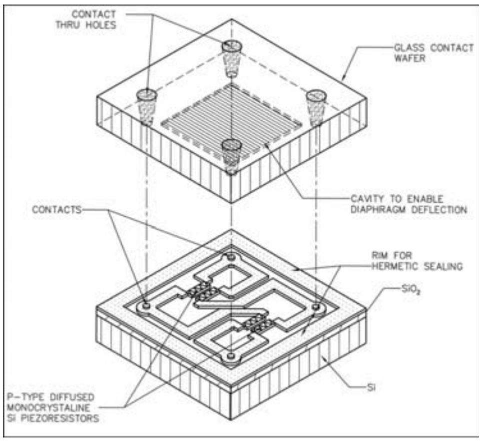
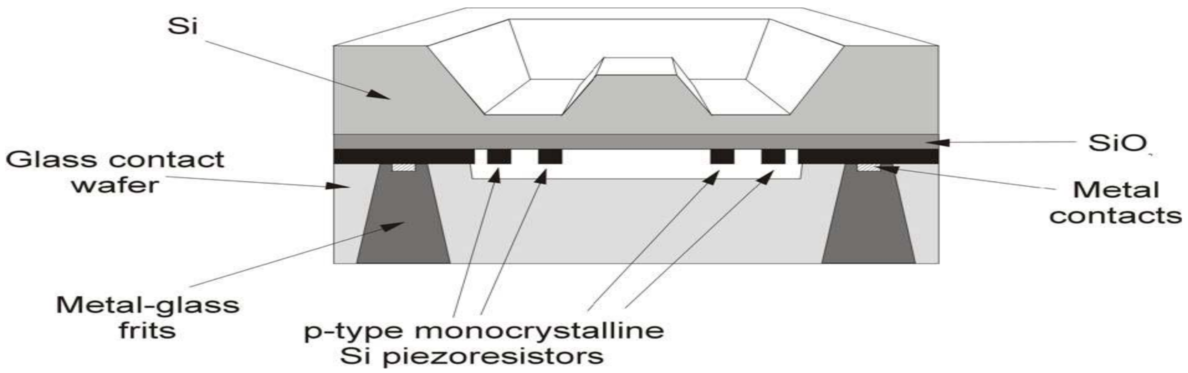


Figure 5

a) Finite Element Analysis modelling was performed to better understand the present designs and to fine-tune the new designs. The new designs were established to improve performance such as enabling larger, more linear, and more stable output characteristics for a specific sensor diaphragm thickness. Increasing the sensors output also created an opportunity to increase the diaphragm thickness for the respective design (in obtaining the same outputs), thus leading to further improvements in the overall stability and repeatability of the sensors.
b) A significant effort is underway at Kulite to improve the metallisation scheme on the sensing chip in order to enable device operation at ultra high temperatures. New metallurgical systems have demonstrated the capability of the metallised contacts on the sensing chips to withstand exposure to temperatures up to 650°C (1200°F) for many hours.

As part of on ongoing effort at Kulite for developing silicon pressure sensors for high temperature operation, we have investigated the behaviour of sensor insulating layers at high temperatures. We have tested the dielectric isolation of SOI pressure sensors for operation above 700°C. Testing was performed by applying a DC voltage between the piezoresistive layer and the substrate, and by measuring the corresponding leakage current through the dielectric isolator. Testing was performed at wafer level, using a high temperature probe station. Isolation tests were conducted with voltages up to

Figure 6
SIDE VIEW OF THE "LEADLESS CHIP COMPOSITE" AFTER FILLING WITH GLASS-METAL PASTE FOR CONTACTING



100V without any dielectric breakdown occurrence up to temperatures well above 700°C.

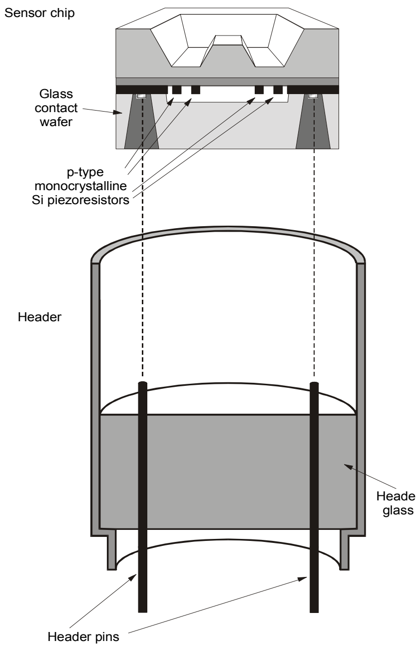
THE LEADLESS PACKAGING

To avoid the use of gold ball bonds and fine gold wires, a high temperature metal frit is used to provide the electrical connection between the sensing chip and a specially designed header. The frit is a mixture of high conductivity metal powders in appropriate physical form and glass, and is used to fill the holes in the cover wafer after it is attached to the sensor chip (**Figure 6**).

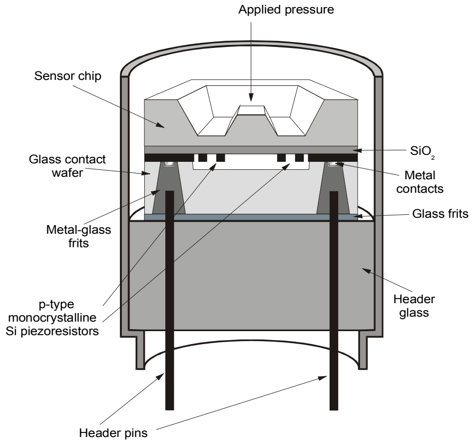
The specially designed header contains a group of four hermetically sealed pins protruding from its surface, which are spaced so as to fit the holes drilled in the cover wafer. The leadless sensor is bonded to the header at a high temperature using a non-conductive glass frit, and during this process the metal frit 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. **Figure 7** shows the mounting process of a leadless chip onto a header and also a section of the pressure capsule mounted in the header.

Previous work [7,8] described transducers essentially assembled by these methods that were evaluated up to 580°C (1075°F) and to 593°C (1100°F) respectively.

Figure 7



SENSOR CHIP AND HEADER BEFORE MOUNTING



CROSS-SECTIONAL VIEW OF THE LEADLESS SENSOR MOUNTED IN THE HEADER

However, by varying the composition of the metal frit and its firing characteristics, and through continuous improvement in the metallisation scheme used in the contact regions, significant improvements in high temperature reliability were obtained. The utilized leadless method allows the tip of the transducer to operate at temperatures in excess of 607°C (1125°F). Once the chip is mounted onto the header, and the electrical interconnections are established, only the non-active side of the diaphragm is exposed to the pressure media. 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.
The hermetically sealed pressure-sensing capsule bonded to the header is the starting point for the assembly into a pressure transducer. Typically most transducers must be attached to a mounting surface, which is exposed to the pressure media frequently by means of a threaded port. In addition, the header pins must be electrically connected to a high temperature cable assembly without the use of solder joints, which may fail at high temperatures. The high temperature cable assembly must also contain material which will provide electrical insulation between individual leads, while the interconnects between the header and the cable as well as the cable itself must be strong enough to withstand the mechanical stresses of handling. The package is completed using a building block approach and **Figure 8** shows the assembly of a typical ultra high temperature leadless pressure transducer [8].

A sleeve is welded between the first header and a second header. A high temperature (HT) cable containing nickel wires is used to interconnect to the pins from the first header. The exposed leads from the first header are welded to the second header to ensure low resistance electrical connections between the leads of the HT cable and the header leads. The header/ HT cable assembly is then inserted into a port and welded to the port. At the end of the port is a tubulation, which is crimped to secure the HT cable. A cover sleeve is then assembled over the HT cable to give additional support and is welded to the rear of the cover, which in turn is welded to the port.

STATIC PERFORMANCE

Test data from the latest generation of manufactured leadless transducers ranging from 5 PSI up to 1000 PSI have confirmed the original results and, in fact, has demonstrated operability of these sensors up to and above 600°C (1100°F). The new leadless SOI sensors were tested up to 607°C (1125°F). This data, as shown in **Figure 9**, was extremely stable and repeatable. The units, compensated with a single span resistor, exhibited excellent span and zero shifts over the entire temperature range from room temperature to 607°C (1125°F), and reconfirmed the previously reported data where devices have shown to have excellent performance characteristics. All units tested exhibited only minor changes in performance characteristics after repeated exposure to high temperatures.

DYNAMIC PERFORMANCE

The design of the high temperature sensor is such that it should have high frequency response characteristics similar to those of more familiar, low temperature capability Kulite sensors. To verify this experimentally, a Dynamic Response Time Testing was performed using a shock tube. A shock tube is an apparatus where a pressure medium is separated into two chambers that are isolated by a Mylar diaphragm. The device under test is mounted at the end of the first chamber with its pressure-sensing element exposed to the inside of the chamber. A specified pressure level is applied to a second chamber and the Mylar diaphragm, which separates the two chambers, is ruptured using the shock tube control system. This produces a square wave pressure pulse that travels through the first chamber and excites the pressure-sensing element of the device under test. The dynamic response of the device under test is captured on a digital storage oscilloscope.

Figure 8

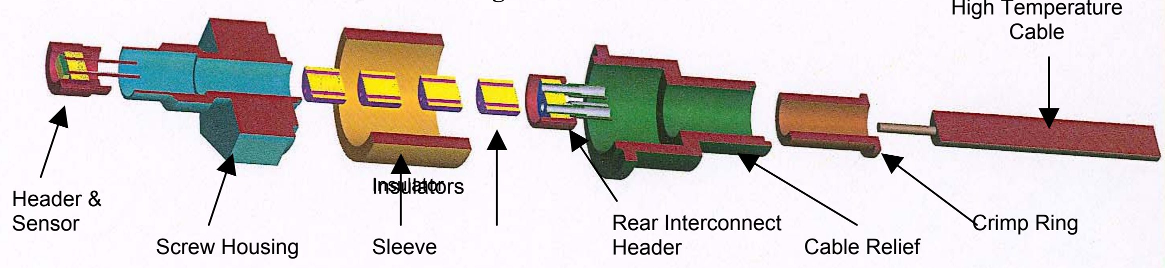
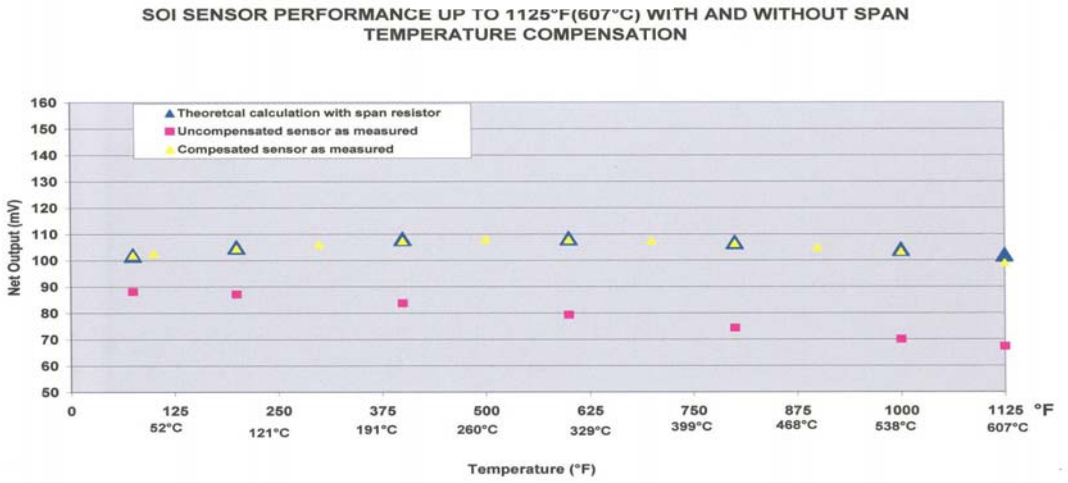


Figure 9



To test the dynamic response time of the latest leadless sensors a number of leadless high temperature devices were evaluated by mounting them to the end of the first chamber and applying a pressure source in the second chamber. The shock tube control system pierced the diaphragm, which sent a square wave pressure pulse to the device under test.

The dynamic response of the device was captured on the digital storage oscilloscope, which was recorded to be from 150 KHz up to 1 MHz for sensors ranging from 5 psi up to 1000 psi.

MECHANICAL ROBUSTNESS EVALUATION

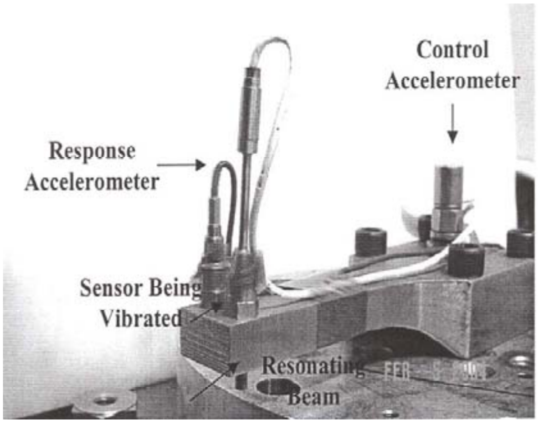
In order to evaluate the robustness of its transducers, Kulite has developed and established its own testing and evaluation technology. Using standard vibration test apparatus, accelerations up to 50G can be achieved, in the 100 Hz to 3000 Hz range. In order to test components to significantly higher G levels, a resonant beam apparatus is used to achieve the high acceleration levels on standard vibration test equipment.

The beam is designed to amplify the acceleration level around the beam's resonant frequency with an amplification essentially being the Q of the system. The resonant frequency is chosen based on design requirements at the high acceleration level.

Typically, aircraft structures have the highest G requirements at about 1,000 Hz and the beam dimensions, such as length and cross section, are selected to achieve the frequency and amplification required. The beam is fastened to the vibration table as shown in **Figure 10**, allowing the low acceleration levels to act as the system input. The device under test, which will experience the amplified G level, is placed at the end of the beam. The amplification can be in the order of 10 to 250 times.

Two accelerometers were used on the beam to measure the vibration (acceleration levels). Accelerometer #1 was used to sense the shaker- produced vibration, while accelerometer #2 was used to measure the amplified vibration levels. A number of leadless transducers were evaluated by being mounted on the beam next to the measuring accelerometers (#2) followed by the beam being vibrated at its resonant frequency (at approximately 1100Hz) with a G of 2-50 in the shaker. By varying the beam dimensions, various Q's were obtained, thus enabling application of up to 1000G to the sensors. All transducers were held at these high vibration levels for two hours without any sign of degradation.

Figure 10



For applications where extremely high levels of acceleration or vibrations are present and low amplitude dynamic pressures are required to be measured, an Acceleration or Vibration Insensitive leadless sensor design can be incorporated.

ACCELERATION INSENSITIVE SENSOR

The acceleration insensitive sensor is a variant of the leadless technology described earlier, except that the chip is produced using two stress-deflecting diaphragms mounted adjacently, as opposed to one. On each diaphragm, a half Wheatstone bridge is formed using two piezoresistors in series. One piezoresistor of each pair increases in resistance with a positive normal stress to the plane of the diaphragm whilst the other decreases. The two diaphragms are both exposed to the inertial stresses (vibration and centrifugal acceleration induced), but only one is exposed to the pressure to be measured (see **Figures 11 and 12**).

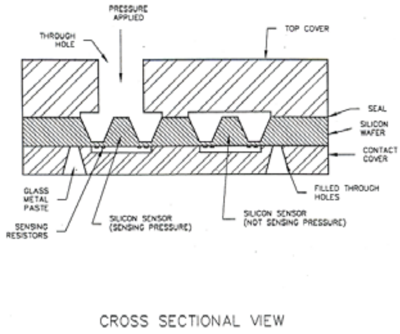


Figure 11 Cross Section of Acceleration Insensitive Sensor

The two half-bridges from each diaphragm are electrically coupled to form a full-bridge such that for a positive stress applied substantially normal to both diaphragms, the bridge output of 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 (and indeed any stress other than that due to pressure) applied to both diaphragms is cancelled out. Complete cancellation is dependent on the two deflecting diaphragms having exactly the same size, thickness, with matching piezoresistive characteristics.

The pressure and temperature sensitivities of six 'g-insensitive' sensors were investigated in Oxford (Ainsworth et al, 2000 [9]). using a computer controlled environmental chamber. These experiments have enabled the measurement of the following sensor characteristics: span sensitivity, offset sensitivity, fractional slope sensitivity and the temperature coefficient of bridge resistance.

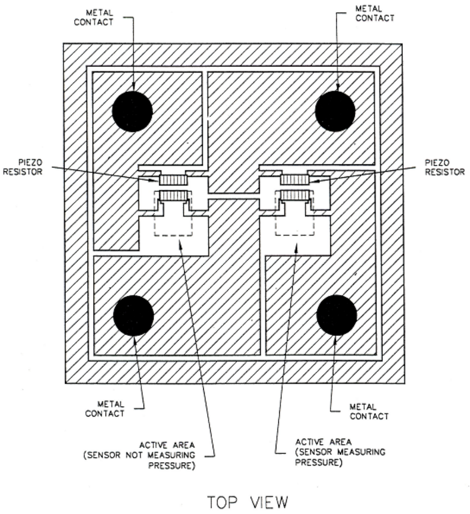


Figure 12 Plan view of Acceleration Insensitive Sensor

The experimental work involved the rotating of both conventional and acceleration insensitive sensors in a spinning rig and observing the outputs from both sensor types via a slip ring for "g" levels up to 5000g

A typical plot of the transducer outputs as the spinning rig is accelerated to the maximum speed of 4300 RPM is shown in **Figure 13**. The maximum change in voltage during the test is -4 μV which represents an acceleration sensitivity of approximately 1E-6 % (0.000001%) of full-scale per g. The data which was simultaneously recorded from a 'conventional' sensor shows a linear relationship between sensor output voltage and acceleration. The acceleration sensitivity is 4E-4 % (0.0004%) full-scale per g, which is in close agreement with the figures quoted in Kulite literature.

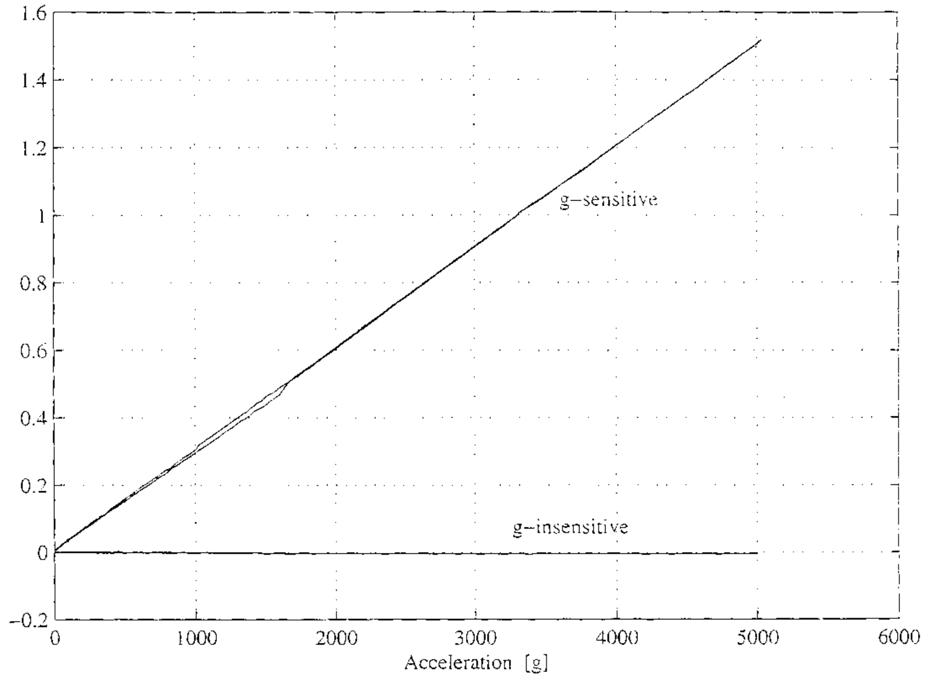


Figure 13 Sensor Signal Output v Centrifugal Acceleration (for "g-insensitive" & "conventional" sensors)

CONCLUSIONS

As part of an ongoing effort to increase both the temperature operability limit and the performance characteristics of the piezoresistive transducers, the latest generation of leadless sensors has been designed, fabricated, and evaluated at Kulite with very encouraging results.

These sensors have been demonstrated to:-

1) operate up to and above 607°C (1125°F)
2) exhibit excellent static and dynamic performance characteristics
3) withstand very high G-level (acceleration) without any signs of degradation.

The acceleration compensated design of leadless SOI pressure transducer has demonstrated a reduction in g sensitivity of 400 times and is available as an option in most sensor designs.

The SOI technology combined with the leadless packaging approach create an opportunity to push the silicon-based sensors to operating temperatures previously thought to be impossible. An effort to increase such temperature capability to even higher levels is presently underway. The results of this work will be subject of future technical papers.

REFERENCES

[1] A.D. Kurtz, "Development and Application of High Temperature Ultra Miniature Pressure Transducers", Fundamentals of Aerospace Instrumentation (ISA) Volume 3 1970.

[2] A.D. Kurtz, A.A. Ned, US Patent #5,286,671 issued to Kulite Semiconductor Products, Inc., Leonia, NJ 1994.

[3] A.A. Ned, A.D. Kurtz, "High Temperature Silicon on Insulated Silicon Pressure Sensors with Improved Performance Through Diffusion Enhanced Fusion (DEF) Bonding", International Instrumentation Symposium, Reno. NV, June 1998.

[4] A.D. Kurtz, A.A. Ned, US Patent #5,955,771 issued to Kulite Semiconductor Products, Inc., Leonia, NJ 1999.

[5] Dr. Anthony Kurtz, Alexander A. Ned, Robert Gardner, Scott Goodman, "Ruggedized High Temperature Piezoresistive Transducers", 45th International Instrumentation Society, Albuquerque, NM May 1999

[6] Dr. Anthony Kurtz, Alexander A. Ned, Dr. John W.H. Chivers, Dr. Alan Epstein, "Further Work on Ruggedized High Temperature Piezoresistive Transducers for Active Gas Turbine Engine Control", International Instrumentation Symposium, Seattle, WA, May 2000.

[7] Anthony D. Kurtz, Alexander A. Ned, Scott Goodman, Professor Alan H. Epstein, "Latest Ruggedized High Temperature Piezoresistive Transducers", NASA 2003 Propulsion Measurement Sensor Development Workshop, Huntsville, Alabama, May 13-15, 2003

[8] A.D. Kurtz, Scott Goodman, Robert Gardner, US Patent #6,363,792B1 issued to Kulite Semiconductor Products, Inc. Leonia, NJ 2002.

[9] Ainsworth, R.W., Miller, R. J., Moss R.W., and Thorpe, S.J., 2000, "Unsteady Pressure Measurement", Meas. Sci. Technol. **11** pp1055-1076.