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AMPLIFIED PRESSURE TRANSDUCERS USING SOI SENSORS AND SOI ELECTRONICS, SUITABLE FOR HIGH TEMPERATURE OPERATION (250°C)

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ABSTRACT

In an effort to improve efficiency, reliability and reduce costs, engineers are moving towards distributed control systems on trains, cars, planes and other systems in place of centralized control systems. In a distributed control system, sensors, processors and actuators are all located together at remote locations [1]. Distributed control systems require significantly less cabling which leads to weight reductions and therefore cost and energy savings. To implement distributed control, in many applications sensors and their electronics must be able to withstand higher temperatures. Kulite Semiconductor Products has therefore developed a high temperature amplifier to be coupled with high temperature pressure sensors. While the suitable sensing technologies have been under the development for some time, the development of an Application Specific Integrated circuit (ASIC) utilizing SOI technology is now introduced and optimized. This paper reports on the latest developments of the Silicon-On-Insulator (SOI) piezoresistive sensors, the SOI application specific integrated circuits (ASICs) and the high temperature packaging of the two together. The design of the latest miniature amplified-pressure transducers capable of operating reliably under extreme environmental conditions (in excess of 250°C and under accelerations of greater than 200g) is described in detail. The performance of such amplified pressure transducers is presented and indicates that ruggedized, piezoresistive transducers with excellent static and dynamic performance characteristics are capable of operation in extremely harsh, high temperature environments.

INTRODUCTION

A large number of applications across numerous industries require amplified pressure measurement in harsh environments and high temperatures. In order to facilitate such measurement: the sensing technology, the electronics and the packaging must all be suitable for these environments.

For years significant efforts were in place to develop pressure transducers capable of withstanding most severe environmental conditions including extreme temperature. These achievements were made possible through continuous development of our Silicon-on-Insulator (SOI) piezoresistive sensors, advanced packaging materials and techniques as well as the introduction of innovative compensation methods. Silicon is an excellent material for sensor fabrication due to its piezoresistive gauge characteristics and its overall mechanical capabilities. It was discovered that degeneratively doping silicon to form piezoresistive gauges on an insulating layer reduces temperature sensitivity and provides for significant temperature stability [2]. This results in a device that exhibits no electrical leakage between itself and other gauges, or to the semiconductor substrate, up to and above 600°C [3], plus as a majority carrier device the presence of thermally generated carriers has much less effect on the gauge's operation when compared to other electrical components. The gauge factor, resistivity, and all other electrical characteristics remain exceptional up to and above 600°C. Silicon is an excellent high temperature structural material that does not plastically deform, at the used stress levels, in excess of 600°C [4,5]. Silicon carbide (SiC) piezoresistive sensing technology may seem to have a advantage due to its even higher maximum temperature operational capability, but SOI sensors fabricated out of silicon are a much more mature technology, with easier fabrication capability, and exhibit significantly better overall piezoresistive characteristics. The latest SOI sensor technology is clearly capable of operation at high temperatures, and is shown to be suitable for various high temperature packaging schemes targeted for 250°C operation.

An integral part of a high level output sensor is the signal conditioning electronics. In traditional electronics the individual circuit components are isolated by reverse biased PN junctions [6]. At high temperatures the leakage currents of these PN junctions double approximately every 5°C, eventually becoming so large that the circuit becomes unusable [7]. The SOI integrated circuits either eliminate or drastically reduce the amount of isolation junctions in the circuits thus achieving a much higher operational temperature. While high temperature SOI electronics currently are commercially available, they consist of discrete circuit components, such as op-amps, regulators, and individual components. While it is possible to construct a hybrid circuit out of these components to achieve a signal conditioner, the size of this device would prohibit its use to the larger size sensors. To overcome this limitation and to fully compliment the SOI pressure sensing capabilities, the SOI, application specific integrated circuits were developed similar to the SOI sensors, using dielectric isolation of the individual components of the integrated circuit (transistors, resistors, etc.) [8].

This paper presents the latest development in the SOI piezoresistive sensor arena, and combines the capabilities of the SOI sensors with the advantages of the SOI integrated electronics. The various SOI piezoresistive sensor technologies, the latest SOI electronics and the latest associated packaging methods are all separately discussed in this paper. The technical challenges that were overcome are presented and discussed. The high temperature sensing sub-assembling and the electronics sub-assemblies are manufactured separately and integrated using a modular building block packaging approach. Performance of the latest miniature amplified transducers suitable for high temperature harsh environment operability is presented and addressed. Amplified pressure measurement in extreme environments upto 250°C is clearly demonstrated.

SOI PIEZORESISTIVE SENSORS

The piezoresistive silicon technology has been a subject of significant on-going improvement [9]. The latest evolutions of high performance sensors, including: 1) the leadless sensor, 2) oil filled sensors, and 3) the glassed gauged metal diaphragm sensors all use the latest silicon on insulator (SOI) technology [10,11].

In a typical SOI sensor the 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 induced in the silicon diaphragm as it deflects, the stress increasing linearly as a direct function of the applied pressure.

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, eliminating any need for a bonding layer that gives rise to creep, offset or slippage.

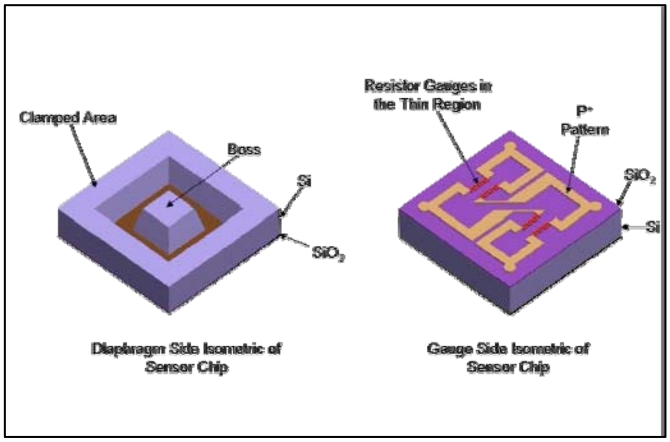

Figure 1: Isometric view of the SOI sensor.

The presence of a dielectric layer provides electrical isolation thus enabling the sensor to function at very high temperatures without any current leakage effects associated with the p-n junction type isolation. Since the device is capable of operating at high temperatures, a high temperature metallization scheme is introduced to enable the device to interface with the header at these high temperatures as well.

This SOI sensing technology is ideally suited for both the leadless and the oil-filled transducer construction. This SOI sensing technology also applies to gauged metal diaphragm transducers, wherein the piezoresistive silicon-on-insulator strain gauges are interconnected in a Wheatstone bridge configuration, and are electrically isolated from the thin silicon carrier substrate (patch). The thin patch containing the entire dielectrically isolated piezoresistive network is micromachined using a combination of dry and wet etching process. In this approach, rather than being bonded to the silicon diaphragm, these SOI sensing patches get attached to the metal diaphragms via a thermally matched Pyroceram glass.

LEADLESS SENSOR DESIGN

In the semiconductor sensor industry, the standard method of providing electrical connections between a sensor chip and the package is by wire bonding. In addition, with a traditional design 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 media. The key elements in the design of a ruggedized pressure sensor is the protection of these sensor components elements from corrosive environments at high temperatures, hence the reference to the new sensor capsule as the leadless design [12,13,14].

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 when assembled form the pressure capsule.

In the leadless design (Figure 2) the sensor chip contains four piezoresistive gauges strategically positioned inside the sensing diaphragm region and connected together in a Wheatstone bridge. The entire sensing network is hermetically protected (sealed) within an evacuated cavity.

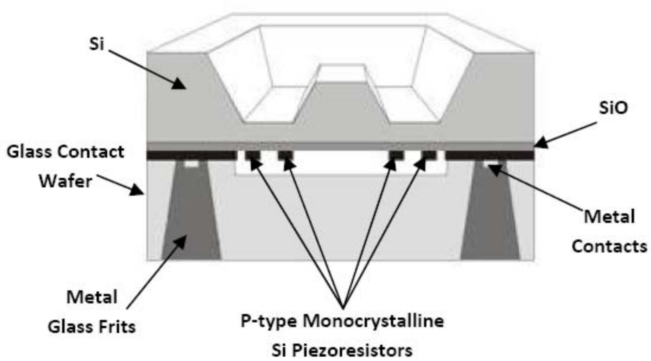

Figure 2: "Leadless" sensor chip (side view).

The leadless sensor is bonded to the header at a high temperature using a combination of conductive and non-conductive glass frits. During this process the conductive frit creates low resistance electrical connections between the header pins and the metal contact pads on the sensor chip, while the non-conductive glass secures the sensor in place. Figure 3a shows the mounting process for a leadless chip attaching to a header. Figure 3b shows a section of this pressure sensing subassembly.

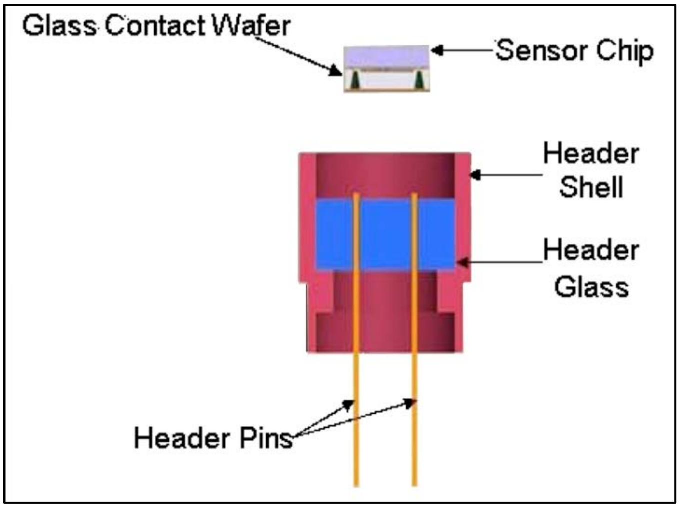

Figure 3a:
Sensor chip and header before mounting.

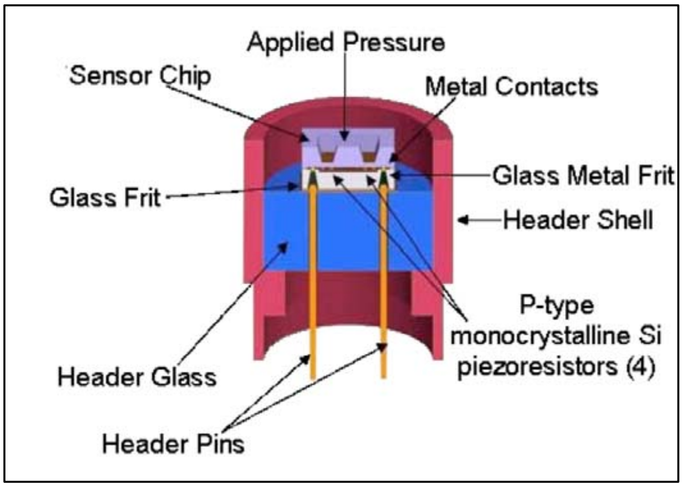

Figure 3b:
Cross-Sectional view of the leadless sensor mounted in the header.

With the leadless approach [15,16] 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 entire sensor network, contact areas, and electrical interconnections are hermetically sealed from the environment and the pressure media.

The leadless sensor chips were redesigned specifically for integration with SOI electronics. The following Wheatstone bridge characteristics where targeted. The input and output impedance, zero offset voltage, zero offset voltage thermal shift, sensitivity, gauge factor, and gauge factor thermal shift were all specifically optimized for integration into a high temperature amplified sensor.

The completed leadless sensor subassemblies were also redesigned to be ideally suitable for integration with the high temperature electronics.

METAL DIAPHRAGM SENSING APPROACH

In addition to the leadless sensing technology, the metal diaphragm sensing approach is well suited for harsh environmental, high temperature operation. There are two principal methods for manufacturing traditional metal diaphragm transducers.

i) "Oil-Filled Sensor" Design

The "oil-filled" method utilized a thin metal diaphragm which is mounted in front a piezoresistive pressure sensor with a small cavity between the sensor and the diaphragm. The cavity is then filled with a non-compressible fluid such as silicone oil. When the pressure is applied to the metal diaphragm, it undergoes a slight deflection. Since the fluid is non-compressible, the pressure is thus fully transmitted to the piezoresistive sensor. As long as the oil retains its non-compressibility, the transducer operates properly. The temperature limitation of the oil itself limits the temperature capability of the transducer to about 250°C.

ii) "Gauged Metal Diaphragm Sensor" Design

The "gauged" method for manufacturing a metal diaphragm pressure transducer relies on affixing strain gauges directly onto the metal diaphragms with either epoxy or glass. In this method, the gauges are located on the side of the deflecting metal diaphragm opposite that from which the pressure media is applied. Strain gauges affixed to the diaphragms can be of either the metal-foil or semiconductor type. Regardless of type, the gauges must be placed onto the diaphragm at specific positions and individually affixed to the diaphragm. For a full-active Wheatstone bridge, four separate gauges must be affixed to each diaphragm. Because of the required precision in positioning the gauges, mounting of the gauges can be a time-consuming task. Thus, when the pressure is applied to the diaphragm, it deflects and the piezoresistive gauges directly measure the amount of strain on the diaphragm. In this way, as compared to the "oil-filled" design the operational temperature is no longer limited by the non-compressible fluid's thermal characteristics.

In the latest "gauged" metal diaphragm approach [17], a complete Wheatstone bridge, consisting of four piezoresistive strain gauges, is used instead of individual gauges (Figure 4). The piezoresistors are arranged on a patch so that two of them are near the edges of the diaphragm, while the other two are near its center. In this way, two resistors are in compression and two are in tension. Furthermore, the Wheatstone bridge arrangement converts a strain into a voltage output that is proportional to the applied pressure. The strain gauge bridge patch uses the latest SOI technology to provide the necessary dielectric isolation between the gauges, and the metal diaphragm.

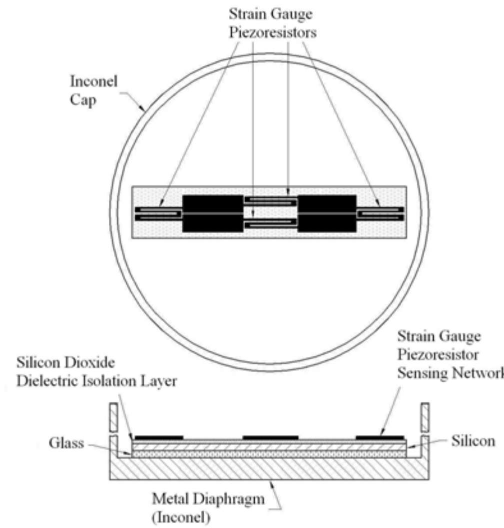

Figure 4:
Piezoresistive SOI wheatstone bridge affixed to an inconel cap.

In this SOI integrated piezoresistive sensor, where the four strain gauges of a Wheatstone bridge are fabricated on a common substrate, electrical isolation between the piezoresistive strain gauges and the substrate is critical for proper device operation. Without such isolation, parasitic leakage currents through the substrate would cause errors. SOI technology solves this issue by providing a thin layer high quality SiO_2 between the piezoresistors and the substrate. The SiO_2 layer is an effective electrical insulator at temperatures far exceeding the 500°C.

After the SOI strain gauge sensing element (patch) is mounted to the metal diaphragm using high temperature, thermally matched, non-conductive glass, the diaphragm is then welded to the transducer body, this the sensing element is hermetically protected from the pressure media. Shown in Figure 5 is a typical subassembly drawing for this type of devices.

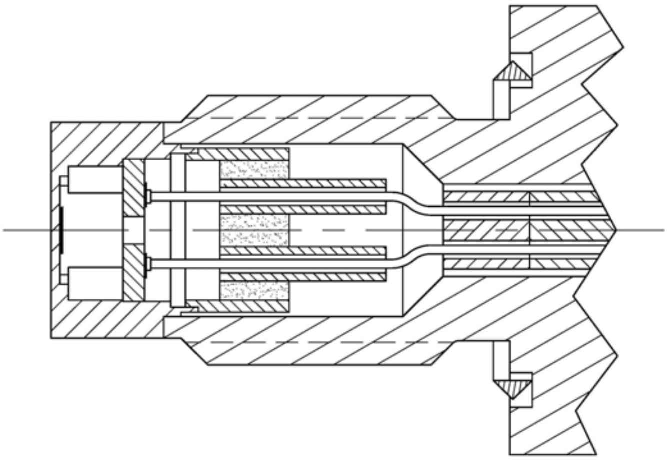

Figure 5:
Subassembly drawing.

SOI ELECTRONICS (ASIC)

Traditional PN junction based electronics are not suitable for operation above 175°C where the leakage of the PN junctions, which are used to electrically isolate individual components of the circuit, becomes significant and leads to failure. In order to obtain electronics operational at higher temperatures a SOI technology was selected [18,19,20]. Additionally, in order to accommodate a small size, an integrated circuit was pursued rather than the use of separate individual SOI components. Recent developments in SOI technology, allow these integrated circuits reliable operation at temperatures in excess of +250°C. A custom SOI Application Specific Integrated Circuit (ASIC) designed to work with the SOI sensors was developed. There were a number of design iterations that took place to overcome the many technical obstacles that appeared during the ASIC's development. The first obstacle overcome was the stability of the bandgap reference circuit over the extended operational temperature range. This was achieved by computer simulation work allowing the correct circuit topology and components to be selected. The next obstacle was the operation of the signal conditioning circuit over the entire operational temperature range. Test data revealed that the operational amplifiers (OpAmps) zero offset voltage and the voltage gain where not linear or monotonic with temperature over the operational temperature range, Test data was accumulated through experimentation, and this information lead to a circuit redesign of the amplifiers input stage utilizing specific transistors to solve the problem. Parasitic currents also proved to be problematic during the ASIC's development and this problem was solved by circuit redesign isolating specific components to alternate locations on the silicon substrate. The stability of the IC's resistors over temperature was an additional problem to be overcome in the development of the signal conditioning amplifier. To achieve this goal the circuits were designed to rely on ratios of resistors as opposed to individual resistor values, utilizing the fact that all the resistors on the substrate have generally the same temperature coefficient so that while an individual resistor changes its valve over temperature the ratio of resistors stays constant.

One final issue encountered with the use of the SOI signal conditioning electronics was associated with the thermal mismatch of the on-the-chip resistors temperature coefficient of resistance (TCR), to the off-chip resistors TCR value. These off-chip resistors are used to set the voltage gain and the offset voltage of the amplifier. The on-the-chip resistors (used in the SOI process) have a very large TCR of up to 1500ppm/°C. The external resistors have a much lower TCR of less than 50ppm/°C. This large TCR mismatch would have resulted in a sensitivity of the output voltage to temperature level, which is an undesired effect in a pressure sensor. Special circuitry and other techniques were developed to reduce the effect of the TCR mismatch between the two types of resistors while allowing the standard compensation and output normalization of the transducer to take place [21].

Another limitation of the SOI electronics is due to the aluminum metallization of the bonding pads. When the circuit is connected to the pins of the package using standard gold wire bonding at high temperature, this aluminum-gold structure fails over time at temperatures in excess of +225°C, due to the formation of a gold-aluminum intermetallic layer. This effect, commonly referred to as purple plague, causes the gold ball bond to detach from the aluminum pad. In order to eliminate this, we introduced the pad metallization, on the SOI ASIC, similar to the one used for the SOI piezoresistive pressure sensors interconnection pads. This Platinum metallization uses several layers of metal films, to achieve a reliable, packaged device capable of operating in excess of 250°C. The top layer of aluminum is replaced with high purity platinum layer to which the gold wire bonds are subsequently attached. The Gold-Platinum interface completely eliminates the purple plague issue.

The diagram for the SOI ASIC is shown in Figure 6, while a picture of the die is shown in Figure 7. The main subcomponents of the ASIC are:

- Preregulator – regulates the high input voltage to +12V
- Precision voltage reference – generates a stable supply voltage for the piezoresistive bridge

- Instrumentation amplifier – provides signal amplification and differential output
- Gain control circuit – allow gain adjustment without external resistors
- Summing amplifier – converts the instrumentation amplifier output to single ended output

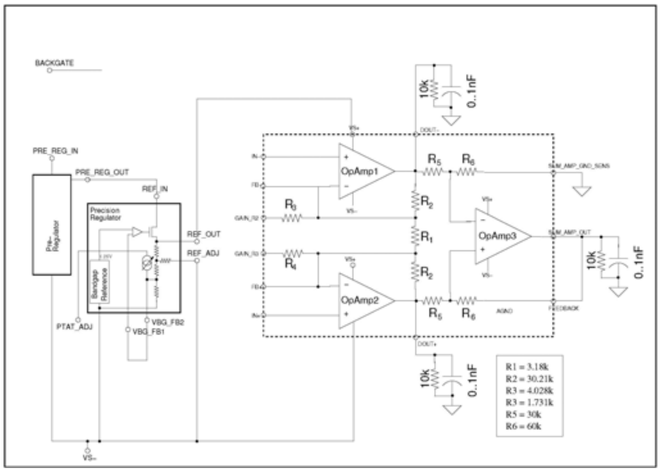

Figure 6:
Diagram of SOI electronics.

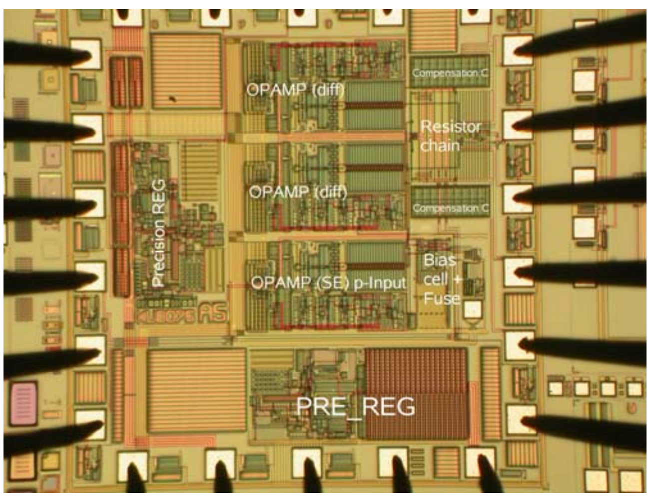

Figure 7:
Picture of SOI ASIC die.

The developed SOI ASIC has been rigorously tested as a function of temperature and time. As part of this testing: Zero offset, Gain and VREF were evaluated. Zero offset is the output voltage reading at a zero input voltage level. Electronic amplifier gain refers to the ratio of the output voltage to the input voltage level, and VREF refer to the portion of the electronics that produces a fixed (constant) voltage irrespective of the resistive loading of the device, the power supply voltage level, and ambient temperature level. It can be seen from Figures 8a, 8b, and 8c that the SOI ASIC operates with consistent performance characteristics up to 500°F (260°C). Further, the ASIC performance remains stable over time. At the aggressive temperature of 250°C, the SOI ASIC continued operating for over 400 hours without deviation (Figure 9). This is the extreme operating temperature limit, and significant longer operating life is achieved at reduced high temperature levels. For example, long-term testing at 225°C was performed for 1000 hours with no deviation in performance. Overall, the developed SOI ASIC was found suitable for high temperature use in pressure transducers.

The resulting transducer utilizing this high temperature SOI ASIC is designed to have significant advantages over other existing transducers:

- High level output, e.g. 5V
- High temperature capability, up to +250°C
- No need for regulated input power, due to its internal regulator
- High bandwidth (15 KHz at room temperature) (Figure 8d)
- DC and AC response
  Very small size

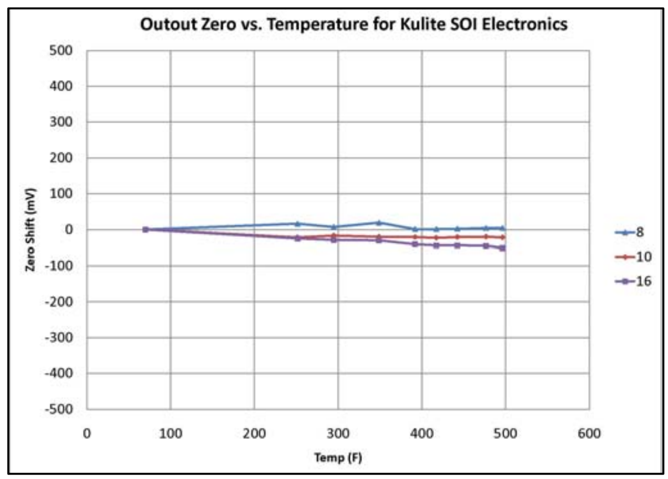

Figure 8a: Output Zero vs. Temperature for Kulite SOI Electronics.

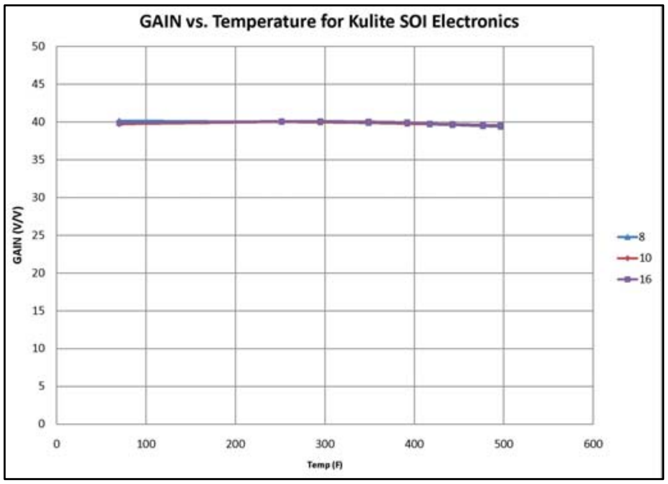

Figure 8b:
GAIN vs. Temperature for Kulite SOI Electronics.

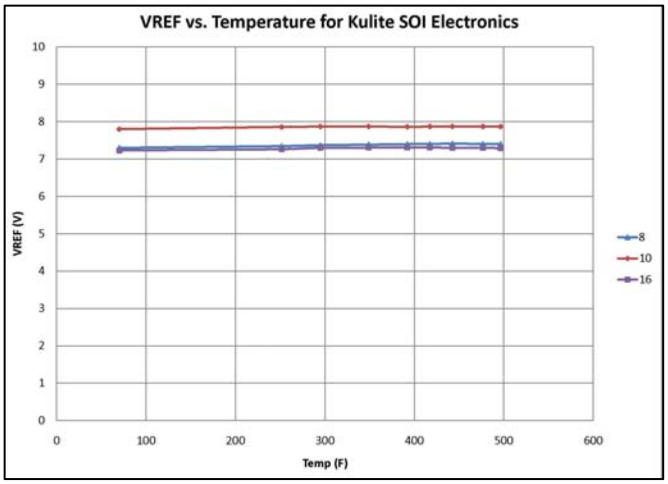

Figure 8c: VREF vs. Temperature for Kulite SOI Electronics.

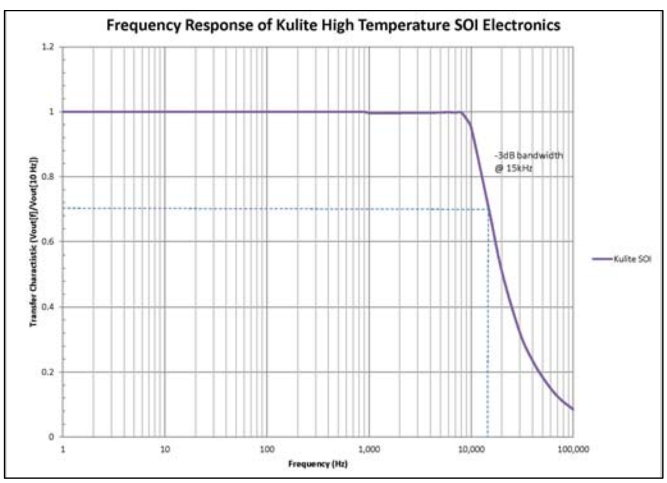

Figure 8d:
Frequency Response of Kulite SOI Electronics.

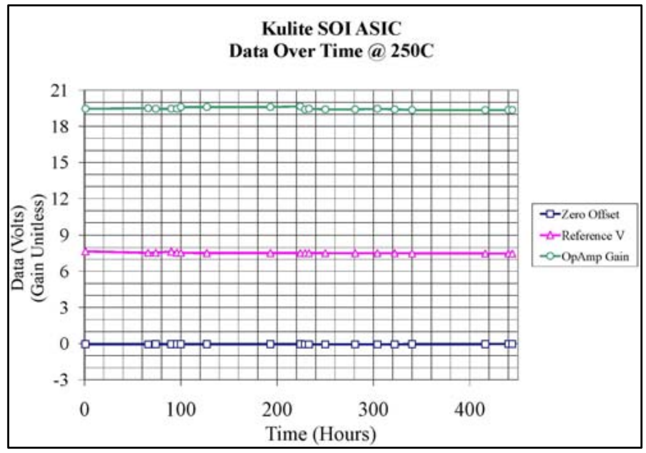

Figure 9:
Kulite SOI ASIC.

TRANSDUCER PERFORMANCE
All three types of amplified high temperature transducer designs were assembled and evaluated. All three of the designs utilize the same SOI electronics subassemblies, but contain different pressure sensing front ends.

i) ETL-UHT-375
The leadless based, amplified transducer construction, shown in Figures 10a and 10b, is suitable for operation from 25 PSI to 1000 PSI with excellent performance characteristics. A screen is typically utilized in this design to provide protection from mechanical damage.

Figure 10a

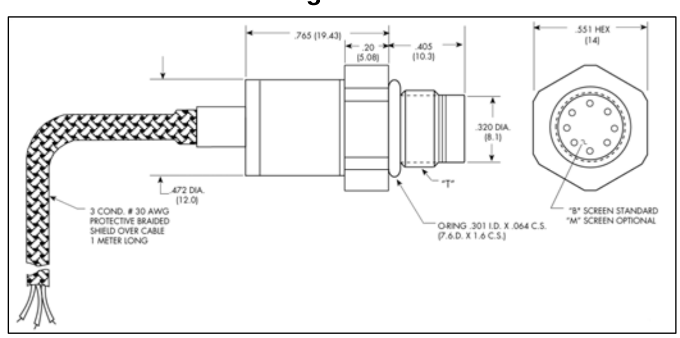

Figure 10b

ii) ETM-UHT-375
The oil-filled based, amplified transducer construction is suitable for operation from 100 PSI to 20000 PSI with

excellent performance characteristics. Although not being able to go to low pressure, this construction offers a more rugged approach than the leadless option and enables performance in applications where silicon is susceptible to chemical attack by the media being measured, or susceptible to damage caused by kinetic impact from partials within the media. The outline of the oil-filled amplified transducer is identical to that of the leadless ETL-UHT-375 and thus the two can be interchangeable. A screen is typically utilized in this design to provide protection from mechanical damage.

iii) ETMER-UHT-375

The glassed gauged metal diaphragm, amplified transducer construction, shown in Figures 11a and 11b, is suitable for operation from 500 PSI to 20000 PSI with performance characteristics comparable to the ETM and ETL counterparts, while providing ultimate environment capability. The outline of the glassed gauged metal diaphragm transducer is identical to that of the leadless ETL-UHT-375 and to the “oil-filled” ETM-UHT-375.

Thus, all three designs are interchangeable. However, a screen is not utilized in the ETMER-UHT-375 design since the thick metal diaphragm is typically found to be adequate in providing protection from mechanical damage.

Figure 11a

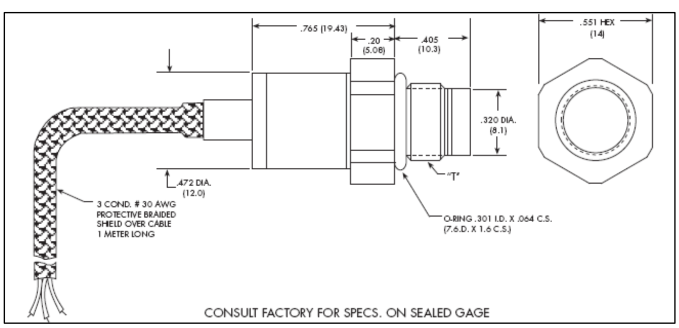

Figure 11b

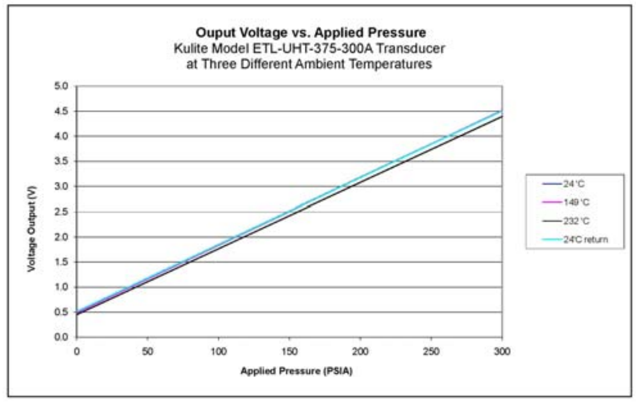

Figure 12:
Output Voltage vs. Applied Pressure for three different ambient temperatures.

These transducers have a high level output of 0.5V to 4.5V, with very good output characteristics over a wide temperature range upto 250°C. As can be seen, these transducers also display high linearity, and very good repeatability, in a very small hermetic package (Figure 12).

CONCLUSION

The development and optimization of the various SOI based piezoresistive sensing technologies and the development of SOI ASICs suitable for use with these high temperature sensors paved the way for the introduction of the miniature amplified high performance transducers to serve in high temperature, harsh environments. Three unique sensing technologies have been developed as alternative transducer constructions: 1) the leadless sensor, 2) oil filled sensor, and 3) the glassed gauged metal diaphragm sensor. The selection of the sensing methodology utilized would be up to the end users preference. The performance of these amplified transducers has been demonstrated, and shown to achieve good characteristics over a wide temperature range. The output linearity, hysteresis, and repeatability are also shown to be very good. The thermal cycling and long term stability studies are presently underway and will be presented upon completion.

The purpose of developing three different front-end sensing technologies in this work was not only to provide alternatives for various application, but to demonstrate how the newly developed SOI ASIC, can successfully interface across the board.

These new type of amplified pressure transducers using SOI piezoresistive sensors and integrated SOI electronics will have applications in numerous fields requiring amplified pressure measurements in high temperature environments. These applications extend to use in jet engines for screech/stall detection, gas turbines, for oil & geothermal explorations, race car engine monitoring and control, etc.

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