

High Accuracy Piezoresistive Internal Combustion Engine Transducers

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Abstract

The engine test environment is extremely challenging and requires significant amount of incylinder pressure measurements. Because of the extreme temperatures and vibration present in all engine tests the transducer selected for this market must be designed to withstand such conditions without any degradation in performance characteristics.

A high accuracy piezoresistive internal combustion engine sensor is developed. This transducer features a small size, capability to perform static and dynamic measurements, high natural frequency for fast data rates, and durability for the extreme engine environment. The device utilizes an innovative transducer design, and a revolutionary "Vibration Insensitive Sensing" VIS™ element. The sensing element is based upon Silicon on Insulator, Leadless technology which enables it to withstand the harsh environment, extreme operating temperatures (500°C), and high vibration in this application. The transducer has a resonant frequency above 150 KHz, and is shown to meet the stringent combustion requirements. On-engine test results are presented and evaluated. Excellent dynamic and static measurements with long term stability and low noise are achieved.

1. Introduction

Many customer requirements for high accuracy combustion sensors clearly indicate the industry wide need for reliable small transducers with high natural frequency capable of operation in extreme internal combustion environments.

Great detail and engineering effort goes into designing the combustion chamber of the engine, for peak performance and efficiency. The sensor must penetrate this chamber wall to measure the pressures during engine operation. As with any measurement system, anything introduced to measure the system, changes the system. This change must be minimized. The small size of the engine sensor is deemed necessary to minimize chamber wall penetration in order to assure minimal changes in the system.

Piezoelectric transducers have been used for this application, with some drawbacks. These sensors require a charge amplifier, to convert the low level piezoelectric signal to higher level signals for data acquisition. In addition, the piezoelectric sensor gives a relative AC signal, that indicates dynamic pressures only, with no DC component. On the other hand, piezoresistive sensors give an absolute pressure reading, so no reference pressure is required. The piezoresistive sensor is capable of static as well as dynamic pressure measurement. Also, the piezoresistive sensor requires no charge amplifier, and can thus be installed in harsh applications.

In order to meet the industry needs for combustion measurements a high accuracy piezoresistive combustion transducer was specifically developed for an engine test application. This sensor features a small size, with a high natural frequency for fast data rates, and durability for the extreme engine environment of heat and vibration. The engine test application demands high data rates and accuracy to determine the efficiency and peak performance. The sensor is designed to be used in engine test cells, or in test track scenarios. Features of the Kulite internal combustion engine transducer include a simple, rugged design capable of high pressures. This design stems from a revolutionary “Vibration Insensitive Sensor (VIS™) Technology” that is based on the Silicon on Insulator Leadless approach. This technology enables the sensor to achieve excellent dynamic performance characteristics, while assuring long term static measurement stability. Both of these features are found to be very important design criteria.

The following sections will explore the construction of the Kulite transducer, piezoresistive technology, silicon on insulator technology, the leadless design, vibration insensitive technology, response time and resonant frequency, and on-engine testing of the transducer.

2. Piezoresistive (SOI) Sensing Technology

For the last 40 years, Kulite has supplied high performance pressure transducers to the automotive industries for both research and development and for production applications.

These transducers are based upon the piezoresistive silicon technology, which Kulite pioneered and developed to its current high levels of performance and reliability. In order to describe the research and development, which has led to the creation of the VIS™ leadless pressure transducer, it is relevant to consider the original silicon-on-insulator (SOI) pressure sensor design¹.

The heart of the piezoresistive SOI pressure sensor is a silicon diaphragm which is supported upon a Pyrex glass 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. An “anodic” molecular bond is used to attach the silicon diaphragm to the glass pedestal which ensures a very stable, permanent assembly without the use of glues or adhesives. Piezoresistive silicon strain gauges are integrated within the silicon diaphragm structure but are electrically isolated from the silicon sensor as shown schematically in Figure 1². The piezoresistors measure the stress in the silicon diaphragm which is a direct function of the pressure of the media³.

SOI TECHNOLOGY

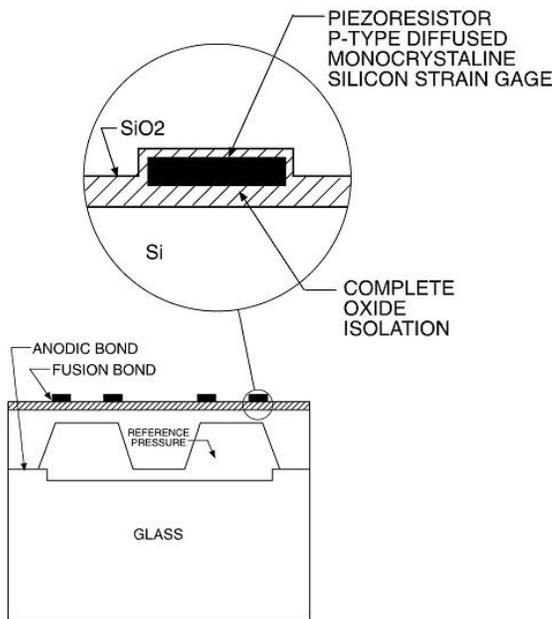


Figure 1: Section of SOI Pressure Sensor

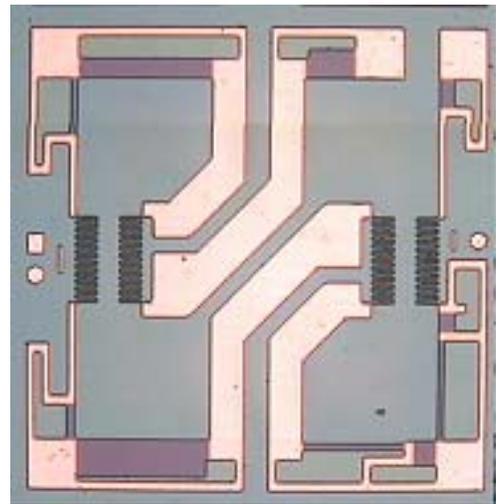


Figure 2: Top-View of Sensor

The silicon diaphragm is usually thinned in selected areas underneath the piezoresistors by anisotropic chemical etching in order to increase the pressure sensitivity of the diaphragm. A photograph of the top of a silicon diaphragm is shown in Figure 2.

The photograph clearly shows the four darker piezoresistors, which are connected electrically via the lighter colored metallic interconnections to form a fully active Wheatstone bridge. At the corners of the diaphragm, five 0.024mm (0.001 inch) diameter gold bond wires would be ultrasonically ball bonded to the sensor metallization to allow electrical connections to the bridge (Figure 3).

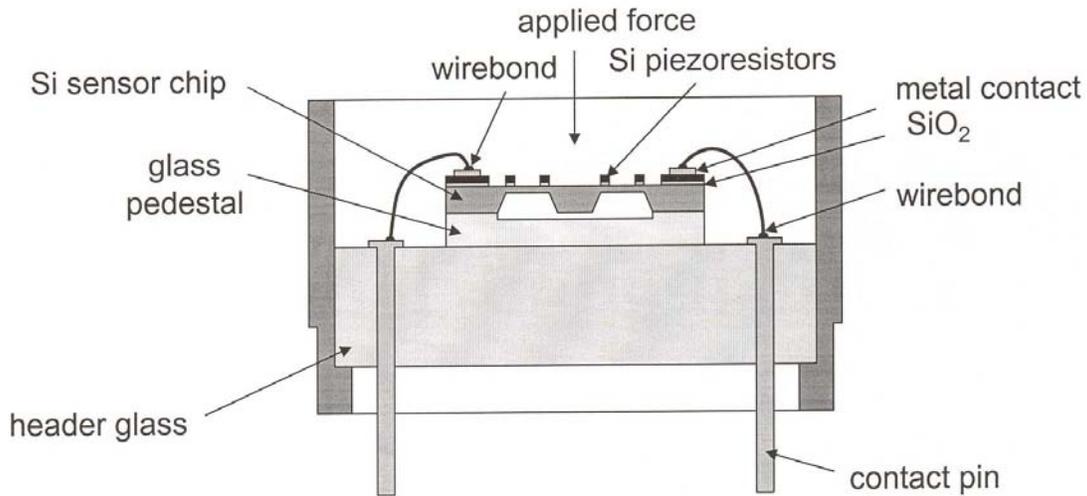


Figure 3 Wire Bonded Sensor

Under extreme conditions of temperature and vibration, the ultrasonic agitation used to form the ball bonds causes abrasion to take place during the welding process and allows microscopic holes to develop in the platinum metallization through which, at high 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 at high temperatures and in the presence of aggressive chemical can fail. The key elements in the design of a ruggedized pressure sensor are the elimination of the gold bond wires and the protection of the sensing elements from harsh environments at high temperatures, hence the reference to the new sensor capsule as the “leadless” design⁴.

3. Leadless Sensor Die Design

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. The sensor chip is manufactured from two separate wafers. First a carrier wafer is fabricated which forms the mechanical structure, the diaphragm. The second wafer is referred to as the sacrificial wafer on which is defined the areas which the high conductivity P^+ piezoresistive strain gauges occupy. After oxidizing the carrier wafer to form an electrically insulating layer over its surface, the two wafers are bonded together using a Diffusion Enhanced Fusion bonding (DEF) process. The bond is a direct chemical molecular bond between the P^+ regions and the silicon oxide and uses no adhesive or additional components. Once the bond is formed, the non-doped areas of the carrier wafer are selectively removed chemically. The piezoresistive P^+ are now permanently bonded to the dielectrically isolated carrier wafer in which the diaphragm is now micromachined.

In order to optimize the mechanical performance of the force collector, the diaphragm is formed in the shape of a picture frame⁵. Figure 4 shows a view of the sensor chip with the four piezoresistive gauges strategically positioned inside the “picture frame” and connected in a Wheatstone bridge. The entire sensing network is P^+ 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 area of P^+ material thus protecting the stress sensing network and all the electrical interconnections from the harsh environmental conditions.

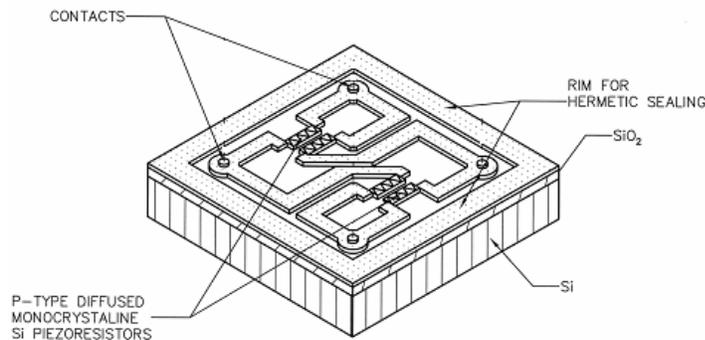


Figure 4: Isometric View of Sensor

The cover wafer is manufactured from either silicon or a Pyrex glass to the same dimensions as the silicon wafer. Four holes are drilled in the cover, one in each corner, which align with the metallized contact pad areas. A recess is also created in the center of the cover wafer to allow the diaphragm to deflect freely when assembled. The sensor chip and the cover wafer are then assembled using an electrostatic bond. Figure 5 shows a top isometric view of the components just prior to sealing. Once the two wafers have been bonded, only the metallized leadout pads are 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.

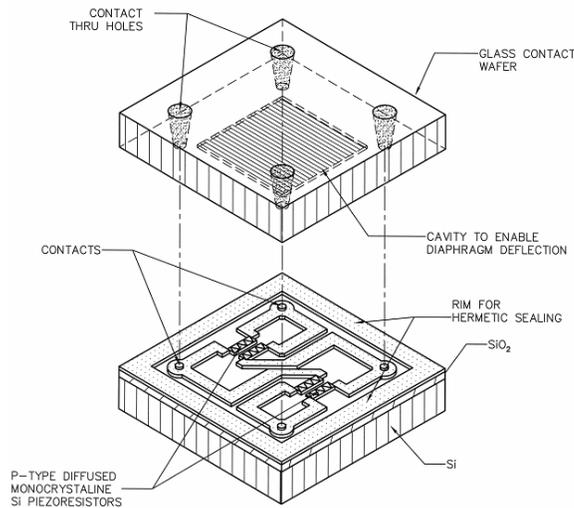


Figure 5: Leadless Sensor Diaphragm & Cover

4. Leadless Sensor Die 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 bonded to the sensor chip.

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. Figure 6 shows a cross-section of the assembled pressure sensor. The pressure sensor is bonded to the header at a high temperature using a non conductive glass frit, during which 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 as shown in Figure 7.

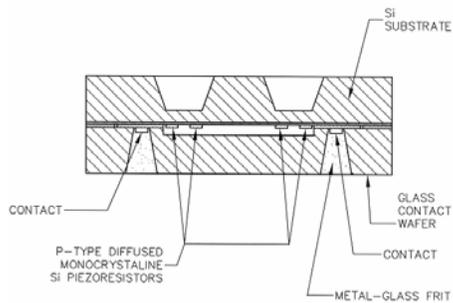


Figure 6: Cross-Section of Leadless Sensor

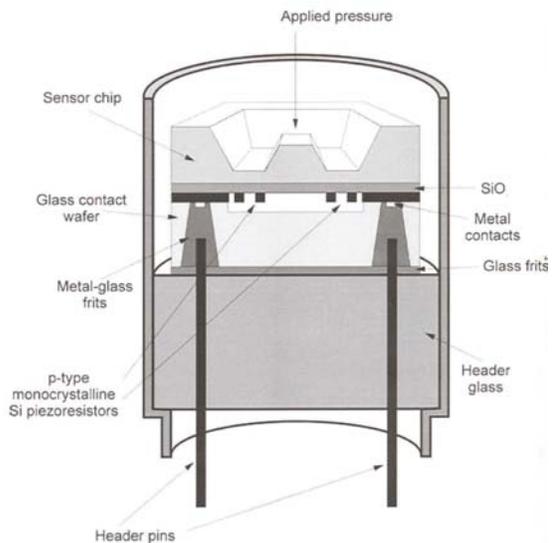


Figure 7: Leadless Sensor Glassed to Header

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.

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. 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.

5. Vibration Insensitive Sensing Technology

The sensor used in this device is a newly developed vibration insensitive sensor^{6,7}. In this sensor two stress-deflecting diaphragms are fabricated on one structure, as shown in Figures 8 & 9. On each diaphragm, one half of the 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 while the other decreases. One sensing diaphragm, is exposed to the media while the other sensing diaphragm is isolated from the media (Figure 10). Due to this geometry of the sensing element, both sensing diaphragms will see any shock or vibration, however, only one sensing diaphragm will respond to the applied pressure signal. 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, thus providing an output that is proportional to pressure only. Complete cancellation is dependent on the two deflecting diaphragms having exactly the same size, thickness, and matching

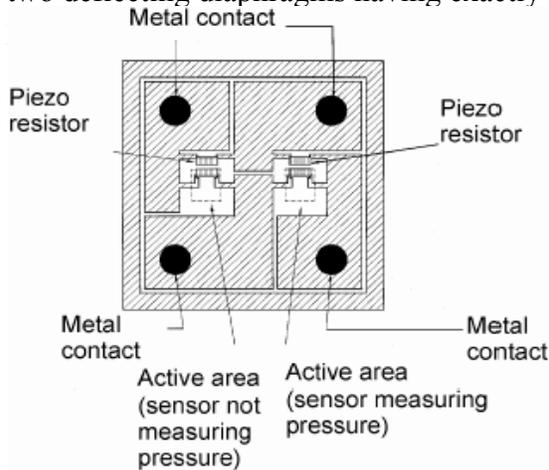


Figure 8 – Top-View Sensing Chip

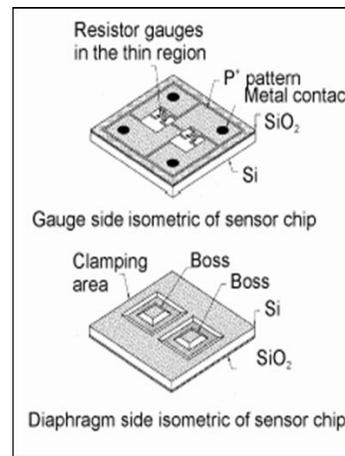


Figure 9 – Isometric Views of Sensor Chip

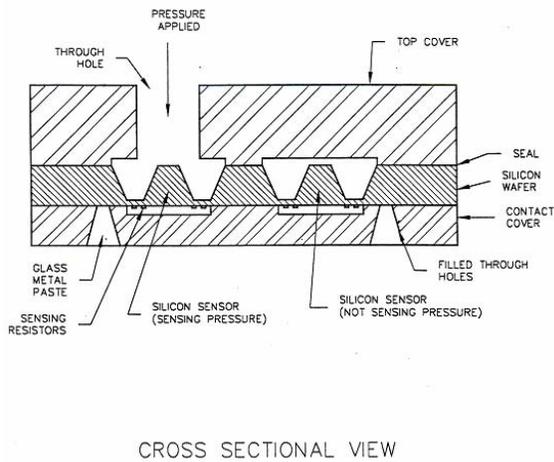


Figure 10: Cross Section of Vibration Insensitive Sensor

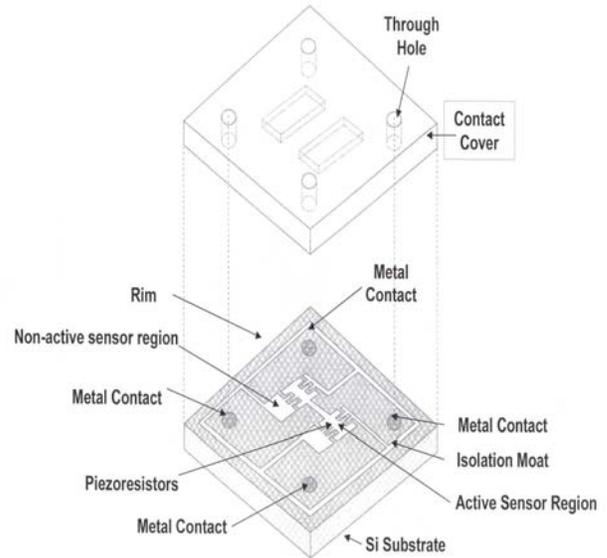


Figure 11: SOI Pattern Wafer & Cover

The Vibration Insensitive chip is fabricated using the previously described SOI Leadless processing technology. The assembly of the SOI sensing pattern wafer and the specifically designed contact cover wafer is shown in Figure 11. A Kulite patent, (Kurtz, 1999 [7]), describes in more detail, the fabrication of this particular device. The vibration insensitive device fabricated with this approach is suitable for continuous operation up to 500°C. Additionally, the side exposed to the pressure media is coated with a platinum film to enable “Flash Protection” for the finished product. This flash protection enables the sensor to withstand extremely high temperatures (up to 2000°C) for very short periods of time.

6. The Kulite ETL-CS-190M-XXX

The Kulite combustion sensor, shown in Figures 12, 13 and 14, has several features making it ideal for the harsh engine environment, with high reliability, small penetration, and high sensitivity and accuracy. The silicon on silicon technology, with no p-n junction, allows the sensing die to be located as close to the combustion chamber as possible, increasing the natural frequency of the sensor, and thus the increasing the data rate that can be achieved. The leadless silicon sensing die, described above, has been developed for applications with static and dynamic pressure and high temperature environments. The sensing circuit and electrical connections are isolated from the pressure media making it ideal for internal combustion engine applications. This design, allows the diameter of the sensor to be minimized, and also eliminates gold wire bonds between the header pins and the sensing diaphragm. The elimination of the gold wire bonds eliminates eight connection points and four wires, increasing reliability, and improving robustness in the harsh temperature and vibration environment.



Figure 12 – The Kulite Internal Combustion Engine Sensor

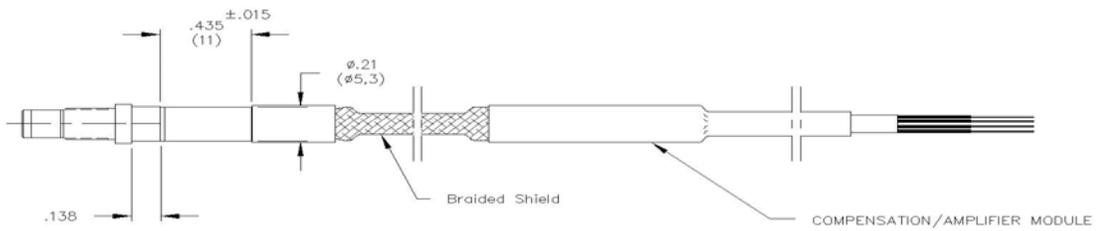


Figure 13 – Internal Combustion Engine Sensor with In-Line Amplifier

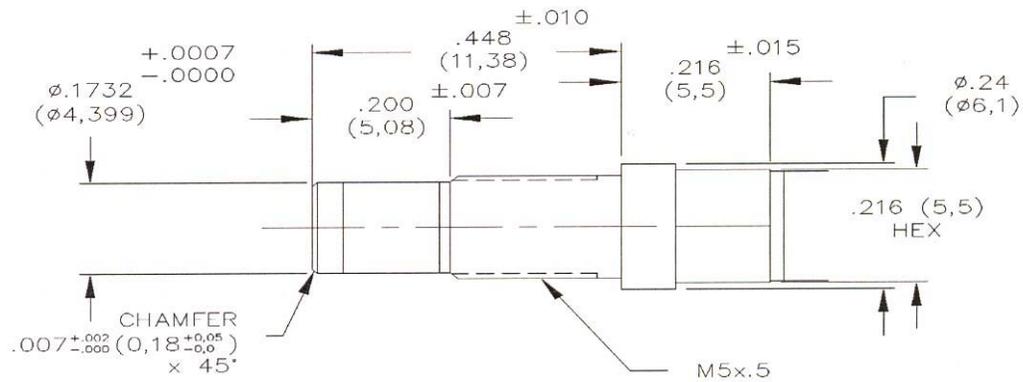


Figure 14 - Nose of Internal Combustion Engine Sensor

The Kulite sensor can also be equipped with external amplifiers, screens, or compensation networks. The basic transducer has a compensation network, to maintain pressure sensing accuracy over a wide temperature range⁸. The network is composed of a group of passive resistors, placed in series with the bridge, or shunts over the sensing piezoresistors. The compensation is required because of the temperature coefficient of the gage factor of the piezoresistors, and zero shift with temperature. An amplifier, external to the sensor, can be added, to provide 5-volt DC or 4-20 milliamp output, instead of a millivolt output. Various screens can be installed to protect the sensing die from combustion debris.

The test cell or test track environment is characterized by high heat and vibration. With the high heat, most elastomer sealing methods, such as o-rings, are unacceptable. Metal-to-metal crush ring or face seals are used, which can withstand the high heat generated, and withstand the shocks and accelerations experienced in the harsh vibration environment.

7. Response Time and Resonant Frequency

The Resonant frequency of the developed transducer was calculated to be above 160 KHz.

To demonstrate the response time, an experimental set up called the “shock tube”, shown in Figure 15, was used. This apparatus has two chambers, one set at a higher pressure, with the sensor installed in the second chamber, at a lower pressure. A thin membrane isolates the high pressure chamber from the low pressure chamber. A mechanism with a needle pierces the thin membrane, allowing the high pressure to enter the low pressure chamber, simulating a step input to the sensor. The sensor output is recorded on a digital oscilloscope. The ringing frequency of the sensor is the natural frequency of the sensor, and the response time or time constant of the sensor can be computed as $f = 1/t$.

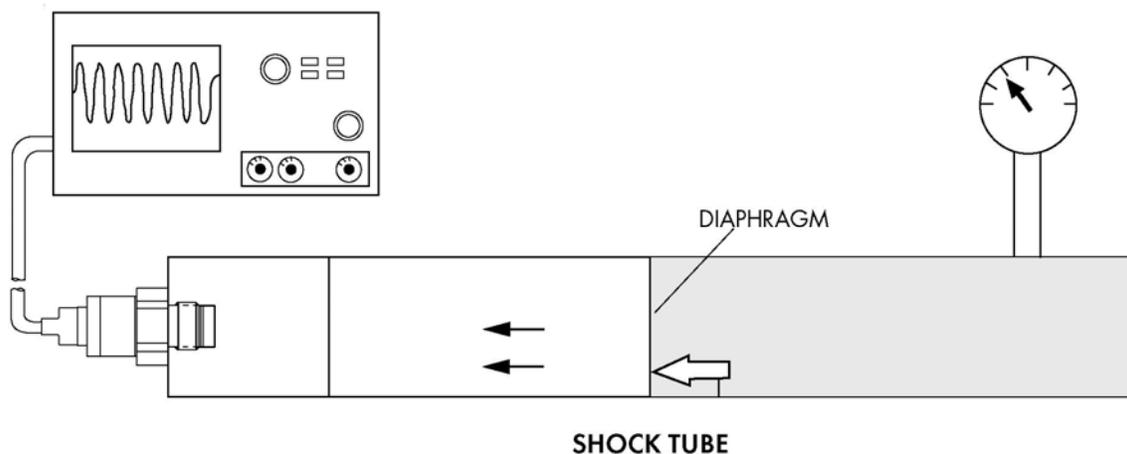


Figure 15- Shock Tube Apparatus

A typical oscilloscope trace is shown in Figure 16. The combustion sensor was demonstrated to have a natural frequency of above 150 KHz.

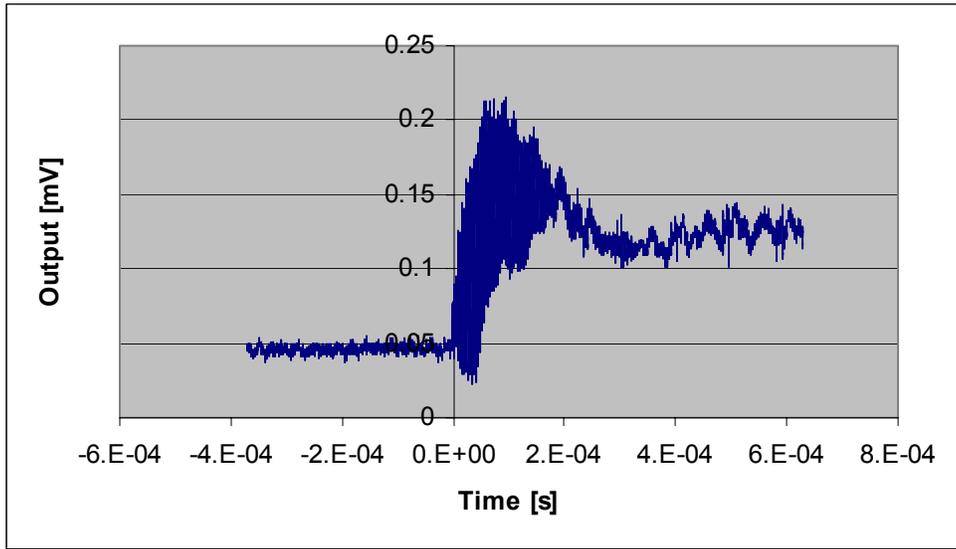


Figure 16 – Typical Shock Tube Trace

8. On-Engine Test

On- Engine testing was performed at one of our customer facilities. Comparative data was obtained on both the Kulite piezoresistive sensor, and a piezoelectric sensor. Several engine cycles were recorded at very high data rates. A typical set of cycles, plotted vs. time is shown in Figure 17.

Comparison between Kulite and Piezoelectric Sensor

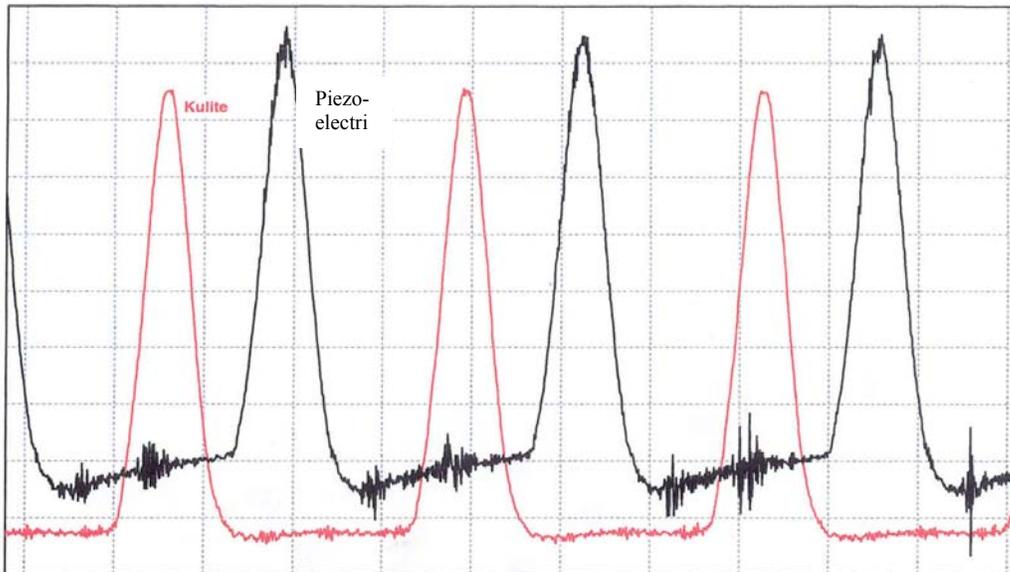


Figure 17 –Typical On-Engine Test Data

Two benefits of the Kulite transducer can be observed. First, the noise induced on the Kulite signal is much lower, resulting in a smoother, cleaner trace, compared to the piezoelectric sensor. In the Vibration Insensitive Kulite sensor, this vibration is cancelled out, providing a true pressure measurement. Second, at the low pressure trough, the Kulite sensor shows a level, steady pressure measurement, while the piezoelectric measurement is drifting upward. This drift of the piezoelectric sensor effects the quality and accuracy of the data obtained.

9. Conclusion

A small internal combustion engine sensor has been developed and successfully evaluated. This sensor offers several features required for the harsh engine test environment. The sensor utilizes revolutionary VIS Technology that is based on silicon on silicon approach, which eliminates the p-n junction, and allows the sensor to operate at high temperatures. The device is packaged, using leadless technology, to minimize combustion chamber penetration, while the face sealing technology enables the device to withstand the harsh engine environment. The Vibration Insensitive Sensing Technology both dynamic and static pressure measurements in the combustion environments are completely decoupled from vibration related noise. The transducer offers high reliability, and fast response time, with a resonant frequency of over 750 KHz. Several options are available, including amplifiers, screens, or compensation networks. On-engine testing demonstrates the capability of the sensor to measure dynamic and static pressures without noise or drift.

10. Bibliography

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