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0227-7576/87/373-382/$0 + .50pp

TP287

STABLE MINIATURE PRESSURE TRANSDUCER USING INORGANIC BONDING CONSTRUCTION

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ABSTRACT

A compact, 6 gram, aerospace quality absolute pressure transducer with the inherent stability of larger traditional transducers is discussed. The design incorporates a dielectrically isolated piezoresistive sensor on a micromachined silicon diaphragm for superior characterisics over a broad temperature range. the diaphragm is hermetically sealed into the housing wihtout the use of organic materials to eliminate leakage of any pressure media through the transducer. The absolute reference cavity is also hermetically sealed for long term reliability. Benefits of the new design are long term stability, repeatability and accuracy versus temperature. Actual data on environmental capabilities and performance are presented.

INTRODUCTION

Pressure transducers which are required to be hermetic, highly stable and repeatable over time are typically constructed with metal diaphragms and are 25 mm in diameter and 50 mm in length. A much smaller transducer weighing only six grams but with performance approaching that of much larger units is a result of a recent development effort. The unit is intended for aerospace applications and has absolute pressure ranges from 15 to 200 psia*. Benefits of the design include hermeticity, long term repeatability, and accuracy versus temperature. Topics included in this report will be the unique sensor, transducer construction, calibration, performance, environmental capability and long term stability.

SENSOR

The heart of this transducer is its unique silicon microsensor. It is a small sensor only 2 mm in diameter. This sensor has two important features which distinguish it from most commercially available sensors and gives it considerably better performance for certain applications.

The first feature is the fact that the strain gages are not a part of the silicon pressure diaphragm. Conventional diffused piezoresistive sensors have strain gages diffused into the silicon itself. Using integrated circuit fabrication processes, only the gage and conductor areas of the diaphragm are heavily doped for high conductivity. These areas are electrically isolated from the remainder of the silicon by a p-n junction diode. The gages have p-type conductivity while the remainder of the silicon is n-type. This works well but has some limitations. The isolation begins to break down at temperatures around 140° C due to current leakage of the diode. The performance of the sensor rapidly deteriorates when this occurs. The diode is also susceptible to noise, especially if electrically connected to other equipment by conductive fluids whose pressures need to be measured.

The sensor (reference 1) in the present transducer has its strain gages on top of a thin oxide layer which provides electrical isolation up to very high temperatures. This is illustrated in Figure 1. The gages and diaphragm structure are formed from two separate silicon wafers. One wafer has a layer of silicon dioxide on one side. This side is diffusion bonded to the second wafer using pressure and temperature. The result is two wafers physically bonded together by the oxide layer but electrically isolated from one another. One side is sculptured into pressure diaphragms by etching. The other side is etched to a thickness of about one micron and then patterned into strain gages and connections to form the Wheatstone bridge circuit. The single crystal gages are heavily doped, which decreases the gage factor but also makes electrical properties less dependent on temperature. Note that this construction does not include a diode to limit temperature capability. This sensor is currently used in one transducer design for temperatures of 300°C. It will also be used in another design (under development) up to 480°C. The temperature limiting feature of this sensor is the aluminum interconnection pads which melt at 577°C.

The second feature which is a major difference between this sensor and others is the sculpturing of the diaphragm. Most sensors have thin round or rectangular diaphragms of uniform thickness. The present sensor has two relatively large stiff sections in the center of the diaphragm as shown in Figure 2. There are large thin areas to the sides of these stress concentrators and three narrow ones at their ends and between them. The strain gages are located at these three narrow thinned areas.

The stress concentrators force most of the strain from pressure into these areas. This gives the sensor over twice the output of similarly sized flat diaphragms and also a greater overpressure capability. Given 5 volts applied to the sensor, it yields a nominal 300 mV output at rated pressure and will measure at least two and one half times rated pressure with good linearity. The sensor also has a very high resonant frequency due to its very small size and rigid diaphragm.

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* 1 psi = 6894.7 Pascal

TRANSDUCER CONSTRUCTION

To take full advantage of the sensor's characteristics and to provide a hermetic seal to the pressure media , the sensor has been mounted into a metal pressure fitting using only inorganic materials. This eliminates the familiar adhesive creep which exhibits itself as zero drift of transducers over periods of time or after many pressure cycles.

The construction of the basic sensor assembly is shown in Figure 3. The sensor is attached to a support piece made of Pyrex glass. The bond to the glass is made using an electrostatic field assisted bond. This bonding process (see reference 2) utilizes no intermediate material between the silicon sensor and the glass support . When a voltage of a few hundred volts is applied with the proper polarity above about 350°C, the two materials (when sufficiently polished) will form a hermetic seal together with strength exceeding that of the glass. The result is a bond which is extremely stable and creep free, making it ideal for sensor mounting. The measured pressure reaches the sensor through a hole in the glass support.

In order to make electrical connection to the sensor, thin film circuit traces have been deposited onto the top of the glass support. Aluminum wires are ultrasonically bonded to connect the aluminum pads on the sensor and the thin film traces on the glass. After the sensor connections are made, a rectangular silicon cup is placed over the sensor and wires and hermetically sealed to the glass support with a sealing glass. The cup is sealed in a near vacuum and serves as an absolute pressure reference for the sensor as well as excellent environmental protection for the sensor and wiring. Portions of the thin film traces extend outside the reference cavity so that electrical connections can be made to the sensor. The resulting assembly is an absolute pressure sensor constructed only of glass and silicon. The absence of epoxy or silicone adhesives yields a basic sensor with excellent repeatability and long term stability.

The next step in the assembly is to attach the sensor assembly to a metal fitting which carries the pressure to be measured to the sensor. The transducer is shown in cross section in Figure 4 with the sensor assembly mounted. Titanium was chosen as the fitting material. It has good corrosion resistance, and its relatively low thermal expansion facilitates the seal to the low expansion Pyrex. A thin wall tubular feature is machined into the fitting for acceptance of the glass support. Its purpose is to minimize the stresses transmitted from the fitting to the glass. A high temperature sealing glass is used to hermetically seal the Pyrex glass support into the Titanium fitting. With this seal the basic transducer structure is completed using nothing except rigid inorganic materials.

After calibration, the permanent cable is soldered to the compensation board, the board is coated with a silicone, and a cover is installed and welded to finish the assembly. The reulting transducer weighs just 6 grams, is about one inch (25 mm) long, fits into a half inch (13 mm) hex and has a 10-32 thread for mounting.

CALIBRATION

After assembly, the uncompensated transducer has a nominal bridge impedance of 900 ohms which increases by about .16% per °C. It also has a nominal output of 300 mV when full scale pressure and 5 volts excitation are applied. The sensitivity to pressure decreases about .14% per °C. The fact that the slopes of resistance and sensitivity nearly match each other would allow fairly good output versus temperature compensation by simply using constant current excitation. This would require no compensation resistors. However, most of the units have been compensated to operate on a 10 volt constant voltage supply. Figure 5 shows a schematic of the transducer and its compensation circuitry. The strain gages are designated G1 to G4.

Sensitivity compensation is achieved through the use of two thermistors (T1 and T2) printed on the compensation board. The thermistors decrease in resistance by about .20% per °C and are placed in series with the bridge excitation. The thermistors and the sensor impedance act as a voltage divider to apply a certain portion of the 10 volts to the sensor. Typically the thermistors will be trimmed so that about half the excitation (5V) is applied to the sensor at room temperature. As temperature increases, so does the voltage across the sensor. This is caused by the sensor's increasing impedance and the thermistor's decreasing impedance. When the thermistors are trimmed to the proper value, the sensor excitation increases just enough to offset the sensor's loss in sensitivity with temperature. The result is a constant pressure sensitivity over the compensated temperature range.

Zero compensation is accomplished by two fixed chip resistors (R1 and R2) which are applied as shown in Figure 5 or to the left lower leg of the bridge. The resistor R2 is typically between 10 and 100 K ohms. It adjusts the resistance of the one leg versus temperature to cancel the net mismatch of the four legs and maintains a constant zero output over a temperature range. To correct the inherent imbalance of the bridge at room temperature and also the effect of R2, a small resistor R1 (0-50 ohms) must also be added for good zero compensation. With R1 and R2 properly selected, the output

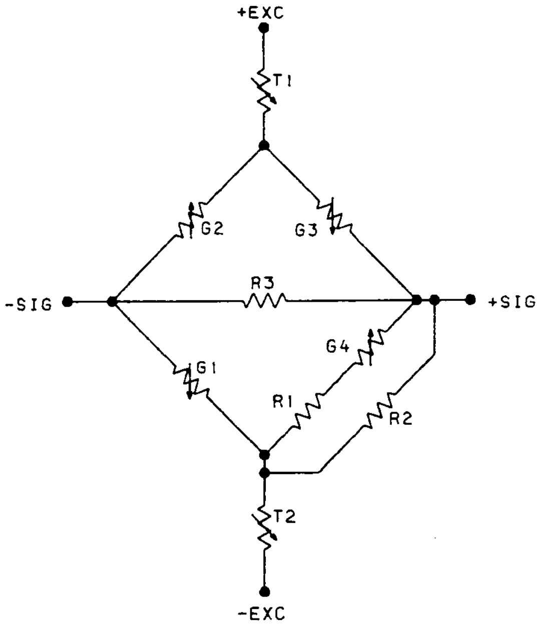

Figure 5. Schematic of sensor and compensation circuitry

with no pressure applied will be small (<10mV) and constant over the compensated temperature range.

Finally, if it is desired that transducers have some specific output with pressure, the resistor R3 may be used to shunt the signal voltage down to the desired value. R3 would typically be a few thousand ohms in resistance.

The transducer's characteristics are quite linear with temperature. This allows good temperature compensation to be applied to any temperature range between -54° and 150°C. The upper limit is due to the soldered connections which are used. A solderless version is planned which should work well to at least 260°C.

PERFORMANCE

The inherent stability of the unit makes it possible to calibrate the transducer for measurements on the order of 1% accuracy or better. Table 1 gives actual measured parameters on a group of nine 15 psia units which were calibrated for the -18° to 65°C temperature range. Notice that thermal effects on sensitivity and zero over the wider -54° to 75°C range are fairly small even though compensation was performed on a much narrower range. All thermal errors reported are relative to the 24°C values. Average and maximum values are given for each parameter. Table 2 gives typical values of additional performance characterisitcs not tested on every unit. The reader is also referred to reference 3 for further description of performance characteristics.

In addition to the information in the tables, a few other comments are in order. Pressure ranges from 15 psia to 200 psia have been made. The units will withstand pressures of 2.5 times full range without damage or degradation. The sensors have very high resonances, however, the acoustic cavity in front of the sensor has a resonance of about 2,400 Hz limiting the frequency response of the transducer. Special tight tolerance calibrations can be achieved if required. One special 15 psia version is being used as a barometer on a tank for air density aiming corrections. This version is compensated so that all readings between 10 and 16 psia and between -20° and 65°C are within ±.16 psi of a best straight line fit of the data. This is a worst case inaccuracy of ±1.07% of full scale output due to all sources. Data covering the entire temperature and pressure range is taken by an automatic test system and supplied with each unit.

ENVIRONMENTAL CAPABILITIES

The transducers have undergone considerable environmental testing and were found to operate in a variety of environments. Table 3 summarizes the shock and vibration testing which has been done. Generally, the units have not been affected by these tests. The last column of the table gives the maximum change which occured in either sensitivity or zero (% FSO) during the test where calibration runs were made. No units have failed to operate due to any of these tests.

Table 4 summarizes a number of exposure tests which have been performed. Only the pressure port of the transducers was exposed on the dust, jet fuel, hydraulic fluid and R-12 tests. Calibration changes have generally been slight. The freon R-12 test is ongoing and precise calibration checks will not be possible until conclusion of the test.

There have been significant calibration changes on one series of tests. Three units underwent the first three tests of Table 4 in sequence. During the salt fog test, one unit changed sensitivity by 3.1% but recovered to within 1.5% after oven drying. Another unit shifted 2.2%. The third remained within .4% throughout the tests. It is believed the changes were due to a poor fixture which allowed the transducers to be immersed in salt water during the salt fog test. This allowed water to enter the units around the cables. The cable seal has since been redesigned for better moisture protection. The units are not designed to be immersed however.

LONG TERM STABILITY

Stability of readings over extended periods of time was the primary goal of this transducer development. The all inorganic construction was considered the preferred method of achieving very low drift rates with time. Some units which were expected to be in storage for awhile were used to test long term stability. A total of thirty-six 15 psia units were run through a standard pressure and -18° to 65°C temperature calibration run and stored for several months. During the storage they were taken out and retested one or two times and all were tested at the end of the test. Not all the units remained in storage for the same time period. The storage times were from 3 to 9 months with the average being just over 7 months. Figure 6 is a histogram of the changes in zero during this test period. Zero shifts averaged .42mV or .15% of full scale output (FSO). Sensitivity shifts averaged .37%. It is believed that the sensitivity shifts are actually smaller than the data indicate. During the test period a problem was found in the pressure test setup which allowed a nonrepeatability of about .3% to occur in the excitation voltage from one sensitivity test to another. This undoubtedly affected the data on some of the units, but it is impossible to determine the overall effect on the data. For this reason only the average is presented. It is estimated that the sensitivity is at least as stable as zero.

CONCLUSION

The transducer which has been described offers accuracy and long term stability in a very small and light package. It is recommended as a candidate for applications requiring hermeticity, repeatability of calibrations over long term periods, small size and weight, and uniform calibrations over a wide temperature range. It has already been selected for some missile and military applications requiring repeatability over years of service or storage.

REFERENCES

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(3.) Endevco Performance Specification Number PS8531, Endevco, San Juan Capistrano, California, January, 1987.

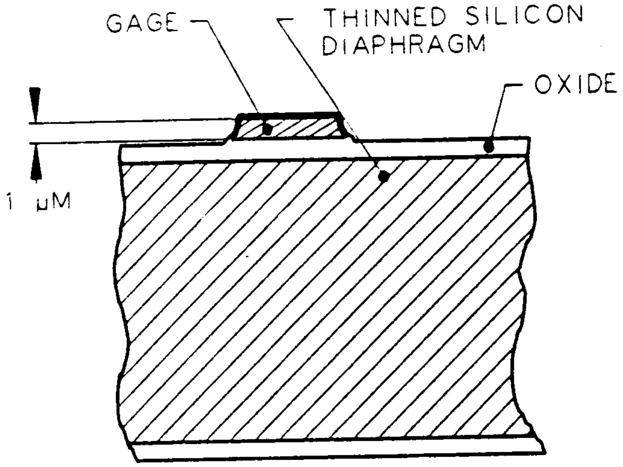

Figure 1. Cross Section of Diaphragm showing Gage on Oxide Layer

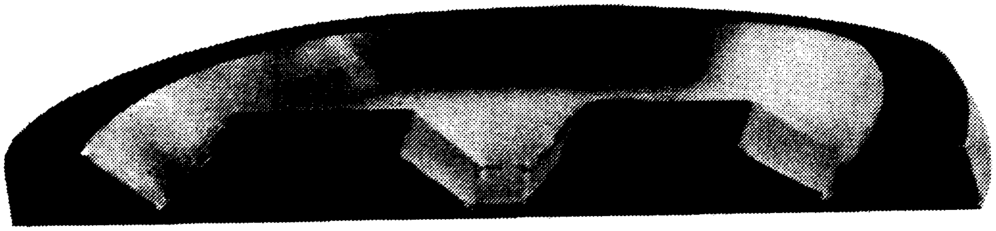

Figure 2. Etched side of diaphragm showing stress concentrators and thinned areas beside them

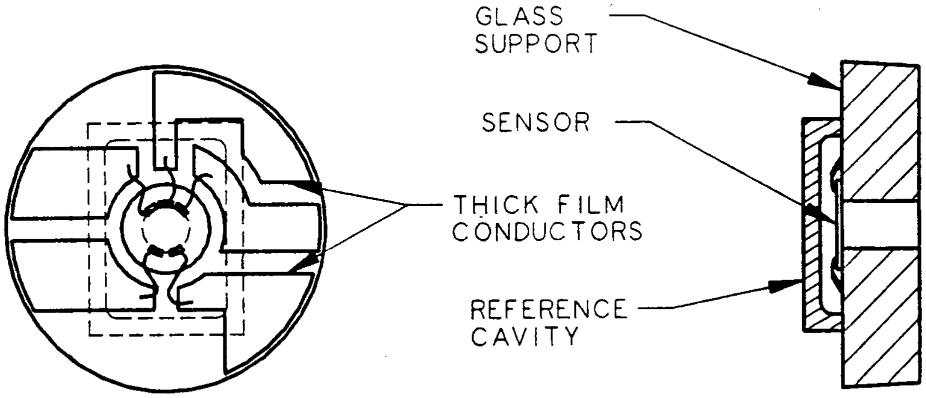

Figure 3. Sensor and Mounting Structure

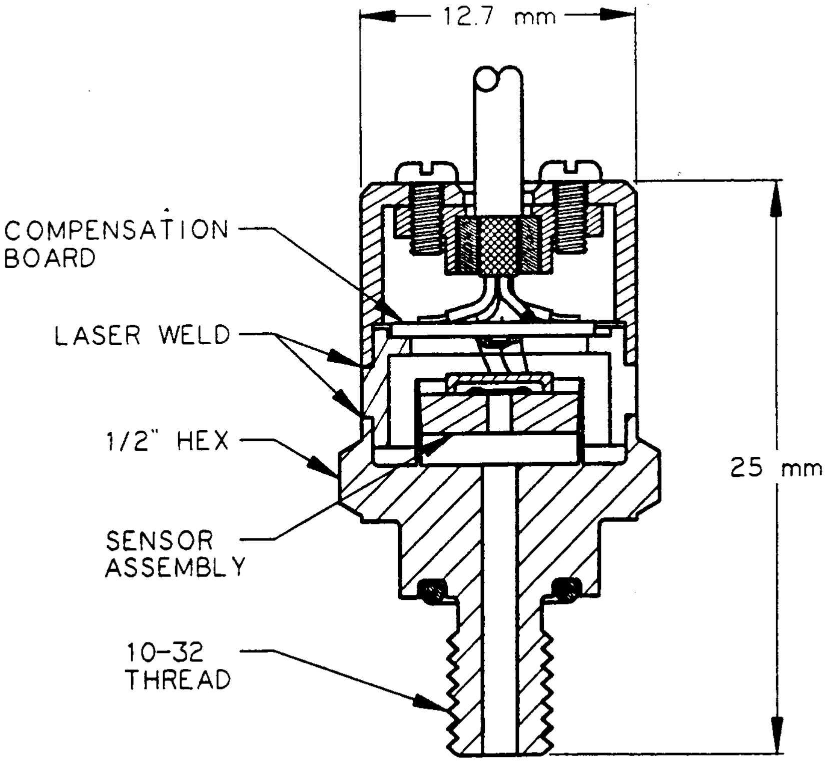

Figure 4. Cross Section of Transducer

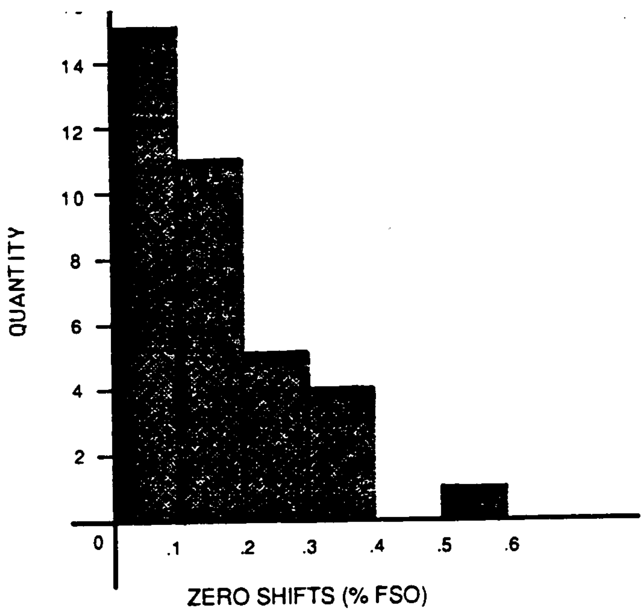

Figure 6. Zero shifts with time
(7 months average)

TABLE I
Measured Parameters

PARAMETER	UNIT	AVERAGE VALUE	MAXIMUM VALUE
Full Scale Output at 10 volts (FSO)	mV	357.5	392.1
Zero Offset	mV	1.9	5.0
Nonlinearity	% FSO	.06	.15
Hysteresis	% FSO	.017	.03
Non-repeatability	% FSO	.017	.03
Combined Effect of Linearity, Repeatibility and hysteresis	% FSO, RSS	.07	.15
Zero Shift after 2.5x overpressure	% FSO	.015	.025
Input Resistance	ohm	1603	2331
Output Resistance	ohm	738	1030
Zero Error due to temperature			
-18° to 65°C	% FSO	.31	.99
-54° to 74°C	% FSO	.62	1.96
Sensitivity Error due to temperature			
-18° to 65°C	%	.25	.53
-54° to 74°C	%	.63	1.39

TABLE II
Other Typical Parameters

PARAMETER	UNIT	TYPICAL VALUE
Diaphragm Resonant Frequency		
15 psia	hz	140000
50 psia	hz	240000
100 psia	hz	280000
200 psia	hz	400000
Flat Frequency Response of Transducer	hz	250
Warmup Time (1% Accuracy)	mS	1
Acceleration Sensitivity	psi/g	3×10^{-4}
Zero Shift with Mounting Torque	% FSO	.1
Nonlinearity at 2X Range	% 2X FSO	.2
Insulation Resistance at 50Vdc	Megohm	1000
Noise (DC to 50000 hz)	µV rms	5

TABLE III
Shock and Vibration Tests

TYPE OF TEST	PARAMETER	NUMBER OF AXES	QUANTITY TESTED	MAXIMUM CALIBRATION CHANGES
1) Basic Design Shock per MIL-STD 810C	40g, 18 ms half sine	3	5	--
2) Ballastic Shock per MIL-STD 810C	130g, 2ms half sine	3	5	.4%*
3) Shock per MIL-STD 202	1000g, .5 ms half sine	3	5	--
4) Vibration per MIL-STD 202	±20g sine wave swept to 2000hz, 4 hrs/axis	3	5	.1%**
5) Shock	10000g***	1	3	†
6) Shock	20000g***	1	1	†
7) Shock	2000g, .3 ms half sine	1	80	†

* Total change during tests (1) and (2) in sequence
** Total change during tests (3) and (4) in sequence
*** Pulse width not recorded
† Not recorded, units operated within specification after shock