COMPENSATION AND CALIBRATION OF A MONOLITHIC FOUR TERMINAL SILICON PRESSURE TRANSDUCER

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A monolithic silicon pressure transducer has been developed which employs a single four terminal shear stress sensitive piezoresistive strain gauge in place of the more common Wheatstone bridge construction. The gauge, which is called a transverse voltage strain gauge, was placed at the midpoint of the edge of a square diaphragm at an incline angle of 45° in order to maximize sensitivity and minimize non-linear effects. Silicon pressure transducers fabricated using this strain gauge technology yield sensitivities of 200-300 uV/V/kPa for a 100 kPa full scale pressure range with non-linearity and pressure hysteresis errors of less than ±0.1% FS. The variation in zero pressure offset is typically on the order of ±8% FS with a temperature coefficient of offset of ±0.025% FS/°C relative to the 25°C value. The temperature coefficient of full scale span is - 0.19 ±0.02%/°C while the temperature coefficient of the input impedance is 0.24 + 0.02%/°C.

In order to improve the performance of the transverse voltage strain gauge pressure transducer over temperature a method was developed by which a compensation and calibration circuit is fabricated on the same substrate as the strain gauge using deposited thin film resistive material. The resistances can subsequently be adjusted to the required values for each transducer using high speed, computer controlled laser trimming techniques. This design has yielded calibrated transducers with total errors, including non-linearity, hysteresis, thermal offset shift and thermal span shift, of less than 1% from 0°C to 85°C.

It is the goal of this contribution to describe the salient features of the design of the transverse voltage pressure transducer along with package design and assembly considerations that help preserve the performance of this device. In addition, a description of the compensation and calibration circuit including important processing and laser trimming techniques will be given.

INTRODUCTION

Monolithic silicon pressure transducers offer many desirable features, being small in size, low in cost, and having good performance characteristics such as high sensitivity, small non-linearity and pressure hysteresis errors, and excellent immunity to mechanical shock and vibration. They are manufactured using the mass production, batch processing technology of the semiconductor industry, allowing hundreds of devices to be fabricated simultaneously on a single silicon substrate. A cross-sectional view of a typical silicon pressure transducer device is shown in Fig. 1.

The most common design for silicon pressure transducers is to arrange four stress sensitive resistors in the form of a Wheatstone bridge [1-3]. When pressure is applied to the diaphragm containing these resistors, the resulting stresses cause the resistors to change in value, unbalancing the bridge and generating an output voltage proportional to the applied pressure. While very high performance pressure transducers can be made using the Wheatstone bridge construction, the calibration and temperature compensation of these devices is often complex due to part-to-part variations in the characteristics of these devices. These part-to-part variations are to some degree inherent in the design of silicon pressure transducers employing the Wheatstone bridge construction. Kim and Wise [4] have published a detailed analysis of the problems associated with the temperature sensitivity variations of a bridge design. In particular, the close matching of the characteristics of the resistors in the bridge required to obtain a well behaved device is difficult to achieve using even the most advanced state-of-the-art semiconductor processing technologies. Therefore, it was concluded that if the full cost advantage of the silicon pressure transducer technology was to be realized, a design was needed which eliminated the need for closely matched stress sensitive resistors. In order to achieve this objective, it was necessary to review the theory of piezoresistivity in semiconductors and the manner in which this theory determines the design of silicon pressure transducers. The result of this study was the transverse voltage strain gauge design, a four terminal piezoresistive device which gives an output voltage proportional to the applied pressure from a single diffused stress sensitive silicon resistor.

THEORY OF TRANSVERSE VOLTAGE STRAIN GAUGE DESIGN

The piezoresistive effect in semiconductors can be described in terms of a phenomenological theory which relates changes in the electrical conductivity of the material to the applied stress through an emperically determined set of constants called the piezoresistive coefficients. In a cubic material such as silicon, the phenomenological theory of piezoresistivity can be expressed by an equation of the form [5]

$$E_i/\rho_o = I_i + \sum_{jkl}\sum\sum \pi_{ijkl} I_j T_{kl} \qquad (1)$$

where ρ_o is the unstressed bulk electrical resistivity of the material, E_i and I_i are the electrical field strength and current density respectively parallel to the x_i crystallographic axis, T_{kl} is the stress acting on the plane perpendicular to the x_l axis in the x_k direction and π_{ijkl} is the piezoresistive coefficient. These piezoresistive coefficients are analogous to the elastic constants in the manner in which they transform from one coordinate system to another and in their relationship to the symmetry of the crystallographic structure of the material[6].

This expression can be further simplified by adopting the Voigt notation for the stress tensor, where a 3x3 rank two tensor T_{kl} is replaced by a 1x6 rank one tensor t_k, and applying the conditions of cubic symmetry to the resulting 6x6 rank two piezoresistive coefficient tensor π_{jk}. Under these conditions, the expression given in eqn. (1) reduces to the following three equations [5]:

$$E_1/\rho_o = I_1\ [1 + \pi_{11}T_1 + \pi_{12}(T_2 + T_3)] + \pi_{44}(I_2T_6 + I_3T_5) \quad (2)$$

$$E_2/\rho_o = I_2\ [1 + \pi_{11}T_2 + \pi_{12}(T_1 + T_3)] + \pi_{44}(I_1T_6 + I_3T_4) \quad (3)$$

$$E_3/\rho_o = I_3\ [1 + \pi_{11}T_3 + \pi_{12}(T_1 + T_2)] + \pi_{44}(I_1T_5 + I_2T_4) \quad (4)$$

These results are expressed in terms of the three independent piezoresistive coefficients π_{11}, π_{12}, and π_{44} as required by the conditions of cubic symmetry.

In the case of a silicon pressure transducer, the stress sensitive resistor can be assumed to be subjected to a state of plane stress due to the plate like nature of the thin diaphragm structure. If it is assumed that the current axis of the resistor is parallel to the x_1 crystallographic axis and the resistor lies in the plane normal to the x_3 crystallographic axis, this plane stress can be described in terms of the two uniaxial stress components, T_1 and T_2, which act respectively parallel and perpendicular to the current axis of the resistor, and the shear stress component, T_6, which acts in the plane of the resistor. All other current and stress components are equal to zero in this case. For this special case of a single stress sensitive resistor subject to a plane stress, there are only two non-zero field equations:

$$E_1/\rho_o = I_1\ (1 + \pi_{11}T_1 + \pi_{12}T_2) \quad (5)$$

$$E_2/\rho_o = \pi_{44}I_1T_6 \quad (6)$$

The effect described by eqn. (5) is that normally employed in silicon pressure transducers of the Wheatstone bridge construction. It manifests itself as an apparent change in the resistance of the stress sensitive resistors in the bridge. By the judicious placement of these resistors with respect to the stress field in the silicon diaphragm and their orientation relative to the crystallographic axes of the material, it is possible to obtain stress sensitive resistors which either increase or decrease in resistance when pressure is applied to the diaphragm. Under these conditions, the Wheatstone bridge becomes unbalanced when pressure is applied and the output signal of the bridge can be maximized.

The second effect described in eqn (6) is generally ignored in the design of silicon pressure transducers. It is a consequence of the loss of the block diagonal property of the resistivity tensor as a result of the piezorestistive effect which causes nonzero off-diagonal components to appear in this tensor property when the material is stressed. It is manifested as an electric field which develops perpendicular to the current axis of the resistor. The significance of this result is that this electric field can be measured in a single stress sensitive resistor. This is the theoretical basis for the design of the transverse voltage piezoresistive strain gauge. A four terminal gauge was proposed by Pfann and Thurston [6] to measure biaxial stress while Mallon et al [7] have described a similar type of strain guage for measuring pressure.

DESIGN OF TRANSVERSE VOLTAGE PRESSURE TRANSDUCERS

The design of silicon pressure transducers is governed primarily by two considerations: (1) the sensitivity of the piezoresistive strain gauge to stress and (2) the distribution of the pressure induced stresses in the diaphragm structure. These two factors directly effect the magnitude of the output of the pressure transducer and the linearity of this output with respect to the applied pressure. This is true in the design of silicon pressure transducers employing the transverse voltage strain gauge technology as well as those of the Wheatstone bridge construction. One of the most significant properties of the piezoresistive effect on semiconductors is the dependence of this effect on the crystallographic orientation of the stress sensitive resistor. This is a consequence of the tensorial nature of this phenomenon and the manner in which this tensor property transforms from one coordinate system to another. As noted previously, this property can be employed to optimize the sensitivity of the silicon pressure transducer.

In the case of the results presented in eqns. (5) and (6) it was assumed that the current axis of the stress sensitive resistor was parallel to a crystallographic axis and that this resistor was located in a plane perpendicular to a crystallographic axis, a highly specialized case. However, similar expressions can be derived for any general case [6]. In the design of silicon pressure transducers it is not necessary to consider all arbitrary orientations since there are other factors which also influence the choice of the crystallographic orientation. Primary among these is the manner in which the silicon diaphragm is fabricated.

For silicon pressure transducers to be fabricated using the batch processing technology of the semiconductor industry, chemical etching is the preferred process for the fabrication of the diaphragm structure. However, since this diaphragm is generally very thin compared to the thickness of the silicon substrate material, a considerable etch time is required to form the diaphragm. Therefore, it is desirable to use an etching process which is highly anisotropic in order to minimize the lateral spreading of the dimensions of the diaphragm during the etch process. Anisotropy is also important if it is desired to fabricate a diaphragm of uniform thickness such as is shown in Fig. 1. Almost without exception solutions which etch silicon anisotropically tend to etch in the (001) directions most rapidly and in the (111) directions most slowly [8]. Therefore, a substrate orientation normal to a (001) direction is typically chosen for such transducers. Under this condition, etchants such as KOH will produce either square or rectangular diaphragm structures which lie in the (001) crystallographic plane with the underlying cavity bounded by (111) type crystallographic planes. For this reason (001) silicon substrates were chosen for the design of the transverse voltage strain gauge pressure transducer.

In the special case of a (001) oriented silicon substrate, it can be shown [6] that the results derived in eqns (5) and (6) are valid for any arbitrary orientation of the current axis in this plane if the crystallographic piezoresistive coefficients π_{11}, π_{12}, and π_{44} are replaced by the corresponding coefficients transformed into the coordinate system defined by the current axis, the normal to the plane of the substrate, and the cross product of these two vectors. Using these transformed piezoresistive coefficients, the two electric field equations become

$$E'/\rho_o = I'_1\ (1 + \pi'_{11}\ T'_1 + \pi'_{12}\ T'_2) \quad (7)$$

$$E'_2/\rho = \pi'_{44}\ I'_1\ T'_6 \quad (8)$$

where the prime superscript indicates that all the quantities are referred to the transformed coordinate system. Because of their orientation parallel and perpendicular to the current axis respectively, the stress components T_1' and T_2' are frequently referred to as the longitudinal and transverse stress components. Their associated piezoresistive coefficients, π_{11}' and π_{12}' are denoted as the longitudinal and transverse piezoresistive coefficients respectively. The coefficient π_{44}' associated with the shear stress component T_6' is similarly referred to as the shear piezoresistive coefficient.

Figure 2 shows how the piezoresistive coefficients π_{11}', π_{12}', and π_{44}' vary with the orientation of the current axis relative to the (110) flat on a (001) silicon substrate. These values were computed for a p-type silicon resistor using the experimentally determined values of Smith [9]. Note that for resistors parallel and perpendicular to the wafer flat, π_{11}' and π_{12}' are at their extreme values while the shear coefficient π_{44}' is maximized at 45° to the wafer flat.

For silicon pressure transducers employing the Wheatstone bridge construction it is common for the stress sensitive resistors to be oriented parallel and perpendicular to the (110) wafer flat on (001) substrates since, as can be seen from eqn. (7), these orientations maximize the sensitivity of the resistors to the uniaxial stresses T_1' and T_2'. In contrast, for devices employing the transverse voltage strain gauge design, the optimal orientation is at 45° to the wafer flat since this maximizes the shear piezoresistive coefficient π_{44}' and hence, from eqn. (8) the voltage perpendicular to the current axis of the resistor.

For both the Wheatstone bridge construction and the transverse voltage strain gauge design, the stress state within the silicon diaphragm is determined by the geometry of the diaphragm structure and the elastic properties of the substrate material. A wide variety of geometries are employed, ranging from circular to rectangular to square diaphragms. In most silicon pressure transducers the placement of the stress sensitive resistors on this diaphragm structure is such that the resistors are subject to a stress state which maximizes the piezoresistive effect. In some cases, however, it is necessary to compromise this consideration in order to achieve good linearity. A primary factor which influences the linearity of the output voltage of silicon pressure transducers is the linearity of the pressure versus stress relationship in the diaphragm structure when integrated over the active area of the stress sensitive resistors. For this reason, the resistors are often oriented such that they lie along lines of constant stress in the diaphragm structure. It is often necessary to greatly extend the dimensions of the diaphragm in order to achieve such a condition over the entire active area of the stress sensitive resistors. In the case of the design of the transverse voltage strain gauge pressure transducer, the condition of constant stress was not felt to be a major consideration, since the active area of this type of strain gauge is quite small, being confined to the region common to the four terminals of the device. In the final design for this device the active area of the transverse voltage strain gauge is less than 1x10-3 mm^2 which, in comparison to the total diaphragm area of over 2 mm^2, is virtually a point condition.

To determine the optimal location of the transverse voltage strain gauge, a finite element stress analysis model was employed to calculate the stress distribution in the diaphragm structure. While a wide variety of diaphragm geometries were evaluated, a square diaphragm was desired in order to minimize the total die size of the device. Figure 3 shows the results of a finite element analysis for a square diaphragm which is rigidly clamped at its boundaries. These results are shown in terms of the principal stress distribution at the centroid of the finite elements. These stresses are indicated in Fig. 3 by orthogonal vector pairs where the length of the vectors pairs where the length of the vectors correspond to the magnitude of the principal stresses and their orientation corresponds to the orientation of the principal stress coordinate system. Only one eighth of the total diaphragm area is shown in this figure, since the remainder of the total stress distribution can be generated by reflection across the symmetry planes of the square diaphragm.

As can be seen in Fig. 3, the region of maximum stress is located at the edge of the diaphragm on the centerline of the square diaphragm. At this point, the principal stress coordinate system is coincident with the coordinate system defined by the edges of the diaphragm, with the principal stresses being parallel and perpendicular to the edge of the diaphragm. The slight deviation from this condition shown in Fig. 3 is due to the fact that the centroid of the finite element is not located exactly at the center of the edge of the diaphragm. By definition the principal stress coordinate system is oriented such that the shear stress component is zero. It is well known, however, that the maximum shear stress state exists in a coordinate system rotated by 45° with respect to the principal stress coordinate system. Therefore, from the results in Fig. 3 and the shear stress dependence given in eqn. (8), the optimum location for the transverse voltage strain gauge on a square clamped diaphragm is near the center of the edge of the diaphragm oriented at 45° to this edge. Under these conditions, the transverse voltage strain gauge is oriented such that the coordinate system defined by the current axis, the substrate normal, and the cross product of these two vectors corresponds to the state of maximum shear stress in the diaphragm structure.

Recalling that the shear stress piezoresistive coefficient, π_{44}' is maximized when the current axis of the transverse voltage strain gauge is oriented at 45° to the (110) wafer flat on a (001) substrate, it can be seen from eqn. (8) that, if the edge of the diaphragm is also oriented parallel to the wafer flat, the output of the pressure transducer will be maximized. Fortunately, such a condition can be easily satisfied in silicon pressure transducers, since the normal orientation of an anistropically etched diaphragm on a (001) substrate is such that the edges of the diaphragm are parallel and perpendicular to the (110) wafer flat as a result of the crystallography of the substrate.

Figure 4 shows schematically the layout of a silicon pressure transducer employing a transverse voltage strain gauge using the design rules developed in this section. As can be seen in this figure, the stress sensitive resistor is oriented at 45° to the edge of the square diaphragm and is located along the center line of the diaphragm near the edge. The two voltage taps used to sense the transverse field generated by the pressure induced shear stress are located at the midpoint of the resistor at right angles to the current axis. These voltage sense taps can be fabricated with the same photolithography and diffusion steps used to fabricate the stress sensitive resistor itself, allowing these taps to be very accurately positioned with respect to the resistor. The importance of this ability will be discussed later. A secondary, heavily doped enhancement diffusion is employed to minimize the total impedance of the device, to eliminate the need for metal runs on the silicon diaphragm, and to provide for good ohmic contact to the metallization.

PACKAGE AND ASSEMBLY DESIGN

Since silicon pressure transducers are very sensitive strain gauges, special requirements are placed on the packaging schemes used to manufacture the devices. In order to maintain the best possible performance of the transverse voltage strain gauge pressure transducer as well as take full advantage of the mass production techniques of the semiconductor industry, a package was designed that reduces non-pressure related stresses to a minimum as well as provide a form that lends itself to high speed automated assembly and testing techniques. A cross-sectional view of this package is shown in Fig. 5. After processing is complete the transverse voltage pressure trandsucer wafer is bonded to a silicon substrate using a glass frit that has a thermal coefficient of expansion close to silicon (see Fig. 1). The bonded pair of wafers are sawn and the individual die bonded to the base plate using a soft silastic adhesive which isolates the transducer die from assembly and thermally induced stresses. After attaching wires to the die the package is filled completely with a soft, hydrostatic methyl-silicone gel to protect the surface of the die from harsh environments and a metal cap heat staked to the top. The chip carrier concept is similar in assembly to lead frame type assembly that is prevalent in the semiconductor industry. The package was designed with chamferred surfaces in order to provide an area where a pressure tight seal can be made quickly and reliably using an automated clam-shell type of test fixture. The package is symmetrical around the plane of the leads, thus enabling the pressure signal to be applied from either side when used in a differential or gauge application as well as radially distributing any stresses due to mounting so that these stresses will not reach the transducer die.

COMPENSATION AND CALIBRATION OF THE TRANSVERSE VOLTAGE STRAIN GAUGE PRESSURE TRANSDUCER

The performance characteristics described in this section are based on the results of the testing of production quantities of the MOTOROLA "X-ducer" MPX series of monolithic silicon pressure transducers which employ the transverse voltage strain gauge technology [10]. All characteristics are given for a 3.00 Vdc supply voltage and at 25°C unless otherwise noted. Both full scale span and zero pressure offset values are ratiometric with the supply voltage.

A typical output voltage versus applied pressure curve for the MOTOROLA MPX-100D silicon pressure transducer is shown in Fig. 6. This is an uncompensated, uncalibrated differential pressure transducer covering the pressure range from 0 to 100 kiloPascals (kPa) measured without any externally applied calibration or temperature compensation techniques. The full scale span of this device is typically 60 mV with a nominal temperature coefficient of full scale span of -0.19%/°C over the temperature range of -40°C to +125°C. Since the offset of this type of transducer depends not on matching resistors but on how well the transverse voltage sense taps are aligned, and this is accomplished in a single photolithography step, the offset was designed purposely to be positive in sign in order to simplify the design of compensation and calibration circuits using this device. The offset typically ranges between 15mV and 25mV with a nominal temperature coefficient of ±15 uV/°C. The temperature coefficient of offset is relatively small due to the fact that again the need to match resistors and TCRs is eliminated in this design and the only change in offset over temperature is due to package related stresses. The resistance of the transducer is typically 460 ohms with a nominal temperature coefficient of resistance of 0.24%/°C. Both the non-linearity and the pressure hysteresis errors are typically on the order of ±0.05% FS. The non-linearity error is measured relative to the end-point straight line fit to the output values at the extreme points of the operating pressure range.

While this device is not temperature compensated and there is part-to-part variability in sensitivity and offset, it was designed such that it can be easily calibrated and temperature compensated over a fairly extensive temperature range using passive components. To see how this is accomplished let us consider the results given in eqn. (8) expressed in terms of the supply voltage, V_o, and the differential output voltage ΔV. For a resistor of length l and width w, the relationship between the output voltage and the supply voltage can be shown from eqn. (8) to be given by

$$\Delta V = (w/l)\pi'_{44}T'_{6}V_o \qquad (9)$$

As can be seen from this relationship the output voltage of the device is ratiometric with the supply voltage. Thus, both the offset and full scale span can be calibrated by adjusting the supply voltage and shunting currents in the output taps. The decrease in the output voltage with increasing temperature is due to the temperature dependence of the piezoresistive coefficient π'_{44}. This dependence is shown in Fig. 6. It is important to note that the results shown in the figure are for a constant supply voltage. Therefore, if the supply voltage were increased with temperature in the proper manner, it would be possible to keep the output voltage constant due to the ratiometric behavior of this device. It is possible to accomplish this by placing a resistor in series with the transducer and driving the circuit at a constant voltage. Since the TCR of the transducer is +2400 ppm the supply voltage across the transducer will increase at the rate of +2400 ppm and will overcompensate the decrease in full scale span of -1900 ppm. However, the "effective" temperature coefficient of resistance of the stress sensitive resistor can be reduced by the simple addition of a parallel resistor of the proper value. Such a circuit is shown in Fig. 7. Thus, the transverse voltage strain gauge pressure transducer can be calibrated for zero pressure offset and full scale span and compensated for changes in offset and full scale span by using only passive components.

A calibrated, compensated pressure transducer using the transverse voltage strain gauge technology and the compensation and calibration techniques described above has been fabricated on a single silicon die. Figure 8 shows the errors due to span shift with temperature over the range of -40°C to +125°C of a transducer of this design, while Figure 9 shows the errors due to thermal offset shift. This type of device was fabricated by depositing thin film resistors on the transverse voltage strain gauge transducer die and using a thin film laser trimmer for adjusting the resistor values on the die. The deposition and patterning of thin film resistor materials is done with similar techniques and processes as the deposition and patterning of the metallization. The use of thin film resistor materials in monolithic integrated circuits is fairly wide spread. A detailed review of the types of materials used and the kinds of devices that are fabricated using these materials is given by Waits [11]. The laser trimming techniques used to fabricate this type of transducer are similar to the techniques used in the fabrication of monolithic high accuracy

16 bit analog-to-digital and digital-to-analog converters save that with the transducer the part is exercised over pressure. It is interesting to note that the device shown in Figures 8 and 9 was exercised over a limited temperature range in order to increase the accuracy of the trim that compensates for thermal offset shift. However, it is possible to fabricate devices that show errors of ±1% FS from 0°C to 85°C without having to change the temperature of the device during trim. Temperature excursions are not required in order to compensate the temperature dependence of full scale span. It is possible to trim this device and compensate for thermal shifts in offset and full scale span without exercising the part over temperature due to fact that it is a single resistive element which eliminates the problem of resistor mismatch [4] and that the offset is defined by a single photolithographic step, making it highly reproducible.

CONCLUSIONS

It has been found that silicon pressure transducers using the four terminal transverse voltage strain gauge technology can give very good performance characteristics. The sensitivity of these devices is comparable to those obtained using the more common Wheatstone bridge construction while offering several advantages. Because of the small size of the active area of this type of strain gauge, very small nonlinearity errors can be achieved while maintaining high full scale span output voltages. Since the zero pressure offset voltage is determined by the same photolithography and diffusion steps used to fabricate the stress sensitive resistor, very good control can be achieved for this characteristic and its temperature coefficient. By using proper doping levels, temperature characteristics can be achieved which allow the temperature dependence of full scale span to be compensated using a single series resistor. A method has also been developed which allows for the fabrication of a compensation and calibration circuit on the same substrate as the pressure transducer using thin film resistor deposition and laser trimming techniques.

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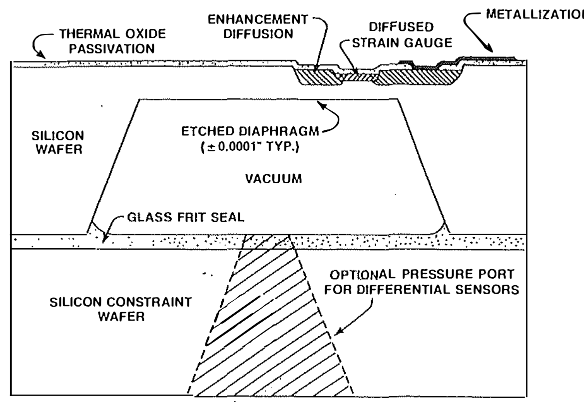

Fig. 1. Cross Sectional View of a Silicon Pressure Transducer

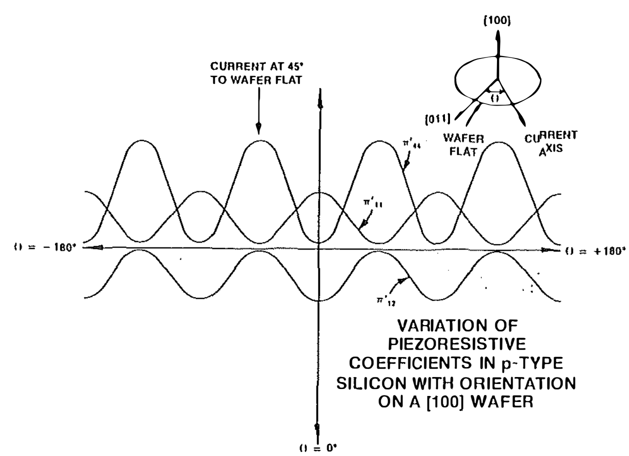

Fig. 2.

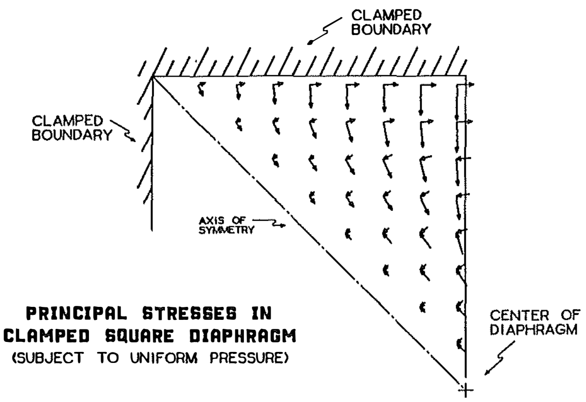

Fig. 3.

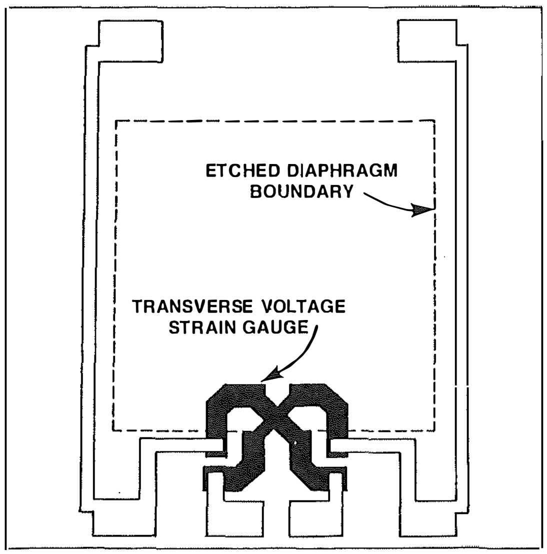

Fig. 4. Plan View of Motorola "X-ducer" Silicon Pressure Transducer.

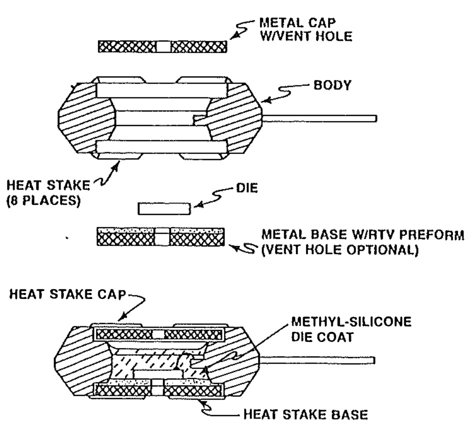

Fig. 5. Cross Sectional View of a Chip Carrier Pressure Transducer Package.

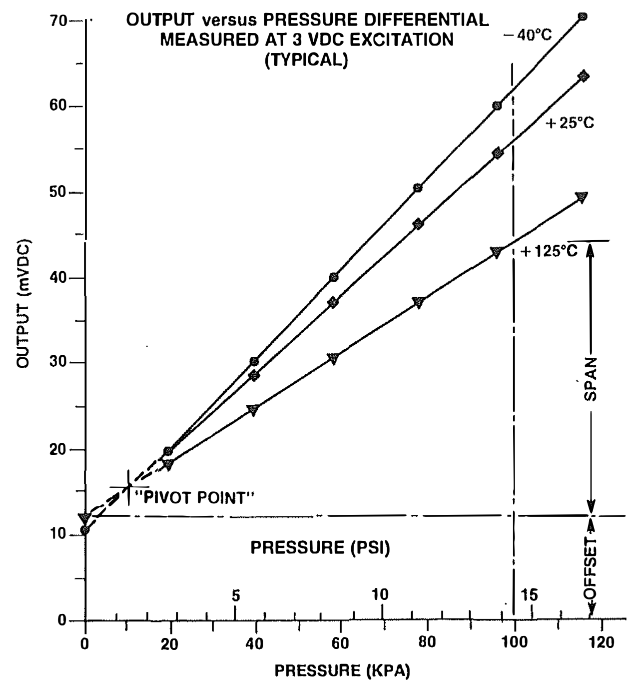

Fig. 6. Output of a Typical MPX-100 Pressure Transducer Demonstrating Temperature Dependence of Zero Pressure Offset and Full Scale Span.

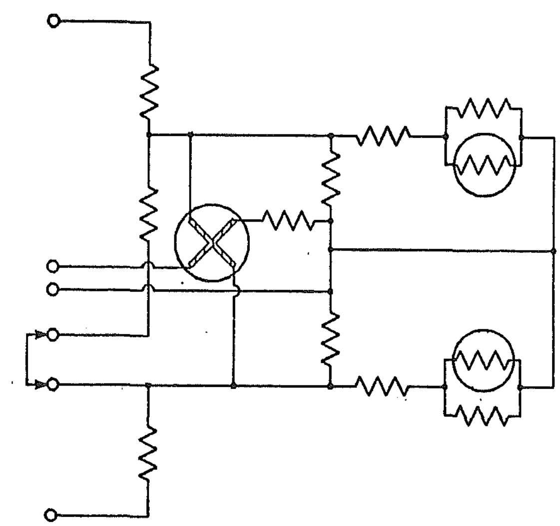

Fig. 7. Circuit Schematic for Compensation and Calibration of a Four Terminal Transverse Voltage Pressure Transducer.

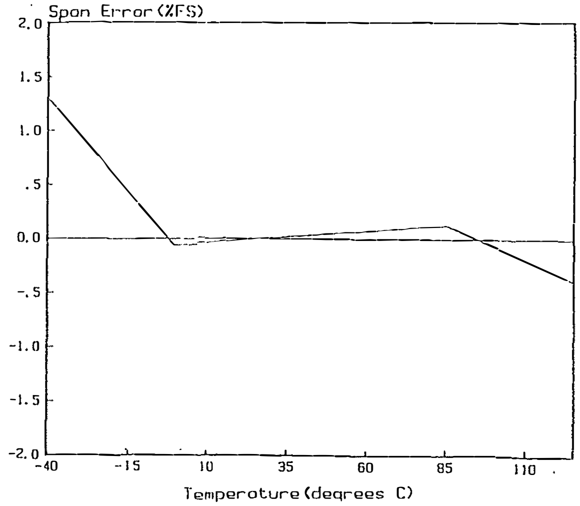

Fig. 8. Span Error vs. Temperature for a Pressure Transducer with On Chip Compensation and Calibration.

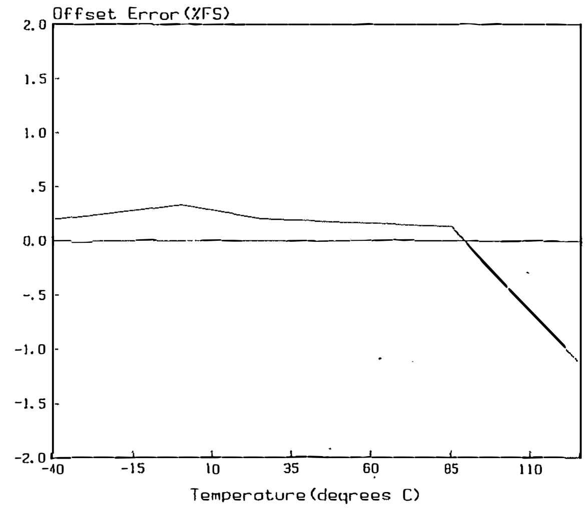

Fig. 9. Offset Error vs. Temperature for a Pressure Transducer with On Chip Compensation and Calibration.