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MEMS Based Pressure Sensors – Linearity and Sensitivity Issues

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Abstract: This paper describes the various nonlinearities (NL) encountered in the Si-based Piezoresistive pressure sensors. The effect of various factors like diaphragm thickness, diaphragm curvature, position of the piezoresistors etc. is analyzed taking anisotropy into account. Also, the effect of modified bending stiffness due to presence of oxide/nitride used for isolation between metal and diaphragm is studied from linearity point of view. *Copyright © 2008 IFSA.*

Keywords: Pressure sensor, Sensitivity, Linearity, Piezoresistance, Wheatstone bridge

1. Introduction

MEMS based Pressure sensors are mechanically similar to traditional sensors with the exception that these are Si based and on micrometer scale. The additional advantages of MEMS based pressure sensors include batch fabrication, high performance, small size, low cost, absence of adhesive bonding layer and easy integration with electronics on single chip. Pressure sensors have a wide-range of applications in various fields like automotive industry, biomedical, space applications and military applications. These pressure sensors are available in wide operating range covering from fractions of psi to 15,000 psi.

A lot of research has been carried out on micromachined piezoresistive pressure sensors in the recent years [1-4]. For high performance demands, the sensitivity and linearity must be improved. In order to increase the sensitivity, the diaphragm thickness should be thin. In present commercial Piezoresistive pressure sensors, Si diaphragms with less than 20 μm thickness are common [5]. Generally thin diaphragms are prone to large deflections and nonlinear effects. It is therefore necessary to optimize the diaphragm thickness with respect to rigidity and strength. Nonlinear higher order piezoresistance coefficients add-up the linearity error further. Proper selection of piezoresistors i.e. orientation, shape, location, doping concentration, dose etc. is essential. Finally the conversion of small resistance change to voltage output is another additive nonlinearity.

This paper reviews the types of nonlinearities in the context of Piezoresistive pressure sensors, giving basic relationships between pressure, stress, deflection, and resistance change and voltage output. The results of numerical simulations of square diaphragm for optimum load-deflection are presented.

2. Nonlinearities in Piezoresistive Pressure Sensor

A Piezoresistive pressure sensor consists of a diaphragm with diffused piezoresistors in Wheatstone bridge configuration (Fig. 1). The diaphragm converts pressure into mechanical stress, the piezoresistors converts this stress into resistance change and finally the resistance change is converted the into output voltage. These subsystems have to be considered and optimized in order to realize a pressure sensor with high sensitivity and good linearity. Nonlinearity of a transducer can be defined as the maximum deviation of the calibration curve from specified best fit straight line. Mathematically, overall non-linearity for Piezoresistive pressure transducer can be given as [5]

$$NL = \sqrt{NL^2{}_{p,d} + NL^2{}_{d,r} + NL^2{}_{p,r}}\ , \tag{1}$$

where $NL_{p,d}$ is the nonlinearity between pressure-deflection (structural nonlinearity), $NL_{d,r}$ is the nonlinearity between deflection-resistance (piezoresistive nonlinearity) and $NL_{p,r}$ is the non-linearity due to difference in the sensitivities to pressure among resistors (bridge nonlinearity). In what follows, these nonlinearities are discussed in some detail.

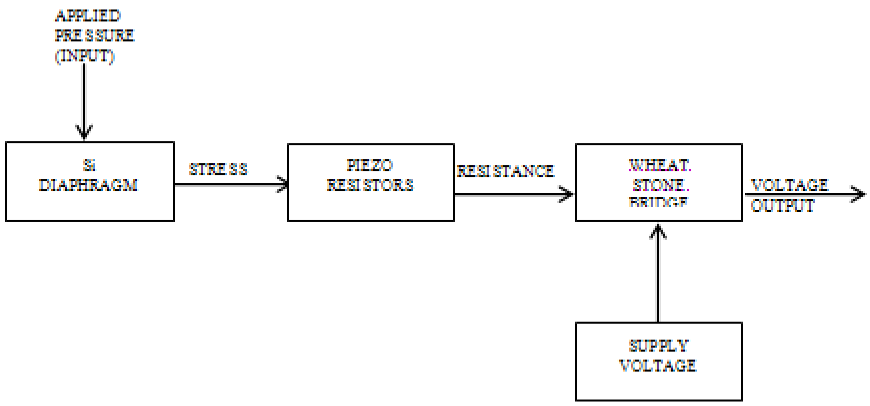


Fig. 1. Principle of Piezoresistive pressure sensor.

3. Structural Nonlinearity

Consider a thin silicon plate subjected to an applied pressure p resulting in lateral bending. The governing differential equation can be written as [6]

$$\frac{\partial^2 M_x}{\partial x^2} - 2\frac{\partial^2 M_{xy}}{\partial x \partial y} + \frac{\partial^2 M_y}{\partial y^2} = -p \tag{2}$$

The above equation (2) can be written in terms of load-deflection form as

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^2 w}{\partial x^2 \partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{p}{D}, \tag{3}$$

where w(x, y) is the deflection which can be found by solving (3) with proper boundary conditions. D refers to flexural rigidity assuming the constant plate thickness, h. Various numerical techniques [7-8] are available to solve such equations with proper boundary conditions. The bending strains at the surface can be written as:

$$\begin{aligned} \varepsilon_{xx} &= -\frac{h}{2}\frac{\partial^2 w}{\partial x^2} \\ \varepsilon_{yy} &= -\frac{h}{2}\frac{\partial^2 w}{\partial y^2} \\ \varepsilon_{xy} &= -h\frac{\partial^2 w}{\partial x \partial y} \end{aligned} \tag{4}$$

Using constitutive equations, the stresses can be found as:

$$\begin{aligned} \sigma_{xx} &= \frac{hE}{2(1-\upsilon^2)}\left(\frac{\partial^2 w}{\partial x^2} + \upsilon\frac{\partial^2 w}{\partial y^2}\right) \\ \sigma_{yy} &= \frac{hE}{2(1-\upsilon^2)}\left(\frac{\partial^2 w}{\partial y^2} + \upsilon\frac{\partial^2 w}{\partial x^2}\right) \\ \tau_{xy} &= hG\left(\frac{\partial^2 w}{\partial x \partial y}\right) \end{aligned} \tag{5}$$

The above description is just a summary of general practice used for calculating stresses and deflection of a square plate clamped at the edges. The detailed analysis is based on small deflection theory. It assumes that the stress distribution is a result of pure bending i.e. neutral plane of the diaphragm is not stretched. This assumption requires that the deflection of the diaphragm be small when compared with its thickness (w≤0.4h). For thin diaphragms, generally encountered in pressure sensors, this analysis is not sufficient. In case of thin diaphragm, if deflection is not small, neutral plane of the diaphragm will also stretch like a balloon. It is called “balloon effect” [14]. The stress caused by the stretch of neutral plane has to be considered in that case.

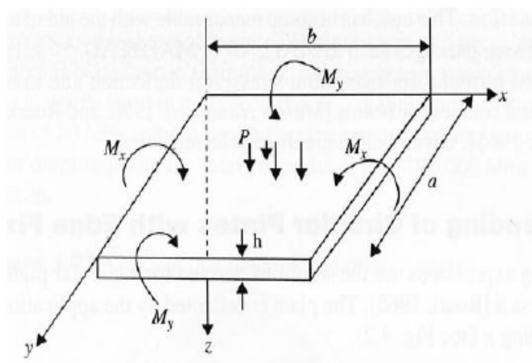


Fig. 2. Plate subjected to uniform pressure load.

The factors that are contributing to structural nonlinearity can be grouped as
(i) Geometric nonlinearity
(ii) Material nonlinearity
(iii) Contact nonlinearity

Geometric nonlinearity occurs when there are large displacements under specified loading conditions. In these cases the small deflection theory is not sufficient to give the deformation behaviour of the plate in full working range. Now strain displacement relations are no longer linear:

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2$$
$$\varepsilon_{yy} = \frac{\partial v}{\partial y} + \frac{1}{2}\left(\frac{\partial w}{\partial y}\right)^2 \quad (6)$$
$$\varepsilon_{xy} = \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) + \left(\frac{\partial w}{\partial x}.\frac{\partial w}{\partial y}\right),$$

where u, v and w are displacements in x, y and z directions respectively. In this case the stress in diaphragm consists of two parts: the first caused by bending of the diaphragm and second stress caused by the stretch of neutral plane. Mathematically,

$$\sigma = \sigma_{bending} + \sigma_{stretch} \quad (7)$$

Here the load (pressure) is shared by the stretch action also, so bending stress will reduce as compare to the value calculated by small deflection theory.

Fig. 3 shows simulation results of linearity error with and without accounting the effect of large deflections for a square diaphragm of width 1054 µm and 10 µm thickness used for 1 bar pressure sensor. The analysis is done using ANSYS [8]. As can be seen, the effect of large deflections is quiet high in this case. The curve is now no longer symmetrical with respect to central point. So the diaphragm is redesigned with optimum dimensions for the same pressure range. Fig. 4 shows the results of linearity error with modified dimensions of 16 µm thickness. The reduction in output signal can be suitably taken care of in the electronic signal processing subject to meeting the sensitivity requirements.

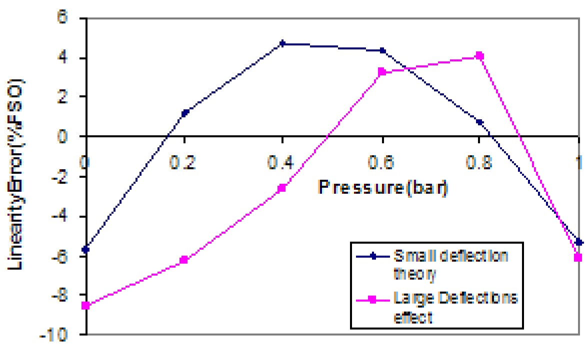


Fig. 3. Linearity error (structural) with and without considering large deflection effect.

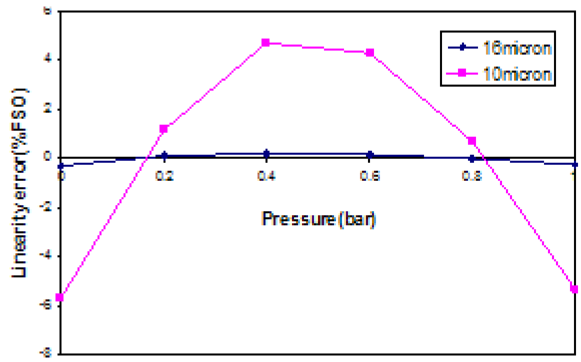


Fig. 4. Linearity (structural) error for two different thicknesses of the diaphragm.

Material non-linearity should be ideally zero in case of single crystal Si diaphragms as the stress-strain relation is linear up to fracture point. However, residual stresses of the fabrication process like deposition/growth, implantation and anisotropic etching etc. contribute to the nonlinearity. Some of these stresses can be relieved during fabrication process itself like drive-in, annealing etc. However complete removal of the stress is not always possible since these are not completely known-qualitatively and quantitatively. Thus the total stress in diaphragm will be:

$$\sigma = \sigma_{bending} \pm \sigma_{residual} \tag{8}$$

It is found [10] that tensile residual stresses increase the bending stiffness (higher stress leads to higher stiffness) of the plate while compressive residual stresses reduce the stiffness and could eventually lead to buckling. This effect was investigated by simulating the diaphragm with grown oxide (having compressive stress) and with both oxide and CVD nitride (CVD Nitride has tensile stress) [10]. It is seen from Fig. 5 that the effect of 0.1 micron grown oxide is negligible as compare to bare Si diaphragm (without oxide). The output increases due to compressive stress and also the structural nonlinearity by about 0.02% FSO. Similarly the effect of Oxide/Nitride layer on the diaphragm is shown in Fig. 6. It shows the degradation of both linearity as well as output as compare to only oxide layer.

Contact Non-linearity arises due to change in boundary conditions. Since edges are assumed to be built-in, in case of thin diaphragm this nonlinearity is negligible compared to the other two described earlier.

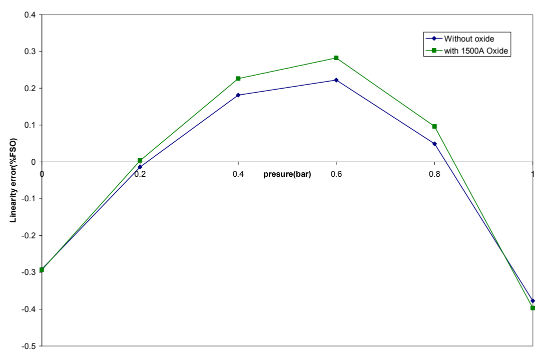


Fig. 5. Linearity (structural) error with and without oxide.

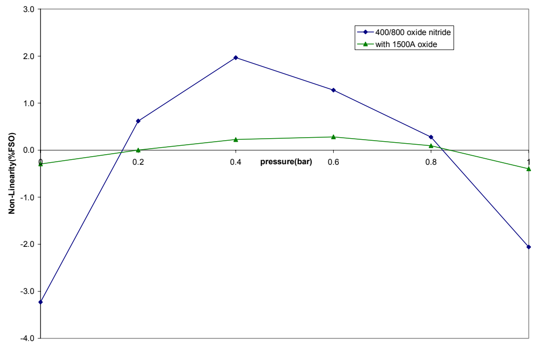


Fig. 6. Linearity error with and without oxide/nitride combination.

The polarity (+ve or –ve) of curvature has also effect on the overall sensor nonlinearity. It is seen (Fig. 7) that the application of pressure on the rear side of the diaphragm gives more nonlinearity as compared to the front side application. As the resistors are implanted on the top surface of the diaphragm with approximately 1 µm depth, these can be assumed as surface resistors. ΔR/R is mainly due to the stress distribution over the resistor area. When the pressure is applied from the top side of the diaphragm, the resistors experience the tensile stress (conventionally taken as +ve). So, the ΔR/R is +ve for longitudinal resistor and –ve for transverse resistor. The reverse effect is seen when the pressure is applied from rear side. Secondly, the longitudinal ΔR/R is generally more than the transverse one. However, for linearity, the longitudinal and transverse ΔR/Rs should be equal in magnitude. These two factors increase the overall nonlinear response of the device when pressure is applied from rear side.

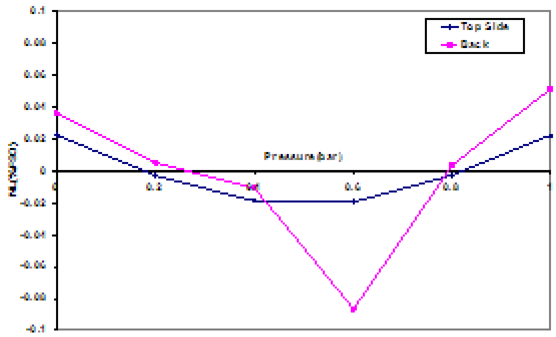


Fig. 7. Nonlinearity comparison for front and-rear side pressure application.

4. Piezoresistive Nonlinearity

For a diffused piezoresistor subjected to parallel and perpendicular stress components, the resistance change is given by

$$\frac{\Delta R}{R} \approx \frac{\Delta \rho}{\rho} = \Pi_l \sigma_l + \Pi_t \sigma_t \quad , \tag{9}$$

where Π_l and Πt are piezoresistive coefficients parallel and perpendicular to the resistor length. This relation assumes that stress levels are relatively small and hence Piezoresistive coefficients of Silicon are independent of stress i.e. when stresses are linear with applied pressure, resistance change will be linear with stress. But, in actual practice extra amount of nonlinearity is observed. This nonlinearity is due to the dependence of piezoresistive coefficients on the stress. However, investigation of the dependence of piezoresistive coefficient on stress is quite involved as there are many components of stress tensor and the measurement of higher order effects requires very high accuracy. The magnitude of this nonlinearity is proportional to the stress value. It has been investigated [12] that nonlinear Piezoresistive coefficients up to third order can play major role in certain crystallographic directions. Up to first order Π_{11}, Π_{12} and Π_{44} can give Π_l and Π_t for any arbitrary direction in the crystal. These three coefficients further are functions of doping concentration and temperature. But for second order, nine more such piezoresistance components are needed to calculate Π_l and Π_t. The observation of Matsuda et al [12], for p-type resistors oriented in <110> orientations with a doping level of $2x10^{18}/cm^3$, the dependence of nonlinearity on stress is shown in Fig. 8.

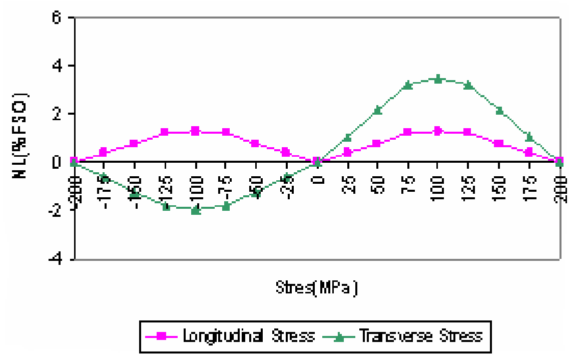


Fig. 8. Nonlinearity of p-type piezoresistors for <110> stress (doping level: $2x10^{18}/cm^3$).

As can be seen, the nonlinearity due to piezoresistive effect for longitudinal resistor is positive for both tensile and compressive bending stresses whereas for transverse resistor, NL is negative for compressive and positive for tensile stresses. It is found that third order polynomial approximation gives fairly good match [14].

Based on this, one of the techniques adopted for reducing this nonlinearity is by using only transverse piezoresistors instead of both transverse and longitudinal piezoresistors. The effect Piezoresistive nonlinearity is seen by diffusing suitable resistors on the diaphragm in full Wheatstone configuration. It was observed that "structural" nonlinearity is partially compensated by the nonlinearity of the Piezoresistive effect. Fig. 9 shows how structural linearity error changes from 0.37 % to 0.23 % FSO for 16 μm diaphragm with piezoresistors.

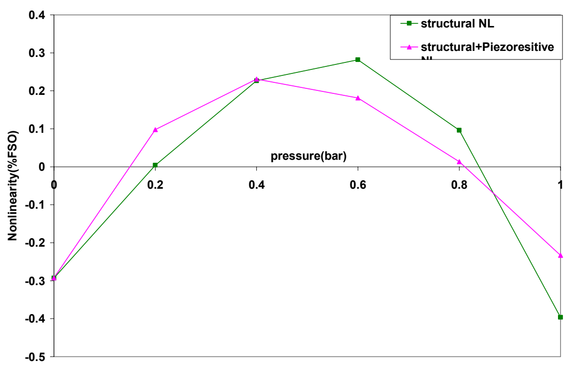


Fig. 9. Structural NL and Overall NL for 0-1bar pressure sensor.

5. Bridge Nonlinearity

When an external pressure is applied, the diaphragm is stressed and the longitudinal and transverse resistors undergo different changes in resistances due to the average stresses being different in each resistor. The expression for the resistance change is given in equation (9). Generally, all the four resistors are connected in Wheatstone bridge – either full active or partial. Considering full Wheatstone bridge configuration the output voltage can be calculated as:

$$\frac{V_o}{V_s} = \frac{(\Delta R/R)_l - (\Delta R/R)_t}{2 + (\Delta R/R)_l + (\Delta R/R)_t} \tag{10}$$

Ideally, in a linear voltage output bridge the output is proportional to the deflection of the membrane and hence to the applied pressure.

The denominator of the above expression (10) introduces nonlinearity which can be eliminated by designing the resistors such that

$$\left|\left(\frac{\Delta R}{R}\right)_l\right| = \left|\left(\frac{\Delta R}{R}\right)_t\right| \tag{11}$$

i.e. sensitivity among the piezoresistors should be same. If the above condition is met then the expression for the output voltage ratio is equal to the fractional change in piezoresistance of the resistors. This nonlinearity can be understood by considering the linear but different resistance change with pressure in longitudinal and transverse piezoresistors. The change in resistance is given by

$$\begin{aligned} \left(\frac{\Delta R}{R}\right)_l &= \alpha p \\ \left(\frac{\Delta R}{R}\right)_t &= -\beta p \end{aligned}, \tag{12}$$

where α, β denotes the sensitivities of the resistors respectively. Substituting (11) in (9), and assuming offset voltage of the bridge is zero, the output voltage (V_0) is

$$V_o = \frac{(\alpha + \beta)p}{2 + (\alpha - \beta)p} V_s \tag{13}$$

The end point nonlinearity at a specific test pressure p_i can be given as

$$NL_i(\%FSO) = \frac{V_o(p_i) - \frac{V_o(p_m)}{p_m} p_i}{V_o(p_m)} x100 \tag{14}$$

Substituting (12) in (13) and assuming maximum nonlinearity for the whole operation range is at $p_i = p_m/2$, i.e. half of maximum applied pressure (p_m), the NL will be

$$NL(\%FSO) = \frac{p_m}{2}\left[\frac{(\alpha - \beta)}{4 + (\alpha - \beta)p_m}\right] x100 \tag{15}$$

It is clear from (15) that as the difference between α and β increases the linearity error will increase. Further, in above equation, it was assumed that the resistance sensitivity varies linearly with pressure, but in actual practice it is not the case. So the difference between resistor sensitivities can still be higher and hence the linearity error. Generally, this nonlinearity component has least effect if location of the piezoresistors is well optimized. The piezoresistors have to be placed properly on the diaphragm. For p-type resistors aligned in <110> on (100) Si wafer, piezoresistive coefficients (Π_l and Πt) are almost equal in magnitude but opposite in sign, the bridge configuration allows maximizing the sensitivity of the output signal.

6. Experimental Results

The simulation results were experimentally verified by fabricating the device [6, 15]. Standard CMOS technology and anisotropic etching technology are used to fabricate the device. An n-type silicon wafer with <100> plane is used as a substrate for sensor fabrication. The piezoresistors, connected in a Wheatstone bridge, are located at (110) for longitudinal direction and (110) for transverse direction [5]. Fig. 10 shows the high resolution photograph of the fabricated device.

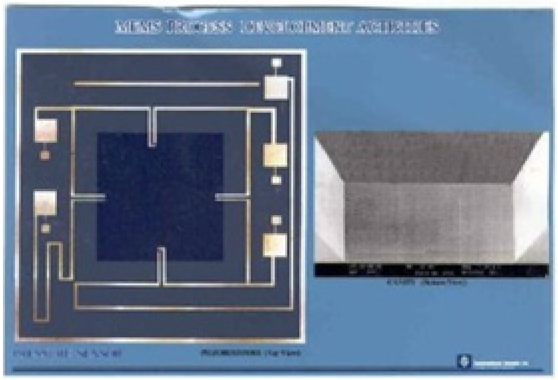


Fig. 10. Image showing top and bottom view of fabricated device.

Packaged devices are calibrated to determine the nominal output, combined nonlinearity and hysteresis and only hysteresis. Primary pressure standard model was used to calibrate the pressure sensor in five ascending and five descending pressure values of equal interval. Excitation to the bridge is kept constant at 3 Volts D.C. and output recorded in mV. By method of least squares, best fit straight line method the non linearity and hysteresis (NL+H) is calculated. Further, all devices are calibrated in both absolute and gauge mode. A high precision controlled current source is used to provide the excitation across the sample and the corresponding voltage is measured by 6½ Digit DMM. The observed as well as calculated nonlinearity for 0-1 bar pressure range is plotted in Fig. 11. Figs. 12 (a), (b) and (c) shows the comparison of hysteresis, combined NL and hysteresis and sensitivity of earlier design (with 10µm diaphragm having oxide/nitride layer over it) and modified design (with 16µm diaphragm having only thicker oxide layer on it).

As can be seen from Fig. 12 (a), considerable improvement in the hysteresis is observed in the modified design in which nitride layer from the diaphragm is completely removed. This is because the deposited nitride layer has high tensile residual stress in it [10], which modifies the bending stiffness of the diaphragm and hence the hysteresis. In addition, it affects the linearity of the device. No significant improvement, however, is observed in the combined non-linearity and hysteresis (Fig. 12 (b)), as only the thickness of the diaphragm is modified without changing the resistor position. (Due to the nature of anisotropic etching diaphragm size also increased while increasing the thickness.) This increased the offset to piezoresistor location from the initial optimized position. These two opposing factors effectively get balanced thus giving no significant change in the combined NL and hysteresis By optimizing the resistor location in the modified size of the diaphragm, improvement in nonlinearity can be achieved. The-results are summarized in Table 1.

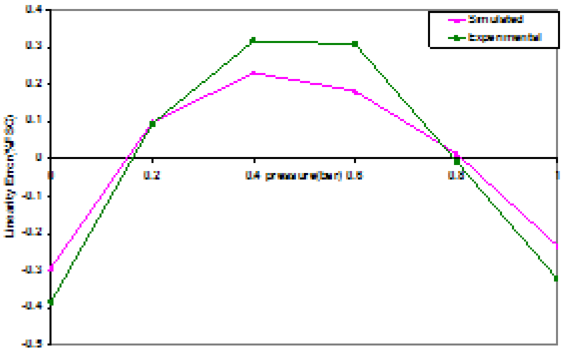
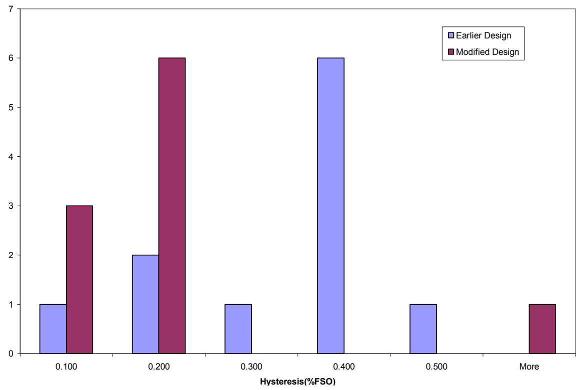
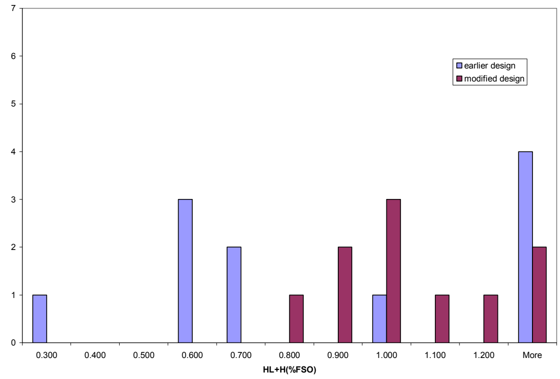


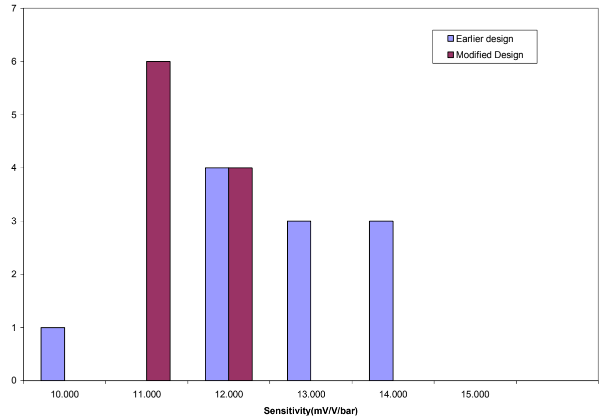
Fig. 11. Observed & Calculated nonlinearity.



(a)



(b)



(c)

Fig. 12. Comparison of (a) Hysteresis (b) NL+H and (c) Sensitivity for 10 µm and 16 µm diaphragm pressure sensors.

Table 1. Design improvement.

	Earlier Design	Modified Design	Improvement
Nonlinearity (%FSO)	1.0	0.40	2.5 times
Hysteresis (%FSO)	0.4	0.2	2 times
Combined NL+H (%FSO)	1.19	0.88	1.35 times
Sensitivity (mV/V/bar)	12.1	10.9	-0.9 times

Improvement of the order of 2.5 times and 2 times in nonlinearity and hysteresis respectively is achieved in the modified design. The marginal reduction in the sensitivity due to the increased thickness of diaphragm which can be taken care of in the post processing electronics

7. Conclusions

Linearity and sensitivity are the two performance parameters of the pressure sensor, which are traded off in the realization of the sensor. An analysis of the various issues involved in the performance optimization is presented in this paper. It is *analytically* as well as *experimentally* found that using 16μm thick diaphragm in place of 10μm shows good linearity response of the order of 2.5 times with tolerable loss in sensitivity which is 0.9 times with respect to 10 μm thickness. Hysteresis improvement of the order of 2 times is seen by replacing the oxide/nitride stack by only thicker oxide layer over the diaphragm. Depending on the causes of nonlinearities, the following approaches are suggested to reduce/eliminate the same:

(a) Using optimum thickness of the diaphragm.

(b) For isolation purposes between metal and diaphragm, avoiding use of nitride (It is always better to use only oxide). If oxide nitride stack is used, thicknesses of these should be properly chosen to have minimum residual stress effect.

(c) Geometric non-linearity can also be well taken care by making $\sigma_{bending}$ and $\sigma_{stretch}$ of opposite nature.

(d) Piezoresistor design to be such that $\frac{\Delta R}{R}$ shall have linear response with load/stress. This can be ensured by proper placement of the resistors.

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Guide for Contributors

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Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

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- Sensor instrumentation;
- Virtual instruments;
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- Microsystems;
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