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Sensitivity Analysis of Pressure Sensor for Environmental Application

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ABSTRACT
In this paper the sensitivity of pressure sensors based on their shape has been studied. Three sensors based on rectangular, square and cross square shaped diaphragms having the same surface area and thickness have been analysed. Performance parameters like the induced stress, deflection and sensitivity of the diaphragms have been calculated using the finite element tool INTELLISUITE. An evaluation of the stress profile across the diaphragms has been done. The analysis shows that the square diaphragm based sensor is more sensitive for environmental application range. It has also been found that the variation in the position of the piezoresistor plays a greater role in determining the sensitivity of the sensor. From the results of the simulations ,the shape and design of the sensor can be optimized for a given pressure range.

Keywords---Diaphragm, Sensors, Piezoresistive, Intellisuite.

I. INTRODUCTION

Pressure Sensors are one among the widely used micro sensors. The property of Piezoresistivity in Silicon causes deformation of energy bands on application of stress leading to change in resistance[1].The sensor is designed using 3D Builder Module of Intellisuite[2]. The mechanical deformation thus caused in the diaphragm is commonly sensed by piezoresistive or capacitive methods[3-5]. Though capacitive sensors have the advantage of greater pressure sensitivity and decreased temperature sensitivity. Despite that, piezoresistive sensors are preferred one,due to advantages such as excellent linear input-output relationship, small size, low phase lag, large dynamic range and easy integration with electronics[6-7]. A typical piezoresistive pressure sensor consists of two components i.e a diaphragm and four piezoresistors. The diaphragm which is the main sensing element can be square , rectangular or cross square[8]. The geometry of sensing element depends upon techniques which occupy lesser area, enable easier lithography and fabrication[9] .

II. DESIGN CONSIDERATION

In this paper the effect of the geometry of the diaphragm on the sensitivity of a Silicon substrate based pressure sensors have been studied .The layout of the paper is as follows—In section II the design of the diaphragm structures is explained. Section III describes the finite element analysis done using Intellisuite. Section IV explains the results of the piezoresistive analysis done on the sensors where the sensitivities are compared. The Conclusions are presented in Section V.

When a uniform pressure P(x,y) as depicted in Fig.1 acts on a diaphragm normal to its surface,the diaphragm undergoes a strain giving rise to

- Normal stress σx and σy which in turn give rise to bending moments Mx and My.
- Shear stress τxy which in turn gives rise to the twisting moment Mxy.

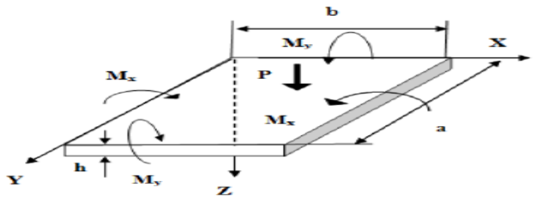


Figure.1 Deflection & Moments

The equation for determining the deflection w(x,y) of a diaphragm with a uniform thickness, and perfectly clamped edges subjected to an applied pressure P can be derived from the small scale deflection theory which is given as

$$\frac{\partial^4 w}{\partial x^4}+\frac{\partial^4 w}{\partial y^4}+2\times\frac{\partial^4 w}{\partial x^2\times\partial y^2}=\frac{P}{D} \quad \ldots\ldots\textbf{(1)}$$

Where D is the flexural rigidity. It is expressed as

$$D=\frac{E\times h^3}{12\times v^2} \quad \ldots\ldots\textbf{(2)}$$

Here E is the Young modulus, ν is the Poisson ratio and h is the thickness of the diaphragm. In this paper piezoresistive effect is used as the sensing principle, which changes the resistivity according to the stress change of the diaphragm. Piezoresitivity is change of the resistivity of a material due to applied pressure. Resistivity change can be calculated using the following equation

$$\begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \\ \rho_5 \\ \rho_6 \end{pmatrix} = \begin{pmatrix} \rho_0 \\ \rho_0 \\ \rho_0 \\ 0 \\ 0 \\ 0 \end{pmatrix} + \rho_0 \begin{pmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{22} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{pmatrix}$$

The stress acting on the material is denoted using σ and it contains six components corresponding to the directions of the stress, π is used to denote piezoresistive coefficient matrix, ρ is the resistivity value of the silicon when stress is acting on the material and ρo is the reference resistivity value of silicon. Using the relationship between the electric field(E), current field (J) and the resistivity (ρ), the resistance change can be calculated as

$$\begin{pmatrix} E_1 \\ E_2 \\ E_3 \end{pmatrix} = \begin{pmatrix} \rho_1 & \rho_6 & \rho_5 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{pmatrix} \begin{pmatrix} J_1 \\ J_2 \\ J_3 \end{pmatrix}$$

The Current density vector can be written in a vector format with unit vectors in the directions of axes x, y & z as denoted by l, m, & n.

$$J = N \times J = l \times J_1 + m \times J_2 + n \times J_3 \quad \ldots\ \textbf{(3)}$$

Now using the equation V=IR the new resistor value R can be calculated as

$$R = \frac{(E_1 l + E_2 m + E_3 n) \times L}{J \times A} \quad \ldots\ldots\ldots\ldots\ \textbf{(4)}$$

where L denotes length of the resistor and A is the cross sectional area of the resistor.

III. DIAPHRAGM DESIGN & FEM ANALYSIS

For the pressure sensor design, a 10µm thick sensing layer with the substrate dimensions of 120µm X 120µm X 10µm is used. Here three different shapes of diaphragms i.e rectangular , square and cross square are modelled and simulated using the finite element method analysis in INTELLISUITE software. According to the FEM analysis results, the diaphragm design which delivers the higher sensitivity for the desired range and high stress concentrated areas; are identified as right place for the piezoresistive elements.While designing the membrane ,the relevant assumptions of thin plate deflection theory are considered , to achieve senser linearity. They are as following:

- The membrane deflection should be less than 20% of thickness of membrane.
- The thickness of membrane should not exceed 10% of length of diaphragm.
- There should not be any initial stress in the membrane.

The first assumption limits the applied pressure to the membrane, which will decide the range of the sensor. The second assumption is easily obtained in this design since membrane thickness is 10µm. Now consider the third assumption, although the MEMS films have very low intrinsic stress, they can be practically assumed as zero. Piezoresistive elements are placed in the high stress concentrated areas.To find the best diaphragm design for desired range, FEM analysis is carried out ,changing the membrane dimensions, based on the assumption that the maximum deflection should not exceed 20% of the diaphragm thickness.The Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system can be apportioned to different sources of uncertainty in its inputs. A practical method is uncertainty analysis, which has focus on uncertainty quantification and propagation of uncertainty. Ideally, uncertainty and sensitivity analysis should run in tandem. Here keeping in view of both normal and tangential stress the sensitivity is given by relation as below

$$S = \frac{2.762 \times 10^{-3} \times \left| \sigma_2 - \sigma_1 \right|}{4 + 0.11 \times 10^{-3} \times \left| \sigma_2 + \sigma_1 \right|} \quad \ldots\ \textbf{.(5)}$$

Where σ_2 and σ_1 are normal and tangential stresses. In present analysis S_{xz} and S_{xy} are normal and tangential stresses respectively.

IV. RESULTS AND DISCUSSION

Design optimization of pressure sensor is done by varying the diaphragm thickness, shape of piezoresistors and the position of piezoresistors. In this paper three sensors has been designed using Silicon as substrate and Polysilicon as sensing layer. The dimension and material property has been explained on next page.

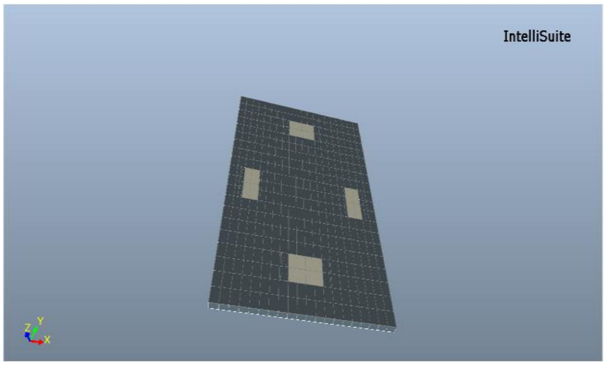


Fig.2 Rectangular Type Diaphragm

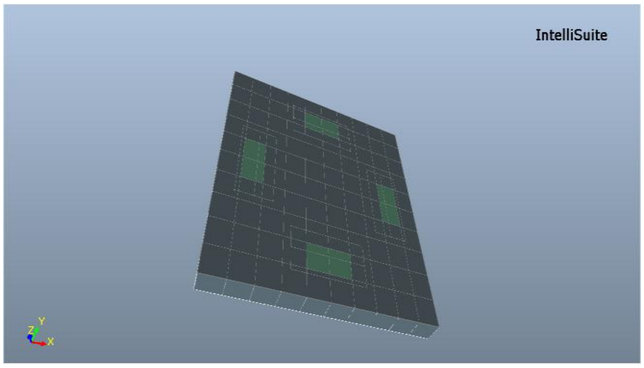


Fig.3 Square Type Diaphragm

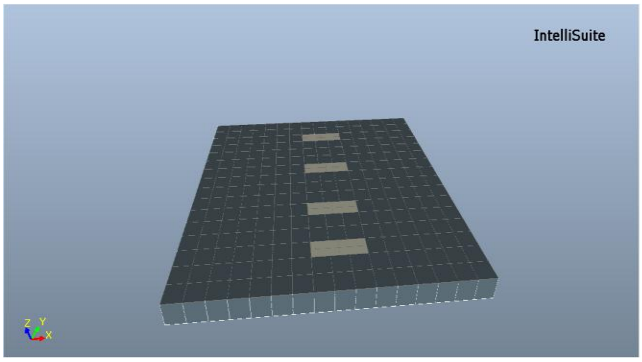


Fig.4 Cross Square Type Diaphragm

Table.1
Dimension & Material Property of Sensor

LAYERS	DIMENSION (µm)	MATERIAL	MATERIAL PROPERTY		
			YOUNG MODULUS (GPa)	POISSON RATIO	DENSITY (gm/cc)
Substrate	160×160×10	Silicon	170	0.26	2.32
Sensing Layer	40×20×10	Polysilicon	169	0.22	2.238

Table.2
Sensitivity Analysis of Rectangular type diaphragm Sensor

Input Pressure (Kpa)	Stress Gradiant S_x (Mpa)	Stress Gradiant S_{xy} (Mpa)	Sensitivity
90	80.8457	116.475	4.532
95	80.8977	116.491	4.526
100	80.9497	116.506	4.521
105	81.0016	116.521	4.513
110	81.0536	116.536	4.501

Table.3
Sensitivity Analysis of Square type diaphragm Sensor

Input Pressure (Kpa)	Stress Gradiant S_x (Mpa)	Stress Gradiant S_{xy} (Mpa)	Sensitivity
90	35.7644	3.4221	20.70
95	35.7769	3.4242	20.71
100	35.7893	3.4263	20.72
105	36.0563	4.0425	20.03
110	36.0811	4.0466	20.02

Table.4
Sensitivity Analysis of Cross square type diaphragm Sensor

Input Pressure (Kpa)	Stress Gradiant S_{xz} (Mpa)	Stress Gradiant S_{xy} (Mpa)	Sensitivity
90	45.2624	76.5536	6.447
95	45.2632	76.5655	6.449
100	45.2636	76.5775	6.451
105	45.2642	76.5894	6.542
110	45.2653	76.6014	6.454

SIMULATIONS RESULTS

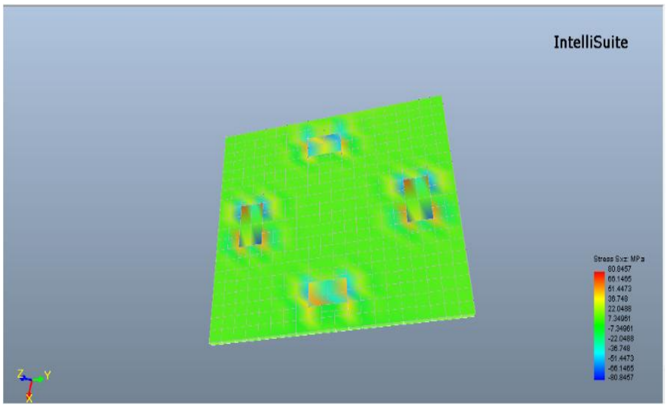


Fig.5 Rectangular Diaphragm (90 Kpa)

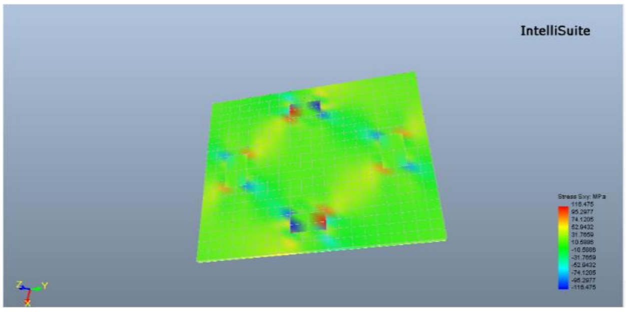


Fig.6 Rectangular Diaphragm (90 Kpa)

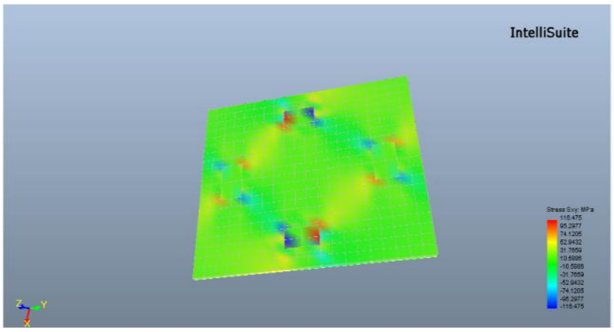


Fig.7 Rectangular Diaphragm (110 Kpa)

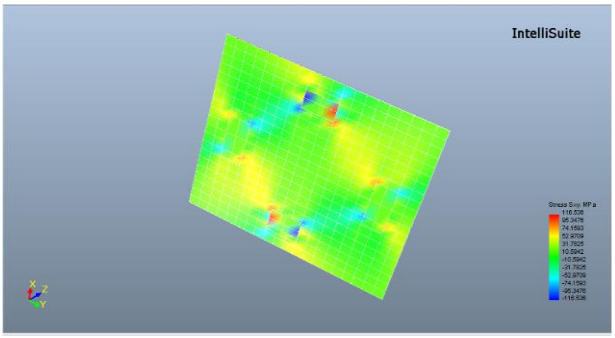


Fig.8 Rectangular Diaphragm (110 Kpa)

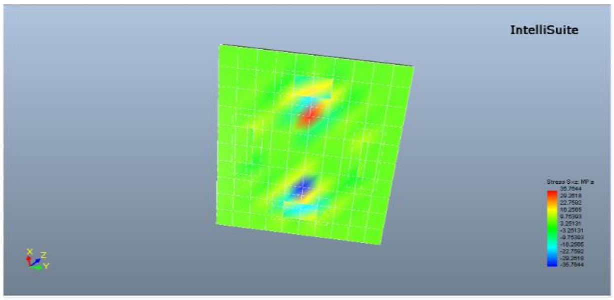


Fig.9 Square Diaphragm (90 Kpa)

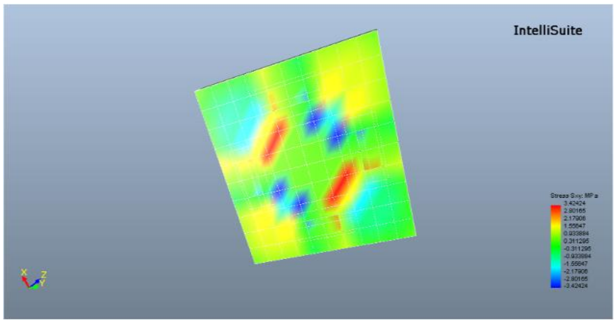


Fig.10 Square Diaphragm (90 Kpa)

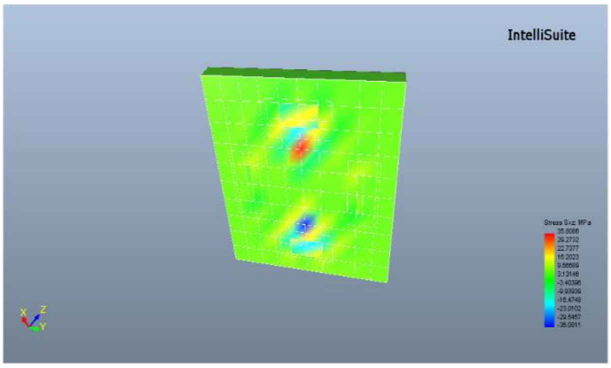


Fig.11 Square Diaphragm (110 Kpa)

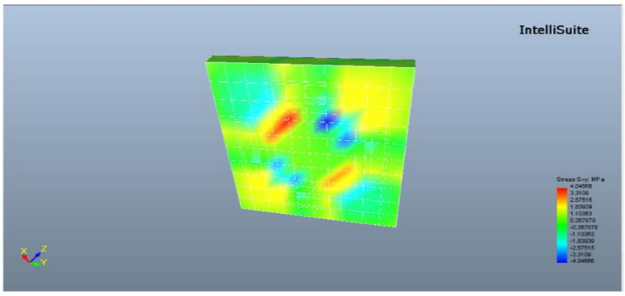


Fig.12 Square Diaphragm (110 Kpa)

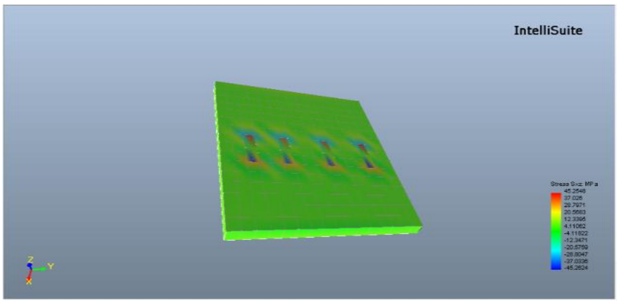


Fig.13 Cross Square Diaphragm (90 Kpa)

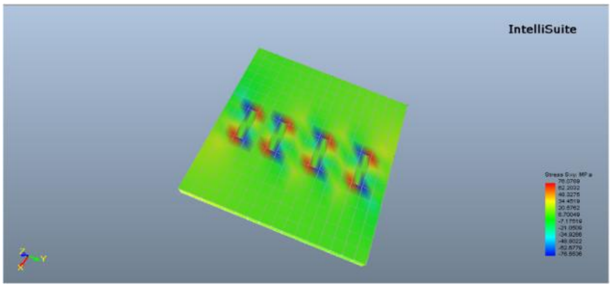


Fig.14 Cross Square Diaphragm (90 Kpa)

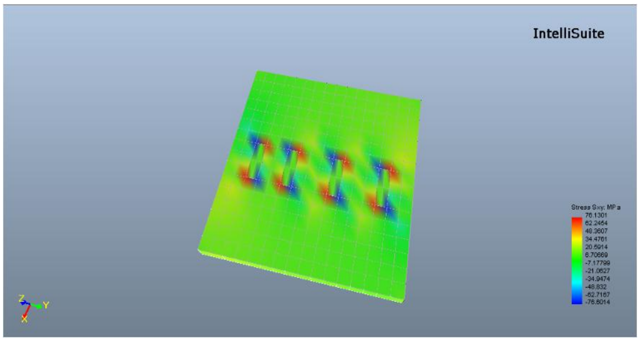


Fig.15 Cross Square Diaphragm (110 Kpa)

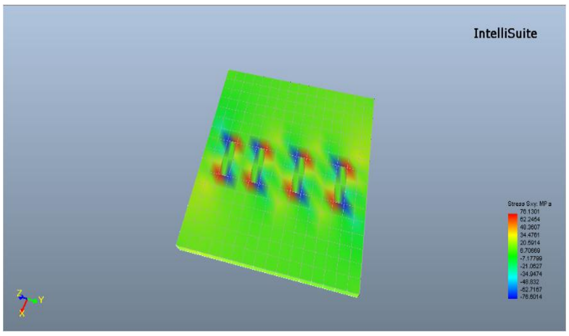
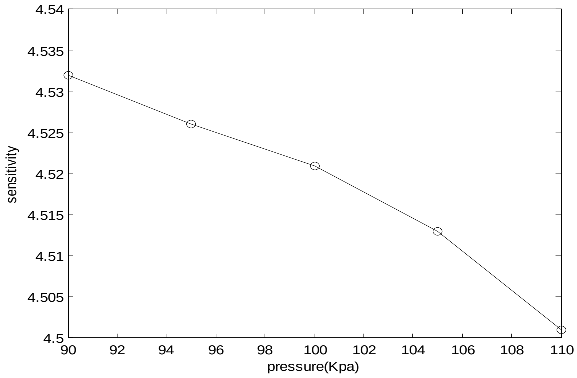
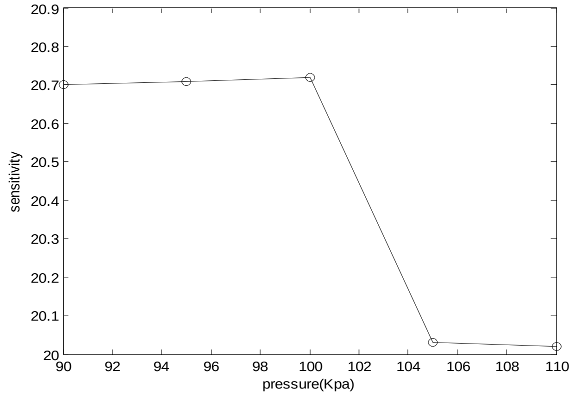


Fig.16 Cross Square Diaphragm (110 Kpa)

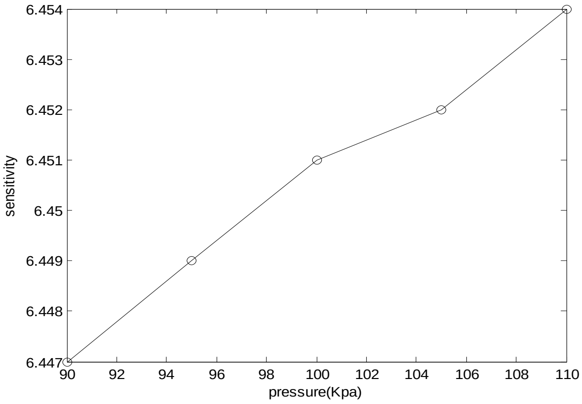
Sensitivity Analysis of Rectangular Diaphragm



Sensitivity Analysis of Square Diaphragm



Sensitivity Analysis of Cross Square Diaphragm



V. CONCLUSION

In this paper the effect of diaphragm geometry and piezoresistor dimensions on the sensitivity of pressure sensor have been analyzed using finite element tools Intellisuite. It clearly indicates the results of sensitivities for different geometries for the diaphragm. From the analysis done it is observed that although cross square and rectangular type diaphragm shows linearities, the square diaphragm has a large sensitivities (magnitudewise) for a given pressure range compared to others type of diaphragm and hence it is more suitable for environmental application. The variation in the length of the piezoresistor plays an important role in deciding the sensitivity of the sensor. In general piezoresistors having smaller dimensions are more sensitive.

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