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DESIGN AND ANALYSIS OF PERFORATED SI-DIAPHRAGM BASED MEMS PRESSURE SENSOR FOR ENVIRONMENTAL APPLICATIONS

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Abstract

The design is advanced which is an intelligent of calculating the output responses of perforated Si-diaphragm pressure sensor as a behavior of pressure and which compare them to piezoresistive Si-diaphragm. The systematic models based on small and large deflection theories have been applied to conclude the sensitivity and linearity of pressure sensors. The main aim of this paper was to design, simulate and analyze the sensitivity of both perforated and non-perforated Si-diaphragm based MEMS sensor to measure the linearity pressure values. The outer-micro machined diaphragms with square shapes are designed and tested to verify the simulation tool. The Intellisuite MEMS design tool has been used to produce and analyze the pressure sensors with perforated and Piezoresistive Si-Diaphragms. Here the study of sensor incorporating square diaphragm with piezoresistive and perforated Si-diaphragm were achieved and compared to realize the pressure sensitive components. In this perforated Si-diaphragm based pressure sensor has been illustrated to measure pressure range of 0.1MPa to 1Mpa. These simulation results have been formalized by comparing the deflection response estimated with piezoresistive Si-diaphragm model that is originated in this work by suitably modifying the bending of piezoresistive Si-diaphragms taking the perforation into account. Therefore a perforated Si-diaphragm based pressure sensor produced better displacement, sensitivity and stress output responses compared with the other type.

Keywords:

MEMS, Perforated Diaphragm, Displacement, Mises Stress and Sensitivity

1. INTRODUCTION

MEMS Pressure sensors are among the very early devices performed in silicon and widely used in various an over the last decade, silicon micro machined pressure sensors have executed appreciable exploration and growth. The overall intention of this article is to determine the development of diaphragm thickness, piezoresistors locations, and residual stress of the deposit oxide layer on the pressure sensor performance [1]. Today the micro constructed piezoresistive pressure sensor is one of the perfect-developed MEMS devices in various applications [2]. Further, the lower pressure range is the thin film diaphragm needs to be to maintain high sensitivity. However, abnormally thin membrane can stimulate large deflection and uncertainty, thus leading about the performance of sensors such as linearity, safety factor and etc., [3]. The method of substrate pattern diaphragm structure which deforms with applied pressure [4]. MEMS sensors are constructed by current manufacturing technologies such as surface micromachining or bulk micromachining [10-13].

Here, presented various Si-diaphragm structures based MEMS pressure sensor are described and analyzed using Intellisuite. Therefore, we found that the simulation results are compared and analyzed with various parameters such as deflection, Mises stress, and sensitivity.

2. OPTIMIZATION OF THE PRESSURE SENSOR DESIGN

The Fig.1 shows the Schematic representation of various Models in Piezoresistive MEMS pressure Sensor. The Si-diaphragm based MEMS pressure sensor which is affected that the dimensions of diaphragm has a reliable structural module, thickness, with entirely clamped edges [5-7]. An essential parameter of the diaphragm used in the simulation is silicon. Young's modulus of silicon = 170 GPA, Poisson's ratio = 0.26 and Young's modulus of silicon dioxide = 64GPa, Poisson's ratio = 0.25.

$$N = \frac{PA}{(100 \times PS)} DS \tag{1}$$

where, PA is the percentage perforated area, DS is the diaphragm side length and PS is the perforation size. The symmetrical distribution of the perforations for the different perforated area is shown in Fig.2. The maximum mechanical deflection of a square diaphragm is given by the following equations, respectively:

$$\omega_o = 0.0151 \times \left(\frac{Pa^4}{Eh^3}\right)^2 \times \left(1 - v^2\right). \tag{2}$$

The load-deflection response of a square diaphragm employed in a pressure sensor is given by Eq.(3),

$$\frac{Pa^4}{Eh^4} = \frac{4.2}{\left(1-v^2\right)} - \left|\frac{y}{h}\right| + \frac{1.58}{(1-v)}\left|\frac{y}{h}\right|^3 \tag{3}$$

where,

P - Applied pressure

y - Centre deflection of the diaphragm (μm)

a - Half of side length of the diaphragm (μm)

E - Young's modulus

h - Thickness of the S_i diaphragm (μm)

v - Poisson's ratio of the diaphragm material

However, it cannot be used for characterizing the load-deflection response of Si-diaphragm. Hence, it is requirement to model this response analytically to explain the deflection response of these diaphragms. Therefore, it is difficult to model the same due to discontinuity caused by the perforations surface of diaphragm. Hence, the Eq.(4) can be modified to depict the load-response of perforated diaphragm. The Eq.(4) shows that the deflection is a part of the applied pressure and device dimension in addition to Young's modulus and poisson's ratio. For small scale deflection (y) can be written as given in Eq.(5).

$$y = \frac{Pa^4}{Eh^4}\frac{\left(1-v^2\right)}{4.2} = \frac{PL^4}{12\times 4.2\times D} \quad (4)$$

where,

$$D = \frac{\left(Eh^3\right)}{12\left(1-v^2\right)}. \quad (5)$$

Here 'E' is the Young's modulus, 'v' is the Poisson ratio and 'h' is the thickness of the diaphragm.

2.1 PIEZORESISTIVE PRESSURE SENSOR

The piezoresistive effect was early exposed by Lord Kelvin in 1856 [14] when he was esteemed that convinced metallic conductors under mechanical strain presented a corresponding change in electrical resistance. The effect of piezoresistive is called when a change in the resistance value of a conductor due to applied strain. The piezoresistive effect in single crystal silicon was early characterized in 1954.

The piezoresistive effect principle change in the resistance of convincing doped materials when they are conducted to stress. The resistivity of a piezoresistive material is a function of stress that is also direction, poor due to the anisotropic crystal structure. Here to achieve the best sensitivity, which is a large stress region when there is a pressure load. The FEM analysis of the MEMS piezoresistive pressure sensor with square diaphragm was explored. A square 400µm × 400µm diaphragm with a thickness of 5µm clamps on the edge, shown in Fig.1 above is analyzed.

2.2 EFFECT OF PIEZORESISTORS LOCATIONS ON SENSITIVITY

The locations of piezoresistors have an essential function in the pressure sensor design. There are three models have been carried out such as Model 1, Model 2 and Model 3 with the piezoresistors locations are changing in the constant diaphragm thickness Shown in Fig.3, Fig.4 and Fig.5. The length (L) and width (W) of the piezoresistors are 100µm and 20µm respectively.

Bending of square plates with all edges fixed, Maximum stress calculated by center of each edge [13-14]. The maximum mechanical stress of a square diaphragm is given by the following equations, respectively:

$$\sigma_o = 0.308\times p\left(\frac{a}{h}\right)^2 \times\left(1-v^2\right). \quad (6)$$

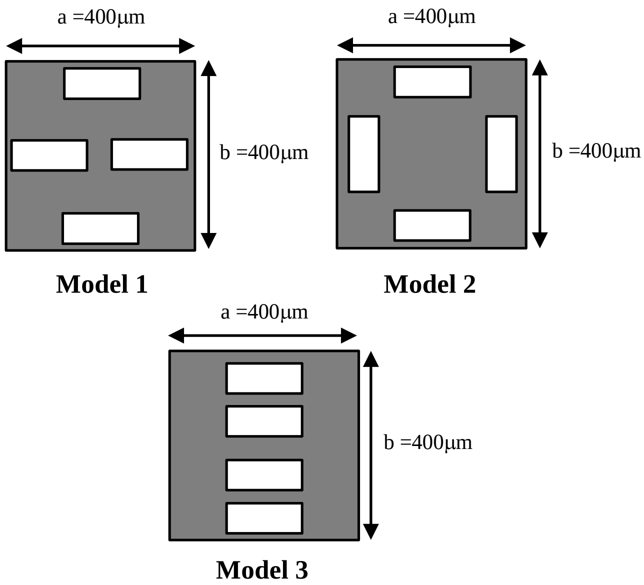

Fig.1. Schematic representation of various Models in Piezoresistive Pressure Sensor

2.3 PROPOSED PERFORATED Si-DIAPHRAGM

The perforated Si-Diaphragm is accomplished with the realization of etch through focuses of dimension (20µm × 20µm) in a symmetrical fashion, leaving adequate area at the surface of the diaphragm as shown in Fig.2. It is a planar silicon diaphragm formed by anisotropic etching convert's pressure into linear deflection.

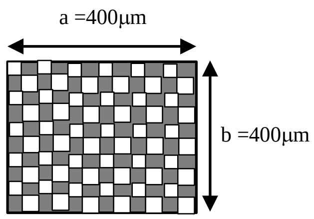

Fig.2. Schematic representation of proposed Perforated Si-diaphragm

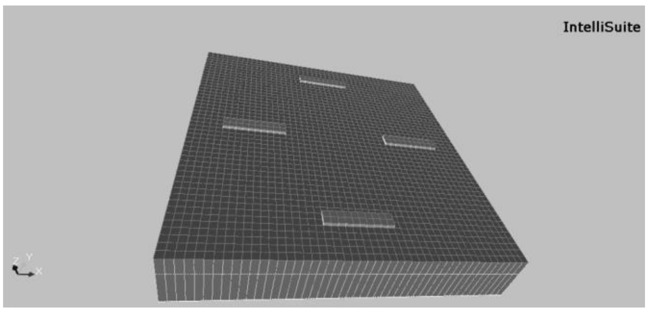

Fig.3. Si-Diaphragm with Piezoresistive Pressure sensor Model 1 Using 3D Builder

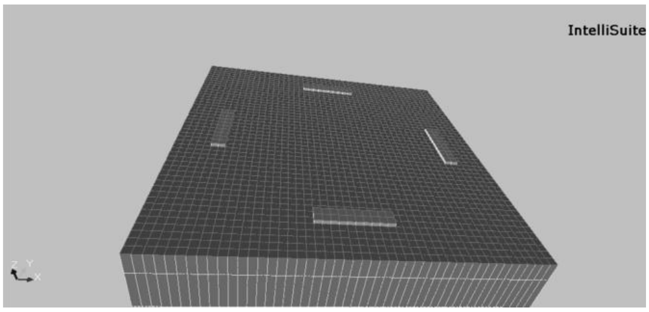

Fig.4. Si-Diaphragm with Piezoresistive Pressure sensor Model 2 Using 3D Builder

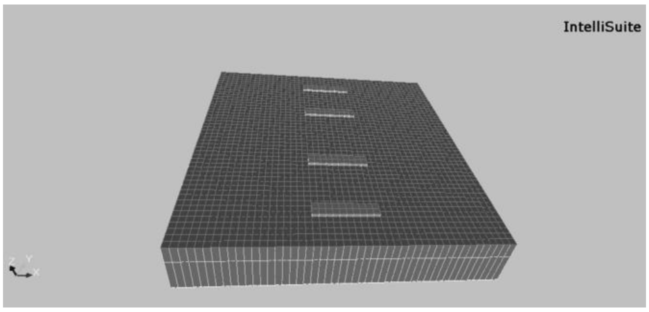

Fig.5. Si-Diaphragm with Piezoresistive Pressure sensor Model 3 Using 3D Builder

The main purpose of this analyze is to measure the performance of perforated Si-diaphragm for low pressure sensing applications in the range between 0.1Mpa to 1Mpa and equate them with that of pressure sensor applying non-perforated diaphragms and validate the results with altered piezoresistive models formulated. The perforated Si-diaphragm structure was designed and simulated using Intellisuite as shown in Fig.6.

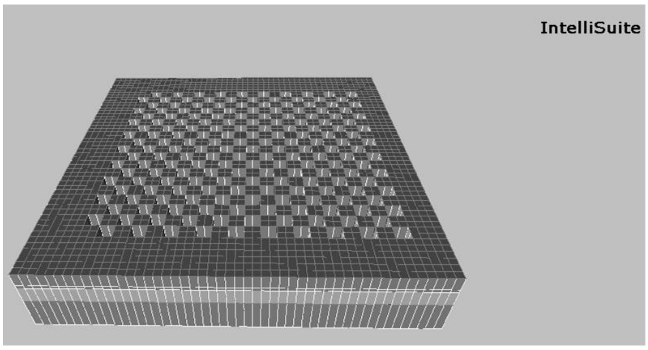

Fig.6. Proposed model of Perforated Si-Diaphragm Pressure sensor using 3D Builder

3. PIEZORESISTIVE PRESSURE SENSOR ANALYSIS

Thermo electromechanical analysis module matched with piezoresistive analysis has been used to analyze the deflection, changes in resistance and sensitivity of the pressure sensor. The diaphragm of piezoresistive pressure sensor, side length of 400μm and thickness of 5μm was an investigated. The simulation results of model 1, model 2 and model 3 such as deflection, maximum stress and sensitivity are obtained from the finite element method is shown in Fig.7 to Fig.12. The maximum deflection built and the stress induced on the model 2 piezoresistive pressure sensor are found and compared with pressure ranges from 0.1MPa to 1Mpa as shown in Fig.8 and Fig.11.

Table.1. Parameter values of diaphragm

Diaphragm Parameter	Value
Material: Silicon	Young's = 170 GPa, Poison's = 0.26 and Density = 2.33q/cm^3
Size: Length , Width and Thickness	400μm × 400μm × 5μm
Piezoresistive Material	P_11:6.6e-5 P_12:-1.1e-5 P_44:138.1e-5
Dimension	100μm × 20μm × 1μm
Perforated dimension	20μm × 20μm

The important parameters used in the simulation are as given Table.1. The maximum stress induced and the deflection produced in the diaphragm are resolved and related to the analytical solutions for a pressure range from 0.1MPa to 1MPa. In this work we achieved well close results are obtained from the simulation and experiment. For example Fig.7 shows the central deflection of the square silicon diaphragm and its pressure values are 0.1MPa and 1Mpa.

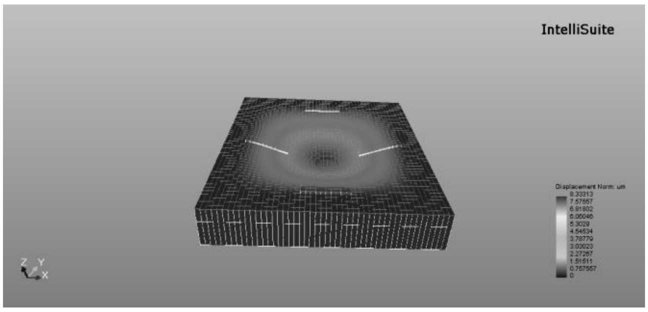

Fig.7. Simulation of Piezoresistive Pressure Sensor Model 1 deformation on the Z axis with maximum pressure of 0.5Mpa

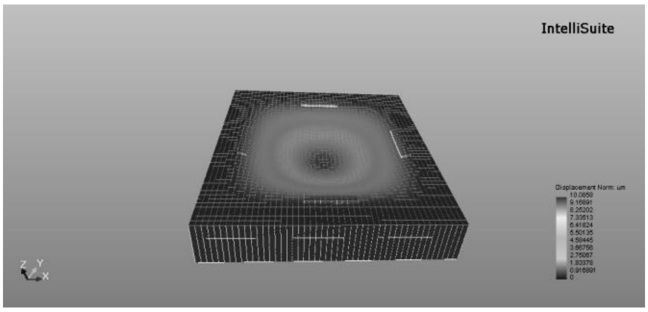

Fig.8. Simulation of Piezoresistive Pressure Sensor Model2 deformation on the Z axis with maximum pressure of 0.6MPa

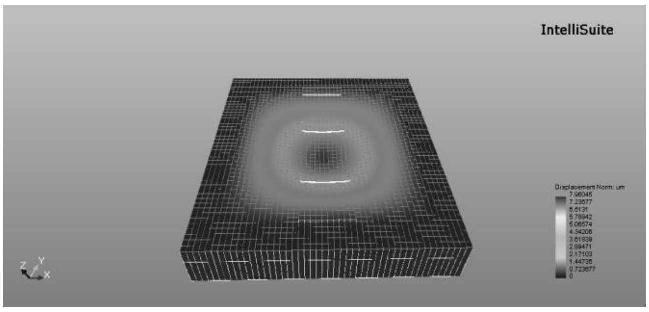

Fig.9. Simulation of Piezoresistive Pressure Sensor Model3 deformation on the Z axis with maximum pressure of 0.5Mpa

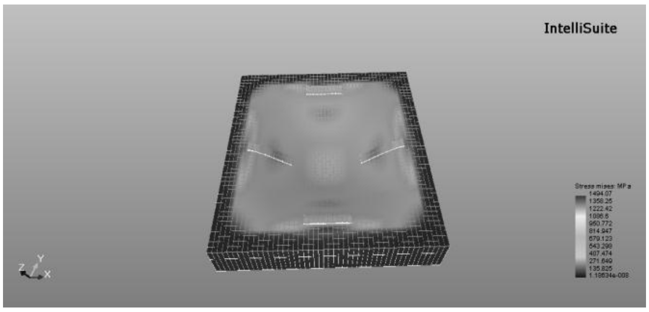

Fig.10. Mises Stress analysis of the Piezoresistive Pressure Sensor Model 1 with Pressure of 1MPa

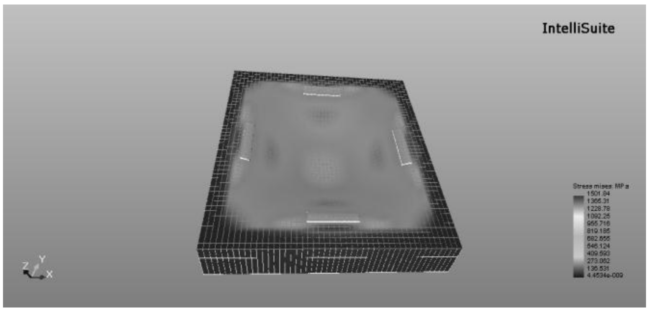

Fig.11. Mises Stress analysis of the Piezoresistive Pressure Sensor Model 2 with Pressure of 1Mpa

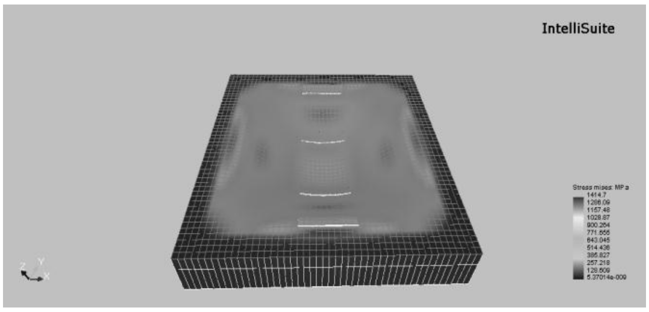

Fig.12. Mises Stress analysis of the Piezoresistive Pressure Sensor Model 3 with Pressure of 1Mpa

The comparison of simulation result are summarized that the maximum central deflection, Mises stress and sensitivity were given in Table.2, Table.3 and Table.4 under the same condition. As can be seen from the results, both simulation and theoretical results show the exactly good agreement with finite element analysis.

Table.2. Comparison of deflection results for various Diaphragm geometries

Pressure (Mpa)	Deflection (μm)			
	Analytical	Simulation		
		Model 1	Model 2	Model 3
0.1	1.66	1.66	1.68	1.59
0.5	8.31	8.33	8.40	7.96
1	16.62	16.66	16.81	15.92

Table.3. Comparison of Mises stress results for various Diaphragm geometries

Pressure (Mpa)	Mises Stress (Mpa)			
	Analytical	Simulation		
		Model 1	Model 2	Model 3
0.1	197.1	149.4	150.2	141.7
0.5	985.6	747.0	750.9	707.4
1	1971.2	1494.0	1501.8	1414.7

Table.4. Comparison of Sensitivity results for various Diaphragm geometries

Pressure (Mpa)	Sensitivity (10E-6/Pa)			
	Analytical	Simulation		
		Model 1	Model 2	Model 3
0.1	16.6	16.6	16.8	15.9
0.5	16.62	16.66	16.81	15.93
1	16.62	16.66	16.81	15.92

Thus the observed that the Model 2 Piezoresistive pressure sensor maximum pressure at given 1MPa and its maximum displacement is accordingly 16.81μm for the diaphragm thickness of 5μm. Over a pressure range of 0.1MPa to 1MPa. Its sensitivity is therefore 16.81[10E-12/Pa.] with a thickness of diaphragm 5μm.The FEM results are compared with the analytical values are found to be in very close with Intellisuite values of showing in Table.2.

The results are obtained from the FEA (finite element analysis) are shown in Fig.13 to Fig.17 shows the analytical and simulated deflection vs pressure of a Piezoresistive pressure sensor diaphragm. Here, Fig.13 shows that the various displacement analysis of both analytical and simulated outputs of model 1, 2, and 3 and also the obtained results are more displacement produced model 2. The Fig.14 and Fig.15 shows that both analytical and simulated results of Mises stress and sensitivity. Hence, the model 2 piezoresistive diaphragm produced maximum stress and sensitivity.

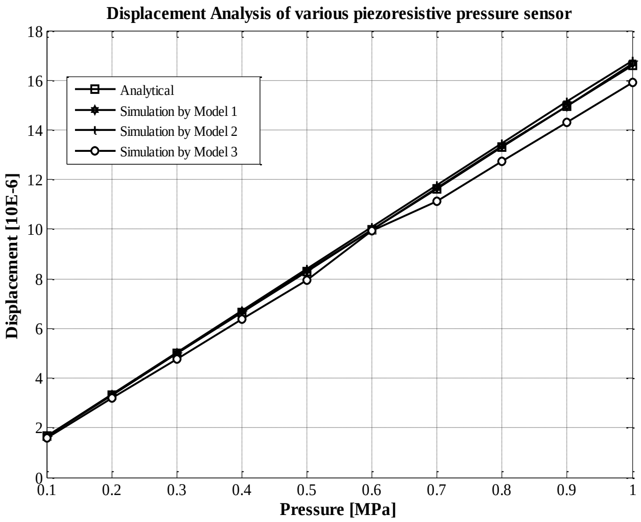

Fig.13. Displacement analysis of various piezoresistive pressure sensors with thickness at 5µm

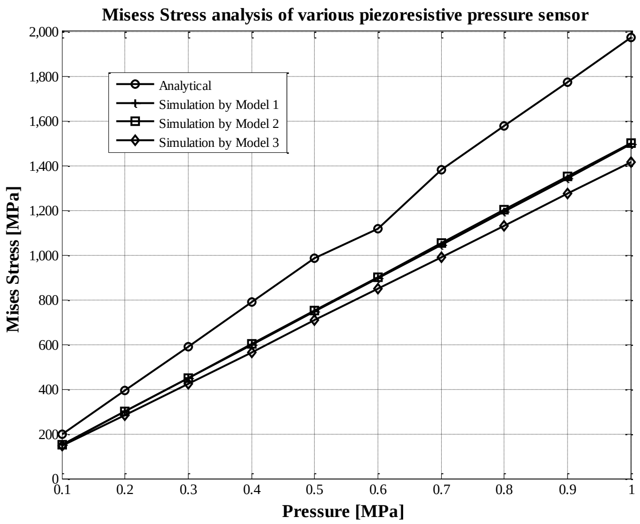

Fig.14. Mises stress analysis of various piezoresistive pressure sensors with thickness at 5µm

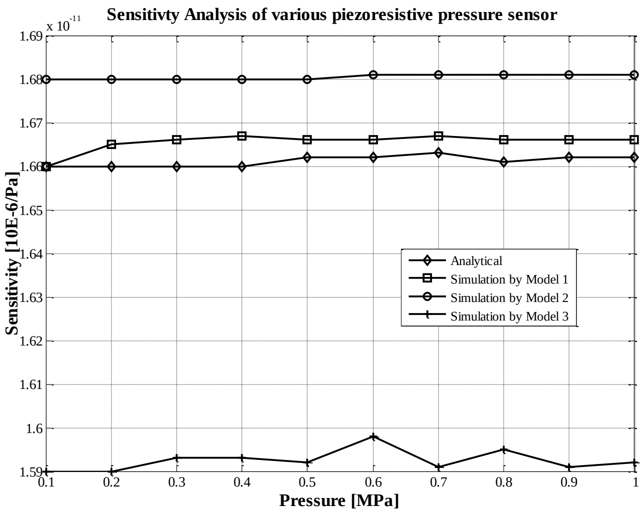

Fig.15. Sensitivity analysis of various piezoresistive pressure sensors with thickness at 5µm

The other simulated results are observed that the varying thickness of the diaphragms as shown in Fig.16 and Fig.17, the central deflection is increased when the applied pressure of 0.1MPa-1MPa and also the thickness of the diaphragm are varying from 2µm to 5µm. However the observed results are obtained from the different thickness of Si-diaphragm pressure sensor has more displacement which can be shown in Fig.16.

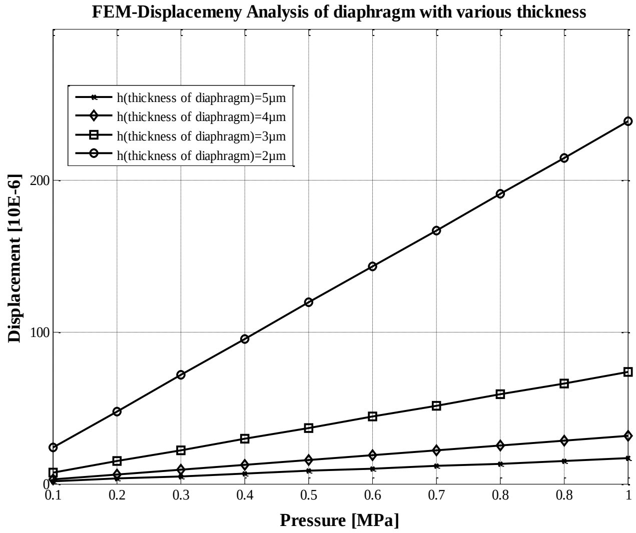

Fig.16. Finite Element Method (FEM)-Displacement analysis of various thickness of Square diaphragm

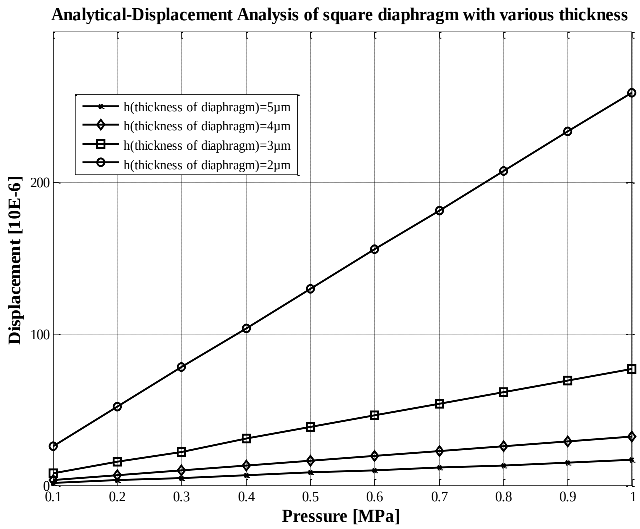

Fig.17. Analytical - Displacement analysis of various thickness of Square diaphragm

The other way of increasing the displacement, Maximum stress and sensitivity of a Piezoresistive pressure sensor can be to decrease the diaphragm thickness, which the both FEM and analytical results are shown in Fig.16 and Fig.17. Here the Fig.16 shows the maximum displacement of the piezoresistive diaphragm with a thickness of 2µm. Therefore the dimensions of thickness can be varied the displacement also increased. Finally, we observed that the comparison results of both analytical and FEM results are closed.

4. PERFORATED SI-DIAPHRAGM PRESSURE SENSOR ANALYSIS

It is evident from the Table.2, Table.3 and Table.4 that the deflections, Mises stress and sensitivity are increasing with increasing piezoresistive pressure sensor and the simulated diaphragm deflection is found. The Table.4 shows that the deflection, Mises stress and sensitivity are compared perforated and non- perforated Si-diaphragm and simulated diaphragm deflection is found to be doubled with compare them piezoresistive diaphragm. The Fig.18, Fig.19, Fig.20 and Fig.21 shows that simulated results of perforated Si-diaphragm output parameters such as deflection, Mises stress and sensitivity are determined.Here the defelection of diaphragm when increased. Here observed the simulated results of perforated Si-diphargm displacement, maximum stress and sensitivity are doubled compare them to pizoresistive prussure sensor.

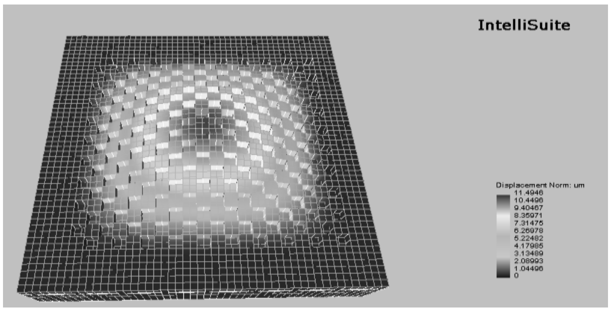

Fig.18. Simulation of perforated Si-diaphragm deformation on the Z axis with maximum pressure of 0.3MPa

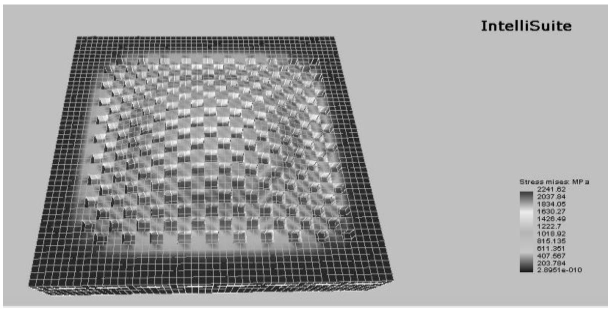

Fig.19. Simulation of perforated Si-diaphragm deformation on the Z axis with maximum pressure of 0.3MPa

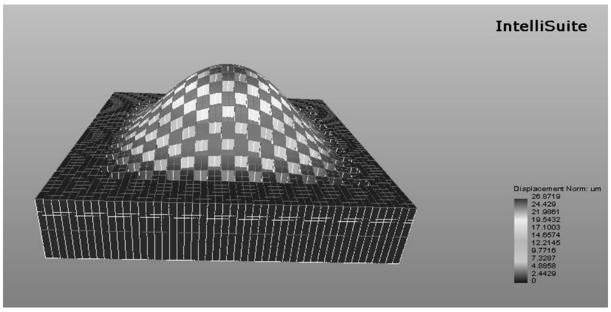

Fig.20. Mises Stress analysis of the perforated Si-diaphragm with Pressure of 0.7Mpa

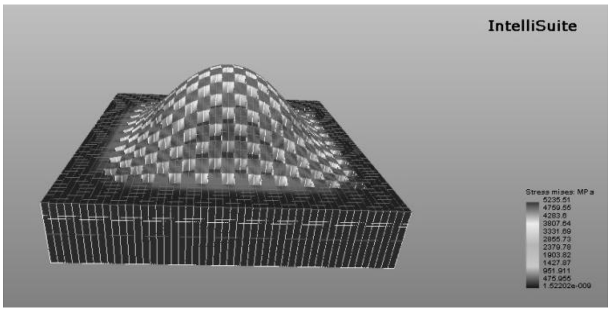

Fig.21. Mises Stress analysis of the perforated Si-diaphragm with Pressure of 0.7Mpa

The Fig.22 and Fig.23 shows the maximum displacement and stress on the perforated Si-diaphragm with a pressure range between 0.1MPa to 1Mpa and also the thickness of the diaphragm is 5μm. The Fig.14 shows the sensitivity of the perforated Si-diaphragm with a pressure of 0.1MPa to 1MPa and also the thickness of the diaphragm is 5μm.

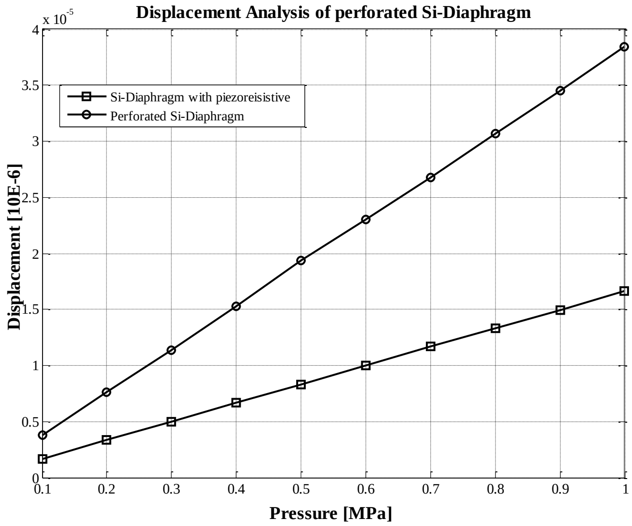

Fig.22. Displacement analysis of Perforated and Piezoresistive Si-Diaphragm

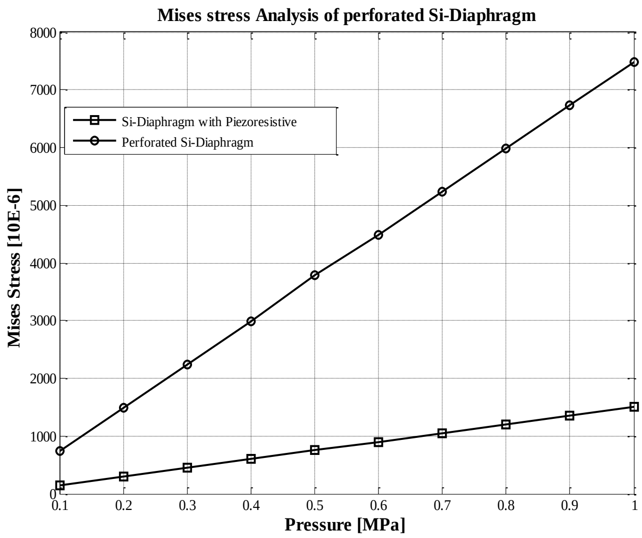

Fig.23. Mises Stress analysis of Perforated and Piezoresistive Si-Diaphragm

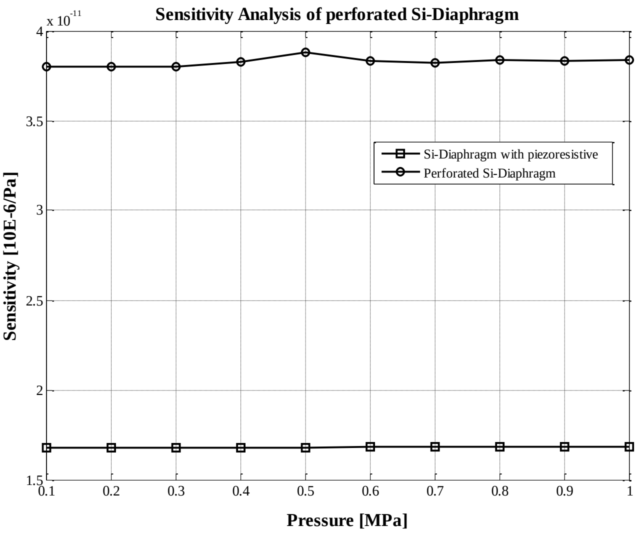

Fig.24. Sensitivity analysis of Perforated and Piezoresistive Si-Diaphragm

The Table.5 focused by the comparison of simulated results of both perforated and non-perforated diaphragm pressure sensor parameters such as displacement, Mises stress and sensitivity. This result also indicates that the high sensitivity of perforated Si-diaphragm to be applied in low pressure range application.

Table.5. Comparison of both Perforated and Piezoresistive Si-Diaphragm

Pressure (Mpa)	Perforated Si-Diaphragm			Si-Diaphragm with Piezoresistive		
	Deflection (µm)	Mises Stress (MPa)	Sensitivity (10E-12/Pa)	Deflection (µm)	Mises Stress (MPa)	Sensitivity (10E-12/Pa)
0.1	3.8	744.6	38.0	1.68	150.2	16.80
0.2	7.6	1493.1	38.0	3.36	300.4	16.80
0.3	11.4	2241.6	38.0	5.04	450.6	16.80
0.4	15.3	2990.1	38.3	6.72	600.7	16.80
0.5	19.4	3788.5	38.8	8.40	750.9	16.80
0.6	23.0	4487.0	38.3	10.09	901.1	16.81
0.7	26.8	5235.5	38.2	11.77	1051.3	16.81
0.8	30.7	5983.9	38.4	13.45	1201.5	16.81
0.9	34.5	6732.4	38.3	15.13	1351.7	16.81
1	38.4	7480.9	38.4	16.81	1501.8	16.81

5. CONCLUSION

The perforated Si-diaphragm for sensing pressure in MEMS pressure sensor is designed and presented. Three different piezoresistive groups of devices were considered and perforations were realized. The comparison of the results of the deflection, maximum stress and sensitivity analysis of both perforated and non-perforated diaphragm clearly demonstrated that perforations results in more increase in stress levels thus indicating that perforated diaphragms are better alternatives for piezoresistive pressure sensors.

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