DOI: 10.21917/ijme.2015.0011

PERFORMANCE ANALYSIS OF SLOTTED SQUARE DIAPHRAGM FOR MEMS PRESSURE SENSOR

A. Nallathambi[1] **and T. Shanmuganantham**[2]
Department of Electronics Engineering, Pondicherry University, India
E-mail:[1]nallathambiarjunan@gmail.com, [2]shanmuga.dee@pondiuni.edu.in

Abstract

In this paper Micro-electromechanical System (MEMS) diaphragm based pressure sensor for environmental applications was discussed. The main focus of this paper was to design, simulate and analyze the sensitivity of MEMS based diaphragm using square and slotted square structures to measure the linearity pressure values. The simulation was done through the finite element tool and specifications related the maximum convinced stress; deflection and sensitivity of the diaphragms have been analyzed using the software INTELLISUITE 8.7v. The change in pressure was to bending of the diaphragm that modifies the measured displacement between the substrate and the diaphragm. This change in displacement gives the measure of the pressure in that environment. The design of these studies can be used to improve the sensitivity of these devices. Here the sensor designs incorporating square and slotted square diaphragm were implemented and compared to realize the pressure-sensitive components. The pressure sensor has been designed to measure pressures in the range of 0 to 1MPa that is in the range of low pressure sensors. Therefore a slotted square diaphragm based pressure sensor produced better displacement, sensitivity and stress output responses compared with the other type.

Keywords:

MEMS, Diaphragm, Displacement, Mises Stress

1. INTRODUCTION

The diaphragm based MEMS pressure sensors were used to monitor and measure pressure in various environments. A wide variety of differential, gauge, and absolute pressure micro sensors based on different transduction principles have been developed using MEMS technology. MEMS pressure sensors work on the principle of mechanical bending of thin silicon diaphragm by the contact medium like gases, fluids, etc. Over the last decade, silicon micro machined pressure sensors have undergone considerable research and growth. To design criteria different ranges of pressure and the related technology based on silicon as the diaphragm material for detecting the burst pressure and linearity considerations [1]. A conventional square shaped single diaphragm silicon pressure sensor is to measure and compare the different performance parameters like deflection, stress and voltage sensitivities [2], [3].

The pressure sensor was designed and analyzed using a 3D builder module of finite element analysis using Intellisuite [5]. The diaphragm covered by consideration was one with conventional silicon diaphragm and it can be analyzed various parameters such as Mises stress, displacement, sensitivity [6]. The square diaphragm based sensor is analyzed more sensitive for environmental application ranges [9]. A silicon microfabrication technology happened concurrently with more popular developments in the areas of Si-based solid state devices and integrated-circuit (IC) technologies that have revolutionized modern life [10]. The capacitive pressure sensor has more sensitivity that is substantially higher than any of the other capacitive pressure sensors known at the present time. The pressure range that the sensor can handle can be increased by simply using a stiffer diaphragm [11]. For example, high temperature MEMS pressure sensors are needed in gas turbine engines, coal boilers, furnaces, and machinery for oil/gas exploration [12]. The diaphragm which is the main sensing element can be square, circular or rectangular. But rectangular or square ones are commonly used since they occupy a lesser area, enable easier lithography and fabrication compared to circular ones [13]. The MEMS pressure sensors can be fabricated either by surface micromachining, bulk micromachining or a combination of both [14].

In this paper presented two different structures: square and slotted square diaphragm based MEMS pressure sensor are designed and analyzed using Intellisuite. Here, we found that the simulation results are compared and analyzed various parameters such as deflection, Mises stress, and sensitivity.

2. DESIGN CONSIDERATION

The main differential 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 [4];

$$\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}\right)\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}\right)=\frac{p}{D} \tag{1}$$

where D is flexural rigidity.

To model the silicon pressure sensor diaphragm, it was assumed that the diaphragm has a uniform thickness, with perfectly clamped edges [6-7]. The flexural rigidity which depends on the properties of the material under consideration, which is given by Eq.(2),

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

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

The solution of eqn. (1) gives the maximum deflection (w_0) at the center of the diaphragm in the direction of the Z axis. Having computed $w(x, y)$ the bending moments M_x, M_y and twisting moments M_{xy} per unit length of the diaphragm are denoted [4].

Bending moment for,

$$Mx = -D\left(\frac{\partial^2 w}{\partial x^2} + v\frac{\partial^2 w}{\partial y^2}\right) \tag{3}$$

$$My = -D\left(\frac{\partial^2 w}{\partial y^2} + v\frac{\partial^2 w}{\partial x^2}\right) \tag{4}$$

$$Mxy = D(1-v)\left(\frac{\partial^2 w}{\partial x \partial y}\right) \tag{5}$$

Bending Stresses can be expressed as,

$$(\sigma_{xx})_{\max} = \frac{6(Mx)\max}{h^2} \tag{6}$$

$$(\sigma_{yy})_{\max} = \frac{6(My)\max}{h^2} \tag{7}$$

$$(\sigma_{xy})_{\max} = \frac{6(Mxy)\max}{h^2} \tag{8}$$

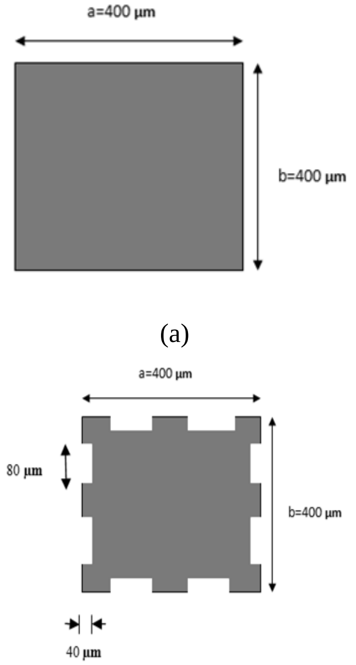
To model the silicon pressure sensor diaphragm, it was assumed that the diaphragm has a uniform thickness, with perfectly clamped edges [15-16]. The flexural rigidity which depends on the properties of the material under consideration, which is given by Eq.(2).

2.1 SQUARE DIAPHRAGM

The square diaphragm was preferred because of it can produce the highest induced stress for a given pressure, which mean it provide a pressure sensor with better sensitivity. Also, it was easy to dice the diaphragm from standard wafers. Therefore few mask design techniques available to avoid the convex corner undercutting phenomenon that always occurs in realizing a perfect square diaphragm [7]. To obtain the maximum sensitivity, which is a high stress region when there is pressure load, the FEM analysis of MEMS pressure sensor with square diaphragm was investigated and proposed by P. Bo et al., [8]. A square 400µm × 400µm diaphragm with a thickness of 5µm and 4µm are clamped at the age, shown in Fig.1(a) above is analyzed. The cross sectional view of the square pressure sensor is shown in Fig.1(a).

2.2 SLOTTED SQUARE DIAPHRAGM

For achieving more sensitive device and reducing the effect of residual stress and stiffness of the diaphragm, slotted diaphragm is proposed. Eight slots with the same dimensions and geometry was formed on the square diaphragm. The dimensions of eight slots are depicted in Fig.1(b). The ratio of slot size with the size of square diaphragm is adapted from [8]. The cross sectional view of the slotted square pressure sensor is shown in Fig.1(b). Table.1 lists the parameter of these diaphragms.



(a)

(b)

Fig.1. Schematic representation of (a) Square diaphragm and (b) Slotted Square diaphragm

Bending of square plates with all edges fixed, Maximum stress calculated by center of each edge,

$$\sigma_{\max} = \frac{0.308pa^2}{h^2} \tag{9}$$

Maximum deflection as calculated by,

$$W_{\max} = -\frac{0.0138pa^4}{Eh^3} \tag{10}$$

The stress at the center of the plate can be derived as follows,

$$\sigma = \frac{6p(m+1)a^2}{47mh^2} \tag{11}$$

And strain at the center is,

$$\varepsilon = \frac{3W}{4\pi h^2} \tag{12}$$

Table.1. Parameter values of diaphragm

Diaphragm Parameter	**Value**
Material	Silicon (Y=170 GPa, v=0.26 and d=2.33q/cm3)
Size	400×400µm
Thickness	4 and 5µm
Slot dimension	80×40µm

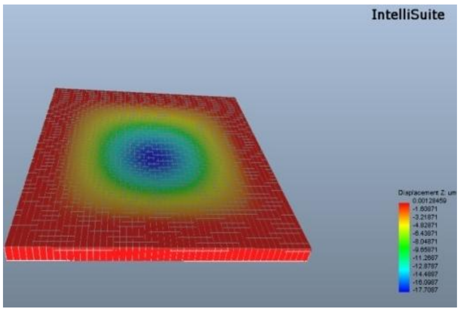


Fig.2. Simulation of square diaphragm deformation on the Z axis with maximum pressure of 1MPa (thickness = 5µm)

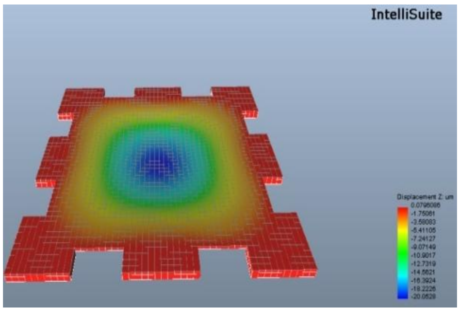


Fig.3. Simulation of slotted square diaphragm deformation on the Z axis with maximum pressure of 1MPa (thickness = 5µm)

The Fig.2 and Fig.3 show the central deflection of the square silicon diaphragm and its pressure values are 0.1MPa and 1MPa. The result shows that the maximum central deflection, Mises stress and sensitivity were given in Table.2 and Table.3 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.

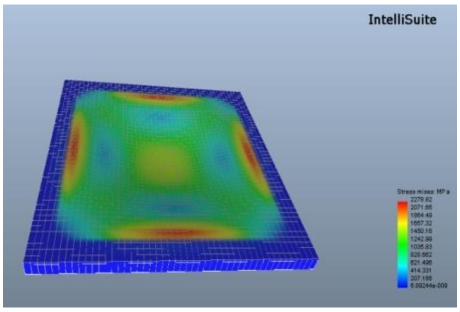


Fig.4. Mises Stress analysis of the square diaphragm with Pressure of 1MPa (thickness = 5µm)

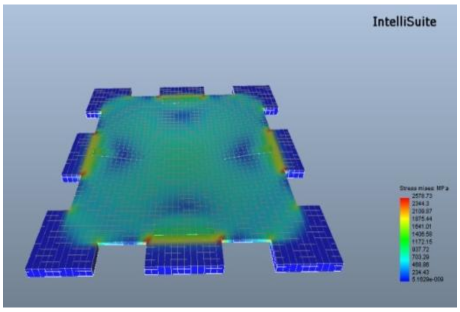


Fig.5. Mises Stress analysis of the Slotted square diaphragm with Pressure of 1 MPa (thickness = 5µm)

3. DESIGN OF DIAPHRAGM AND FEM ANALYSIS

The diaphragm structure was created and simulated using Intellisuite. Square diaphragm of side length 400µm thickness were 5µm and 4µm, slotted square diaphragm of side length as same 400µm and thickness 5µm and 4µm with eight slots have been constructed such that they have the same surface area and two different thicknesses were analyzed. The maximum stress induced and the deflection produced in the slotted square diaphragm are determined and compared with the square diaphragm for a pressure ranges from 0 to 1MPa. The maximum pressure applied was 1MPa. The simulation results such as deflection, maximum stress and sensitivity are obtained from the FEA is shown in Fig.2 to Fig.5.

The diaphragm based pressure sensors are using the module of the FEA tool. Here, the diaphragm material as silicon and the material properties used for simulation are given in Table.1. The maximum stress induced and the deflection produced in the diaphragm are determined and compared with the analytical solutions for a pressure range from 0MPa to 1MPa.

4. RESULTS AND DISCUSSION

The results are obtained from the FEA are shown in Fig.4 and 5. From the analysis done it can be seen that the maximum stress induced at the edges of the diaphragm and the maximum deflection produced at the center of the diaphragm are well in agreement with the analytical expressions given by Eq.(9) and Eq.(10).

Table.2. Comparison of deflection results for square and slotted square diaphragm and geometries thickness as 5µm

Pressure (Mpa)	**Clamped Square**			**Slotted Square**		
	Deflection (µm)	**Mises Stress (MPa)**	**Sensitivity (10E-12/Pa)**	**Deflection (µm)**	**Mises Stress (MPa)**	**Sensitivity (10E-12/Pa)**
0.1	1.77	145.7	17.7	2.01	280.0	20.05
0.2	3.54	291.5	17.7	4.01	560.1	20.05
0.3	5.31	437.2	17.7	6.01	840.1	20.03
0.4	7.08	582.9	17.7	8.02	1120.1	20.05
0.5	8.85	728.7	17.7	10.02	1400.2	20.04
0.6	10.62	874.4	17.7	12.03	1680.2	20.05
0.7	12.39	1020.2	17.7	14.03	1960.2	20.04
0.8	14.16	1165.9	17.7	16.04	2240.3	20.05
0.9	15.93	1311.7	17.7	18.04	2520.3	20.04
1	17.71	1457.4	17.7	20.05	2800.3	20.05

Table.3. Comparison of deflection results for square and slotted square diaphragm and geometries thickness as 4μm

Pressure (Mpa)	**Clamped Square**			**Slotted Square**		
	Deflection (μm)	**Mises Stress (MPa)**	**Sensitivity (10E-12/Pa)**	**Deflection (μm)**	**Mises Stress (MPa)**	**Sensitivity (10E-12/Pa)**
0.1	3.42	227.9	34.2	3.84	433.9	38.4
0.2	6.84	455.8	34.2	7.69	867.7	38.45
0.3	10.26	683.6	34.2	11.54	1301.6	38.47
0.4	13.68	911.5	34.2	15.39	1735.5	38.48
0.5	17.10	1139.4	34.2	19.24	2169.3	38.48
0.6	20.52	1367.3	34.2	23.09	2603.2	38.48
0.7	23.94	1595.2	34.2	26.94	3037.1	38.49
0.8	27.36	1823.1	34.2	30.79	3470.9	38.49
0.9	30.78	2050.9	34.2	34.64	3904.8	38.49
1	34.20	2278.2	34.2	38.49	4338.7	38.49

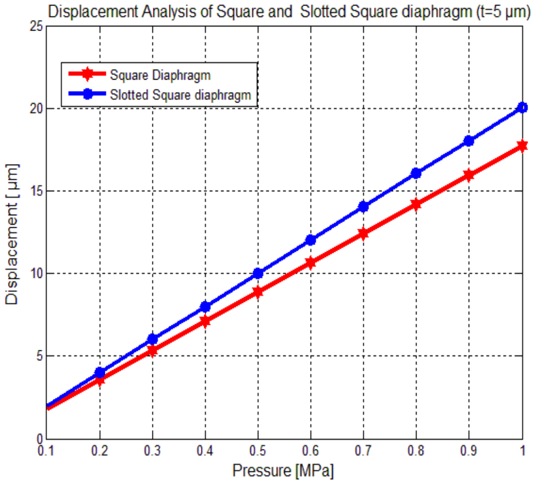


Fig.6. Simulation results of square and slotted square diaphragm with thickness at 5μm

The Fig.6 shows the calculated and simulated deflection vs pressure of a square diaphragm. As can be seen from Fig.6, the central deflection is increased when the applied pressure of 0.1MPa – 1MPa and also the thickness of the diaphragm is 5μm.

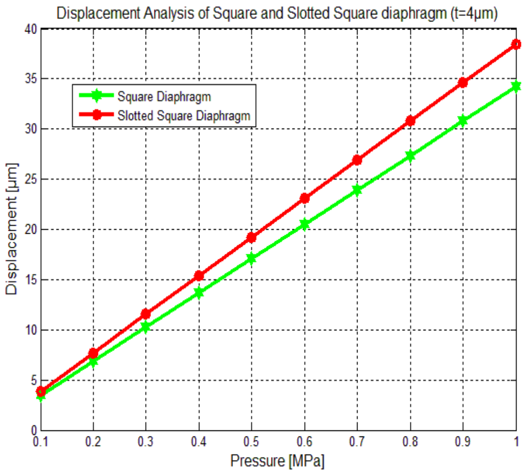


Fig.7. Simulation results of square and slotted square diaphragm with thickness at 4μm

The Fig.7 shows the simulated deflection vs pressure on the square and slotted square diaphragm with a pressure of 0.1MPa – 1MPa and also the thickness of the diaphragm is 4μm.We observed that the slotted square maximum pressure given 1MPa and its maximum displacement is accordingly 20.05μm for the diaphragm thickness of 5μm and 38.49μm for the diaphragm thickness of 4μm. Over a pressure range of 0 to 1 MPa. Its sensitivity is therefore 20.05 [10E-12/Pa.] with a thickness of diaphragm 5μm and sensitivity of 38.4 [10E-12/Pa.] by a thickness of 4μm.

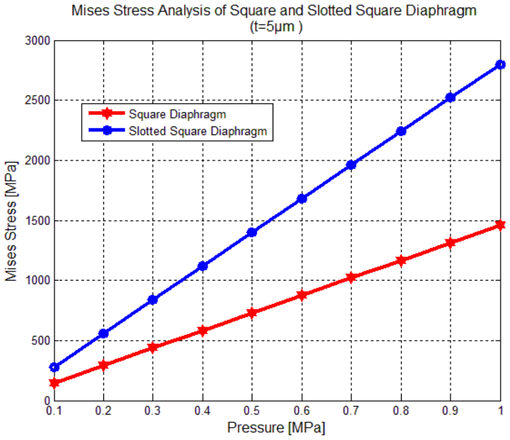


Fig.8. The Mises stress of two different structures: Square, and Slotted square diaphragm at 5μm thicknesses

The Fig.8 shows the maximum stress of square diaphragm with a pressure from 0.1MPa to 1Mpa and also the thickness of the diaphragm is 5μm. And also Fig.9 shows the same as the maximum stress with thickness of the slotted square diaphragm is 4μm. The Fig.10 shows the sensitivity of square diaphragm with a pressure from 0.1MPa to 1Mpa and also the thickness of the diaphragm is 5μm. And also Fig.11 showed that same as the sensitivity with thickness of the slotted square diaphragm is 4μm.

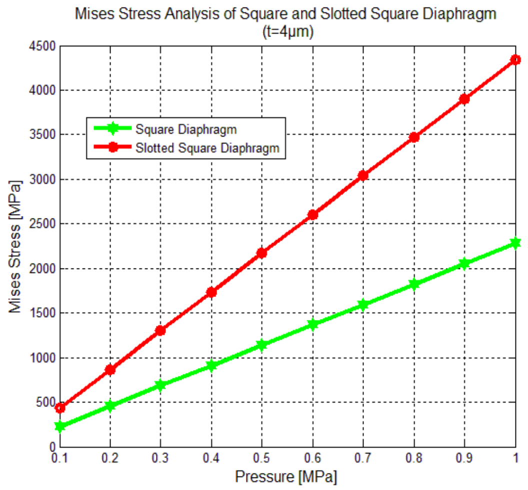


Fig.9 The Mises stress of two different structures: Square, and Slotted square diaphragm at 4μm thickness

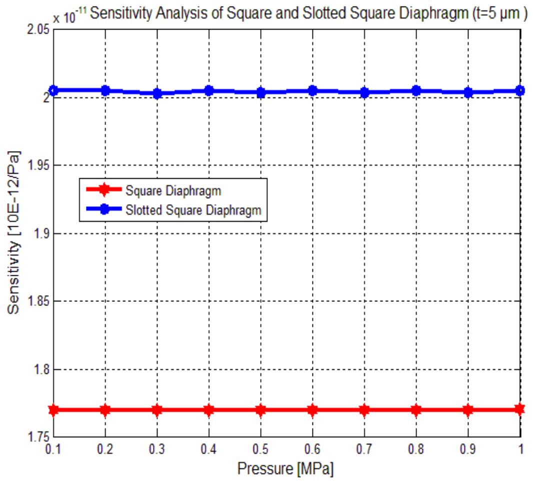


Fig.10 The analysis to sensitivity of two different Structures: Square and Slotted square diaphragm at 5μm thickness

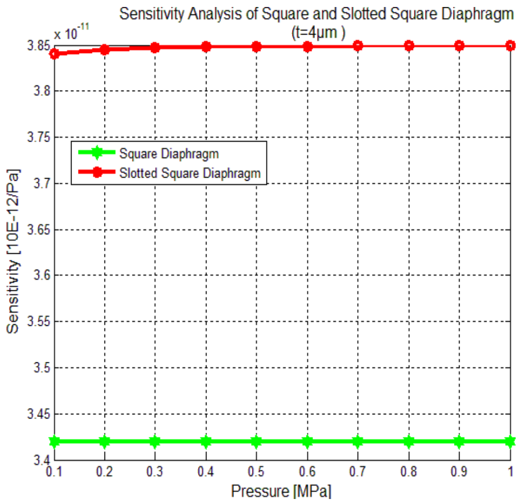


Fig.11 The analysis to sensitivity of two different Structures: Square and Slotted square diaphragm at 4μm thickness

5. CONCLUSION

The relationships between the different geometry of a square and slotted square diaphragm have been analyzed for a pressure range from 0 to 1MPa. The central deflection and stress values under the influence of a uniform external pressure values are calculated. The slotted square diaphragm has the highest displacement and induced stress for a given pressure. Hence it is the preferred geometry slotted square diaphragm for pressure sensors because, the high stresses generated by applying pressure result in high sensitivity. The square diaphragm has the lowest stress on its edges when applying the same pressure as on a slotted square diaphragm. The relations between the particular dimensions of a square, rectangular and circular diaphragm have been evaluated using the Intellisuite 8.7V. The square diaphragm FEA results yields a maximum displacement of square diaphragm is 17.714μm and 34.20μm for the thickness of diaphragm 5μm and 4μm. The slotted square diaphragm yields a maximum displacement 20.05μm and 38.49μm with at the same above thickness.

Thus, we observed that the slotted square shaped diaphragm is suitable for environmental application. Because of the optimized that it has more deflection and sensitivity of simulation in comparing the square diaphragm.

ACKNOWLEDMENT

The authors would like to thank NPMaSS (National Program on Micro and Smart Systems), Ministry of Defense, Government of India for providing the software facilities and support at Pondicherry University, Pondicherry.

REFERENCES

[1] K. N. Bhat and M. M. Nayak, "MEMS Pressure Sensors- An Overview of Challenges in Technology and Packaging", *Journal of Institute of Smart Structures and Systems*, Vol. 2, No. 1, pp. 1-10, 2013.

[2] S. H. Abdul Rahman, N. Soin and F. Ibrahim, "Analysis of MEMS Diaphragm of Piezoresistive Intracranial", *IEEE conference on Biomedical Engineering and Sciences*, pp. 681-685, 2014.

[3] K. J. Suja, E. Surya Raveendran and Rama Komaragiri, "Investigation on better Sensitive Silicon based MEMS Pressure Sensor for High Pressure Measurement", *International Journal of Computer Applications*, Vol. 72, No. 8, pp. 40-47, 2013.

[4] Tai-Ran Hsu, "*MEMS and Microsystem: Design and Manufacture*", Tata McRaw-Hill, 2002.

[5] Michal Gérard Olszacki, "Modelling and optimization of piezoresistive pressure sensors", Ph.D. Thesis, Université de Toulouse, 2009.

[6] W. P. Eaton and J. H. Smith, "Micro machined Pressure Sensors: Review and Recent Developments", *Smart Materials and Structures*, Vol. 6, No. 5, 1997.

[7] A. Nallathambi and T. Shanmuganantham, "Design of Diaphragm Based MEMS Pressure Sensor with Sensitivity Analysis for Environmental Applications", *Sensors & Transducers*, Vol. 188, No 5, pp. 48-54, 2015.

[8] Pang Bo, Zhang Zhao-hua, and Ren Tian-ling, "Simulation and Design of Micro Pressure Sensors Applied to Measure the Intracranial Pressure," *8th IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, pp. 120–123, 2013.

[9] Ashish, Kumari Nidhi Gupta and T.Shanmuganantham, "Sensitivity Analysis of Pressure Sensor for Environmental Application," *Journal of Engineering Research and Application*, Vol. 3, No. 6, pp. 454-458, 2013.

[10] Mohamed Gad-el-Hakby, Ed., "*The MEMS Handbook: MEMS Design and Fabrication*", Taylor & Francis Group, 2006.

[11] Ezzat G. Bakhoum and M. H. M. Cheng, "Novel Capacitive Pressure Sensor", *Journal of Microelectromechanical Systems*, Vol. 19, No. 3, pp. 443-450, 2010.

[12] Bing Qi et al., "Fiber optical pressure and temperature sensors for oil down hole applications", *Proceedings of SPIE: Fiber Optic Sensor Technology and Applications*, Vol. 4578, pp. 182-190, 2002.

[13] Wen H. Ko, Qiang Wang, "Touch Mode Capacitive Pressure Sensors", *Sensors and Actuators A Physical*, Vol. 75, No. 3, pp. 242–251, 1999.

[14] Jan Korvink and Oliver Paul, "*MEMS: A Practical Guide to Design, Analysis and Applications*", 1st Edition, William Andrew, 2010.

[15] E. Surya Raveendra, K. J. Suja and Rama Komaragiri, "Effect of stacked Diaphragm in MEMS Pressre sensor for oceanographic applications*", 6th International Conference on Sensing Technology*, 2012.

[16] Norhayati Soin and Burhanuddin Yeop Majlis, "Development of perfect silicon corrugated diaphragm using anisotropic etching", *Microelectronic. Engineering*, Vol. 83, pp. 1438–1441, 2006.