Sensors & Transducers, Vol. 188, Issue 5, May 2015, pp. 48-54

Sensors & Transducers

http://www.sensorsportal.com

Design of Diaphragm Based MEMS Pressure Sensor with Sensitivity Analysis for Environmental Applications

A. Nallathambi, T. Shanmuganantham
Pondicherry University, Pondicherry, 605014, India
Tel.: 91-9486122185
E-mail: nallathambiarjunan@gmail.com

Received: 10 April 2015 /Accepted: 11 May 2015 /Published: 29 May 2015

Abstract: In this paper Micro-electromechanical System (MEMS) diaphragm based pressure sensor for environmental applications is discussed. The main focus of this paper is to design, simulate and analyze the sensitivity of MEMS based diaphragm using different structures to measure the low and high pressure values. The simulation is 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 is 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 diaphragm based pressure sensor produced better displacement, sensitivity and stress output responses are obtained from the square diaphragm. The pressure range from 0.6 MPa to 25 MPa and its maximum displacement is accordingly 59 µm over a pressure range of 0 to 2 MPa. Its sensitivity is therefore 2.35 [10E-12/Pa]. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: MEMS, Diaphragm, Pressure, Displacement, Stress and sensitivity.

---

1. Introduction

The diaphragm based MEMS pressure sensors are mainly used to measure and monitor pressure value in different environments. A wide variety of absolute pressure, gauge, and differential micro pressure sensors based on various transductions fundamental have been developed using Microsystems technology. The MEMS pressure sensors have work on the basis of mechanical bending of thin silicon diaphragm by the contact medium related gases, fluids, etc. Over the last decade, silicon micro machined pressure sensors have undergone considerable research and growth. Vidhya Balaji, *et. al.* [1] has been analyzed the various diaphragm such as square, rectangular and circular shapes for comparing the stress distribution across these three types of diaphragms and arrived at their relative merits in conditions of the maximum operating pressure conducted by the burst pressure and linearity considerations. Suja K. J., *et. al.* [2] has been analyzed a conventional square shaped single diaphragm silicon pressure sensor to measure and compare the different work parameters like deflection, stress and voltage sensitivities. Ashish, *et. al.* [4] have measured and improved the sensitivity of MEMS pressure sensor, and also achieved good results from membrane to either thin or large to achieved good results. Mohamed Gad-el-Hak, *et al.* [5] have been focused on silicon micro fabrication technology appeared simultaneously with more suitable improvement in the field of Si-based solid state machine and integrated-circuit (IC) technologies that have changed present day life. Ezzat G. Bakhoum *et al.* [6] 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. B. Qi, *et al.* [7] have analyzed a high temperature MEMS pressure sensors are essential in coal, gas turbine engines, boilers, furnaces and system for oil/gas analysis. W.H. Ko, *et al.* [8] have developed square, rectangular and circular diaphragms which are the main sensing element, but square or rectangular any ones are generally used since they involved in lesser area and implement simpler lithography discussed. Oliver Paul Jan G., *et al.* [9] A MEMS pressure sensors can be fabricated either by surface micromachining/bulk micromachining or a combination of both. W. P. Eaton, *et al.* [10] have been designed and analyzed a pressure sensor using 3D builder module with finite element analysis of Intellisuite.

In this paper are analyzing various structures: square, rectangular and circular diaphragm based MEMS pressure sensor are designed and analyzed using Intellisuite. The diaphragm covered by consideration is one with conventional silicon diaphragm. Here, compared and analyzed various parameters such as Mises stress, displacement, sensitivity and also compared both analytical and simulation values of mechanical and electrical quantities.

2. Modelling and Design of Pressure Sensor

The MEMS pressure sensor was one of the earliest testing of micron technology. This system is commercially very successful because of several important features, including high sensitivity and equality. The surface micromachining process is also appropriate with integrated circuits.

In this paper the diaphragm has the result of geometry and a material as a silicon substrate to improve the sensitivity of low and high pressure values has been studied. The main differential equation as conclusive the deflection w(x,y) of a diaphragm with a predictable thickness, and also absolutely clamped edges manipulated to an enforced pressure P can be derived from the miniature scale deflection method which is given as [3];

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

where D is the flexural rigidity. It can be expressed as,

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

where E, v and h are the Young modulus, Poisson ratio and thickness of the diaphragm.

When an identical pressure P(x,y) as described in Fig. 1 acts on a diaphragm standard to its surface, the diaphragm undertakes a strain giving increase to

- Normal stress σx and σy which in curve give an increment to bending moments Mx and My.
- Shear stress τ_{xy} which in turn gives an increment to the twisting moment Mxy.

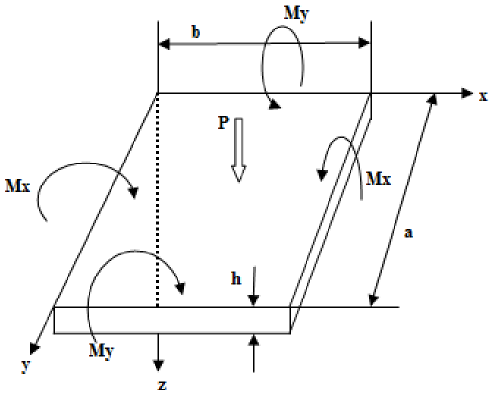


Fig. 1. Schematic diagram of bending of rectangular plate.

The results of Eqn. (1) give the maximal deflection (w_0) at the midpoint of the diaphragm in the Z axis direction. Having estimate w(x,y) the bending moments Mx, My and twisting moments Mxy per unit length of the diaphragm are designate as [3].

Bending Moment as,

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

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

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

Bending Stresses can be expressed as,

$$\left(\sigma_{xx}\right)_{\max}=\frac{6\left(Mx\right)\max}{h^2}, \quad (6)$$

$$\left(\sigma_{yy}\right)_{\max}=\frac{6\left(My\right)\max}{h^2}, \quad (7)$$

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

Fig. 2 shows the dimensions preferred for the different geometries of diaphragms that the diaphragm sizes are chosen in such a method that area is similar for all the three diaphragms.

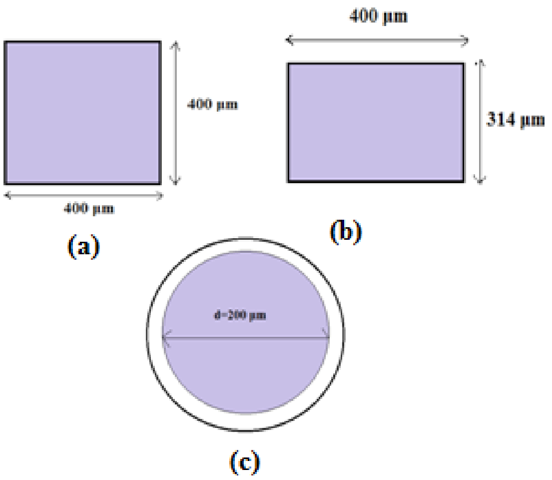


Fig. 2. Schematic representations of (a) square, (b) rectangular, and (c) circular diaphragms.

2.1. Square Diaphragm

The square diaphragm has the maximum induced stress for a given pressure. The bending of square plates with all edges is fixed. Thus the square diaphragm square sensor is approved geometry for pressure sensors because of, the large stresses produced by enforced pressure packing result in great sensitivity. Further, it is simple to dice the diaphragm from typical wafers [3].

Maximum stress calculated by centre of each edge is

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

The maximum deflection at the center for a given pressure is

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

The stress at the centre of the plate can be derived as,

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

And strain at the centre is,

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

2.2. Rectangular Diaphragm

In case of a rectangular diaphragm the deflection in the diaphragm can be simplified as in Eqn. (13) [3]. The length of rectangular diaphragm is 2a and a width is 0.5πa as shown in Fig. 2(b).

A simplified solution for the maximum stress and deflection of the rectangular diaphragms with all edges fixed is as follows:

$$W_{\max} = -\alpha\frac{pb^4}{Eh^2}, \tag{13}$$

$$\sigma_{yy} = \beta\frac{p.b^2}{h^2} \tag{14}$$

Table 1 gives the coefficients of maximum stress and deflection in a rectangular diaphragm.

Table 1. Coefficients of maximum stress and deflection in a rectangular.

a/b	1	1.2	1.4	1.6	1.8	2	∞
α	0.013	0.0188	0.0226	0.0251	0.0267	0.0277	0.0284
β	0.3078	0.3834	0.4356	0.4680	0.4872	0.4974	0.5000

2.3.Circular Diaphragm

The circular diaphragm has the minimum stress on its edges when implementing the equivalent pressure on a square diaphragm, other than the leading centre deflection is able to see in circular diaphragm. Therefore the applications in which maximal deflection of performance as the major role of the circular diaphragm is recommended [3].

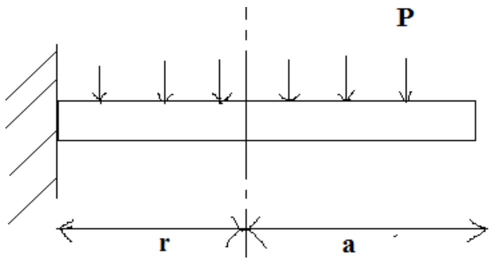


Fig. 3. A Circular plate subjected to uniform pressure loading.

Maximum Radial stress we calculated by,

$$(\sigma_{rr})_{\max} = \frac{3W}{4\pi h^2} \tag{15}$$

And also at edge Tangential stress calculated by,

$$(\sigma_{\theta\theta})_{\max} = \frac{3W}{4\pi h^2} \tag{16}$$

Both these stress at the centre of the plate become,

$$\sigma_{rr} = \sigma_{\theta\theta} = \frac{3\nu W}{8\pi h^2} \tag{17}$$

The maximal deflection occurs at the centre of the diaphragm,

$$W_{\max} = \frac{3W\left(m^2-1\right)a^2}{16\pi E m^2 h^3} \tag{18}$$

Table 2 gives the properties of materials and dimensions of square, rectangular and circular diaphragm.

Table 2. Dimension & Material Property of Square, Rectangular and Circular diaphragm.

Diaphragm	Material Property		
	Young Modulus (GPa)	Poisson Ratio	Density (gm/cc)
Silicon	170	0.26	2.32
Dimension (µm)			
	Length	Width	Height
Square	400	400	10
Rectangular	400	314	10
Circular	D=200		10

Figs. 4, 5 and 6 are show that the central deflection of the square, rectangular and circular Silicon diaphragm simulated through Intellisuite software. The result shows that the maximum central deflection is given in Table 3 under the same condition. As can be seen from the results, theoretical results show good agreement with finite element analysis tool. Figs. 7, 8 and 9 are show the Mises stress value of the square, rectangular and circular Silicon diaphragm.

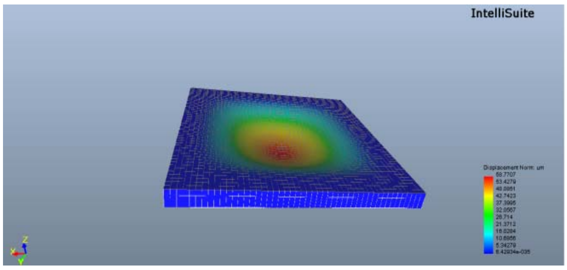


Fig. 4. Simulation of square diaphragm deformation on the Z axis with pressure of 25 MPa.

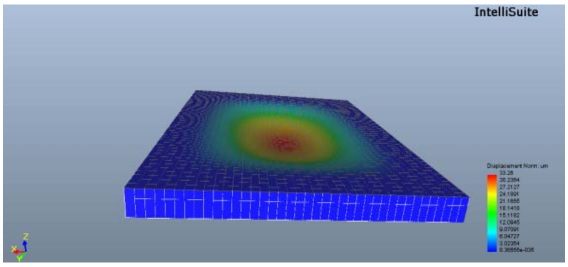


Fig. 5. Simulation of rectangular diaphragm deformation on the Z axis with pressure of 25 MPa.

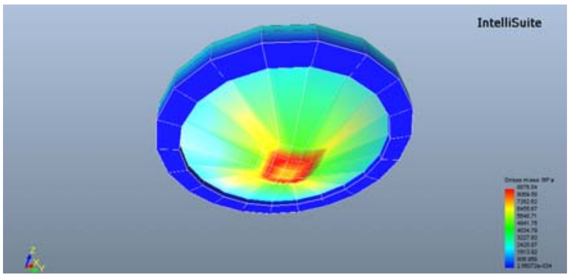


Fig. 6. Simulation of circular diaphragm deformation on the Z axis with pressure of 25 MPa.

Table 3. Comparison of deflection results for various Diaphragm geometries with pressure.

Shape of Diaphragm	Deflection (µm) at 1 MPa		Deflection (µm) at 5 MPa	
	Analytical	Intellisuite	Analytical	Intellisuite
Square	2.1 µm	2.4 µm	10.4 µm	11.8 µm
Rectangular	1.6 µm	1.3 µm	7.9 µm	6.7 µm
Circular	1.7 µm	1.8 µm	8.3 µm	11.5 µm

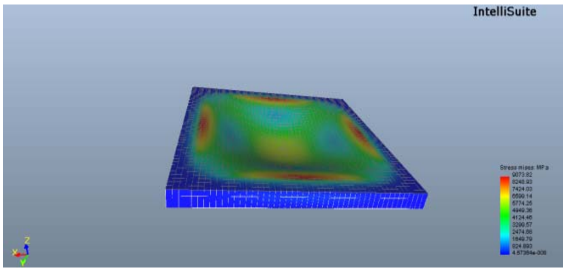


Fig. 7. Mises Stress analysis of the Square diaphragm with Pressure of 25 MPa.

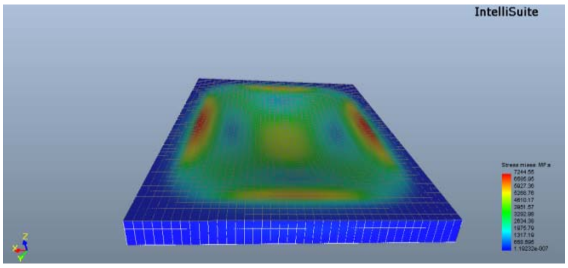


Fig. 8. Mises Stress analysis of the Rectangular diaphragm with Pressure of 20 MPa.

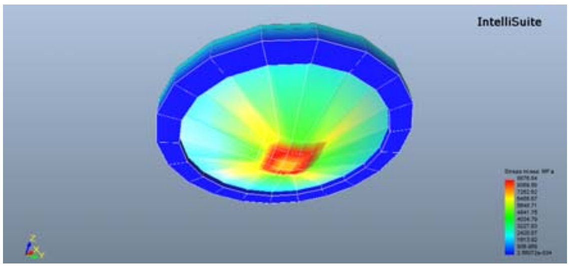


Fig. 9. Mises Stress analysis of the Circular diaphragm with Pressure of 25 MPa.

3. Finite Element Analysis

The diaphragm based pressure sensor is using the module of the finite element analysis tool Intellisuite. The pressure sensing of square diaphragm side length 400 μm and thickness 10 μm, rectangular diaphragm of dimensions is being 400 μm × 312 μm and a circular diaphragm radius 200 μm with thickness of 10 μm have been constructed by using 3D builder. The diaphragm of square, rectangular and circularis designed as silicon substrate and the properties of material used for simulation are given in Table 2. The highest stress induced and the maximum deflection produced in the diaphragm are determined. Then the analytical and simulation results are compared with the pressure range from 2 MPa to 25 MPa.

The results are obtained from the finite element analysis is being done. It can able to see that the maximum deflection produced at the centre of the diaphragm and the highest stress induced at the edge of the diaphragm, and it is to understand with the analytical explanation was given by the Eqns. (9-18).

Table 3 gives a comparison of the theoretical results with the FEM results obtained from Intellisuite. Here, it is observed that he circular diaphragm deflects more when compared to other diaphragms.

4. Results and Discussion

Fig. 10 shows that the determined and simulated outputs of a square diaphragm deflection vs. pressure. As can be seen from Fig. 10, the central deflection is increased when the applied pressure is increased and also both analytical and simulation results are arbitrarily equal. Fig. 11 and Fig. 12 show the calculated and simulated results of rectangular and circular diaphragms as same deflection vs. pressure.

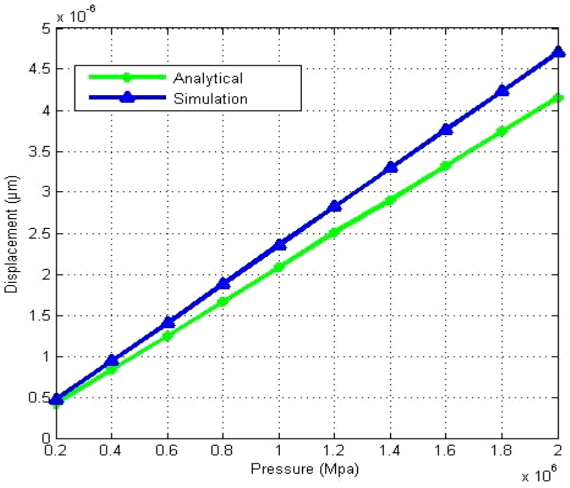


Fig. 10. A comparison of the displacement both analytical and simulation results for square diaphragm.

In Fig. 13 shows the simulated deflection vs. pressure of square, rectangular and circular diaphragms with a pressure from 0.2 MPa to 2 MPa and also the thickness of the diaphragm is 10 μm. The Fig. 14 show the simulated deflection vs. pressure of square, rectangular and circular diaphragms with a pressure from 0.6 MPa to 25 MPa and also the thickness of the diaphragm is same.

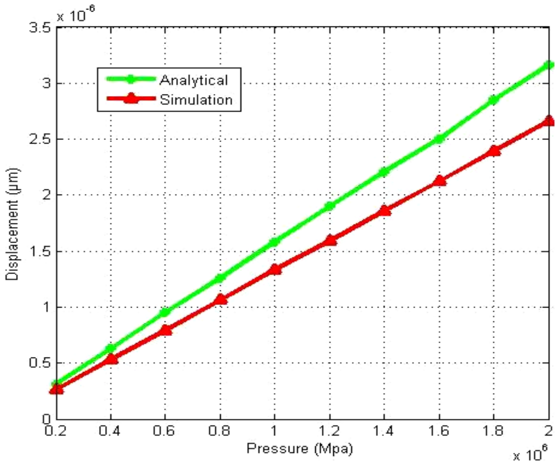


Fig. 11. A comparison of the displacement both analytical and simulation results for rectangular diaphragm.

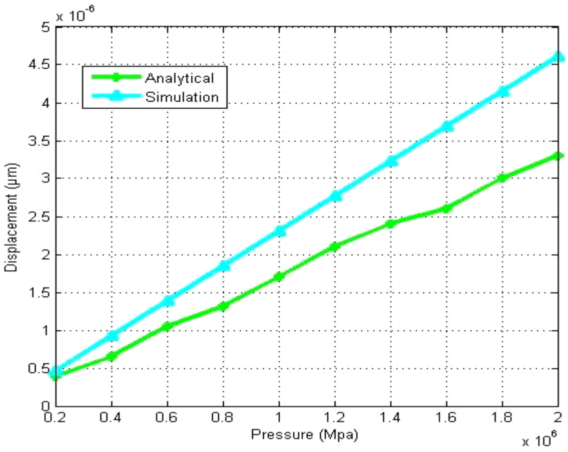


Fig. 12. A comparison of the displacement both analytical and simulation results for circular diaphragm.

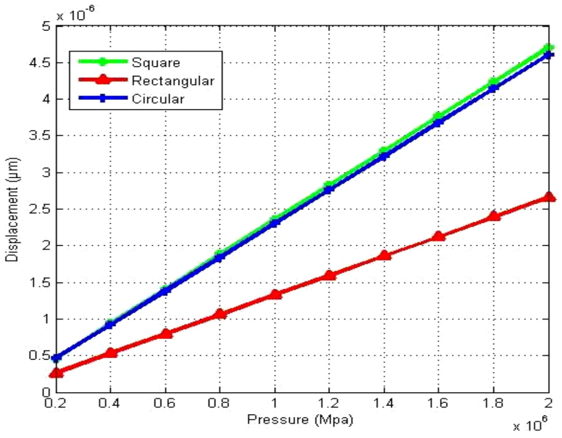


Fig. 13. The displacement of three different structure: Square, Rectangular and Circularat various loads applied (≤ 2 MPa).

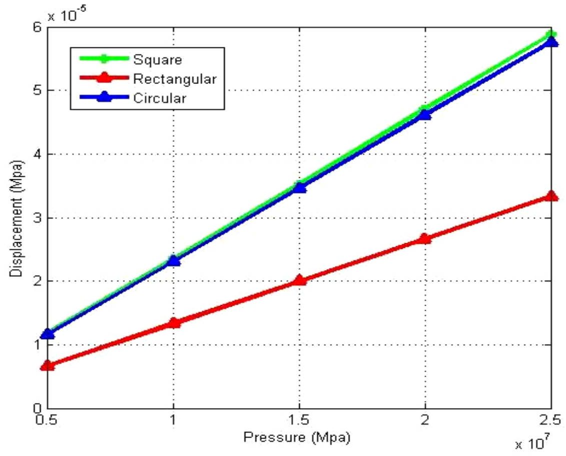


Fig. 14. The displacement of three different structure: Square, Rectangular and Circularat various loads applied (≤ 25 MPa).

In Fig. 15 shows the simulated Mises stress vs. pressure of square, rectangular and circular diaphragms with a pressure from 0.2 MPa to 2 MPa and also the thickness of the diaphragm is 10 µm.

In Fig. 16 shows the simulated Mises stress vs. pressure of square, rectangular and circular diaphragms with a pressure from 0.6 MPa to 25 MPa and also the thickness of the diaphragm is same.

In Fig. 17 shows the sensitivity of square, rectangular and circular diaphragms with a pressure range from 0.2 MPa to2 MPa and also the thickness of the diaphragm is 10 µm.

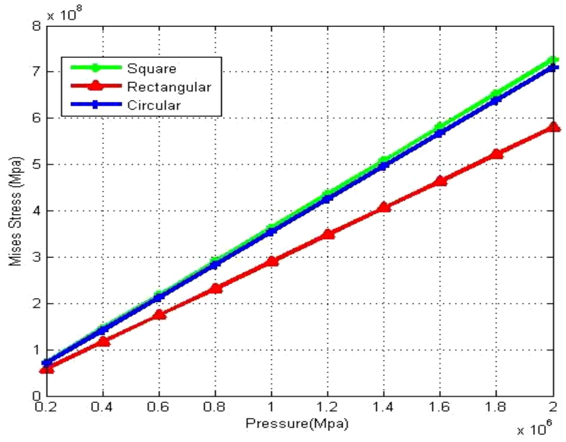


Fig. 15. The Mises stress of three different structures: Square, Rectangular and Circularat various loads applied (≤ 2 MPa).

5. Conclusions

Design an analysis of diaphragm based pressure sensor using various structures such as square, rectangular and circular diaphragms are presented. The central deflection and stress values under the influence of a uniform external pressure are calculated.

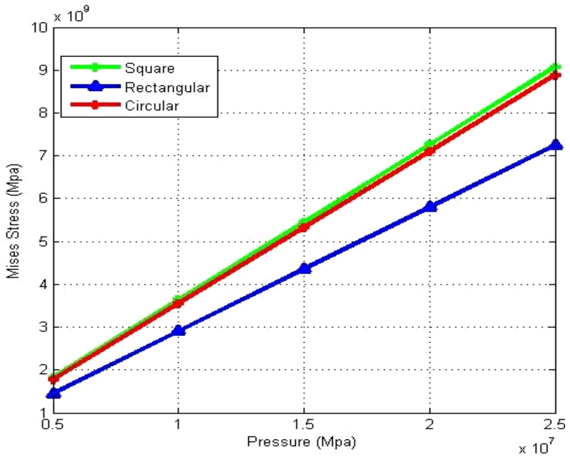


Fig. 16. The Mises stress of three different structures: Square, Rectangular and Circularat various loads applied (≤ 25 MPa).

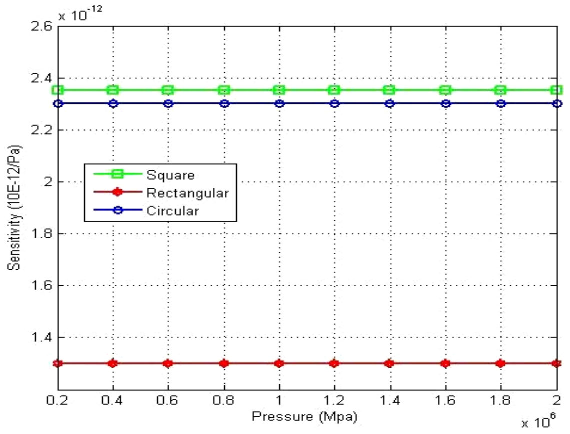


Fig. 17. The analysis to sensitivity of three different structures: Square, Rectangular and Circular at various loads applied (≤ 25 MPa).

Furthermore, the theoretical results are compared with the simulated results through the Finite Element Analysis tool. The relations between the particular dimensions of a square, rectangular and circular diaphragm have been evaluated using the Intellisuite 8.7v tool for a pressure range from 0.2 MPa to 25 MPa. Analytical results yields a displacement of square diaphragm is 1.24 µm and FEA result yield a displacement of 1.4 µm to input pressure of 0.6 MPa. Thus, the square shaped diaphragm is suitable for environmental application. Because of the optimized that it has more deflection and sensitivity of both analytical and simulation in square diaphragm.

Then we can measure both low and high pressure value on the environment by using the silicon square diaphragm. Finally, the equations that relate the applied pressure to the measured displacement the device are moderately simple, and measurement has shown a good agreement between theory and simulation.

Acknowledgment

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]. Vidhya Balaji, K. N. Bhat, A Comparison of Burst Strength and Linearity of Pressure Sensors having thin Diaphragms of Different Shapes, *Journal of ISSS*, (India),Vol. 2, Sept. 2012, pp. 18-26.

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

[3]. Tai-Ram Hsu, MEMS & Microsystem:Design and Manufacture, *Tata McGraw-Hill*, 2002.

[4]. Ashish and T. Shanmuganantham, Design of MEMS Pressure Sensors for Environmental Applications, in *Proceedings of the International Conference on Computer Communication and Informatics*, India, Janaury 2014, pp. 1-3.

[5]. MEMS: Design and Fabrication, Handbook, Mohamed Gad-el-Hak (Ed.), *Taylor & Francis Group*, 2006.

[6]. Ezzat G. Bakhoum, Novel Capacitive Pressure Sensor, *Journal of Microelectromechanical Systems*, Vol. 19, 2010, pp. 443-450.

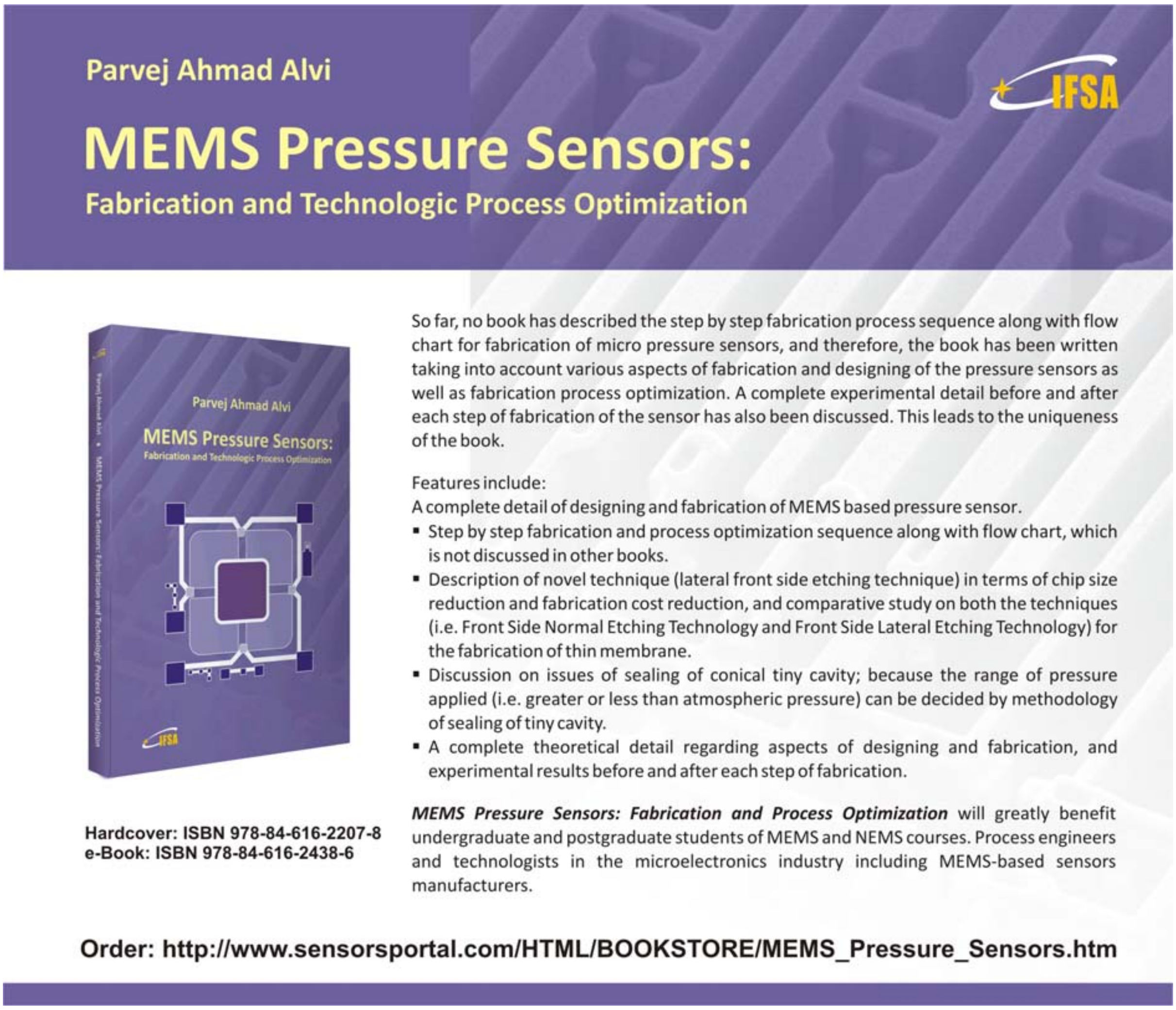
[7]. B. Qi, *et al*., Fiber optical pressure and temperature sensors for oil down hole applications, *Proceedings of SPIE,* Vol. 4578, 2002, pp. 182-190.

[8]. W.H. Ko, Q. Wang, Touch Mode Capacitive Pressure Sensors, *Sensors and Actuators*, A, 75, 1999, pp. 242–251.

[9]. Oliver Paul, Jan G. Korvink (Eds.), MEMS: A Practical Guide to Design, Analysisand Applications, 1st Ed., *Springer*, 2010.

[10]. W. P. Eaton, J. H. Smith, Micromachined Pressure Sensors: Review and Recent Developments, *Smart Material Structure*, Vol. 6, 530, 1997.

2015 Copyright ©, International Frequency Sensor Association (IFSA) Publishing, S. L. All rights reserved.
(http://www.sensorsportal.com)



Parvej Ahmad Alvi

MEMS Pressure Sensors:
Fabrication and Technologic Process Optimization

So far, no book has described the step by step fabrication process sequence along with flow chart for fabrication of micro pressure sensors, and therefore, the book has been written taking into account various aspects of fabrication and designing of the pressure sensors as well as fabrication process optimization. A complete experimental detail before and after each step of fabrication of the sensor has also been discussed. This leads to the uniqueness of the book.

Features include:
A complete detail of designing and fabrication of MEMS based pressure sensor.

- Step by step fabrication and process optimization sequence along with flow chart, which is not discussed in other books.
- Description of novel technique (lateral front side etching technique) in terms of chip size reduction and fabrication cost reduction, and comparative study on both the techniques (i.e. Front Side Normal Etching Technology and Front Side Lateral Etching Technology) for the fabrication of thin membrane.
- Discussion on issues of sealing of conical tiny cavity; because the range of pressure applied (i.e. greater or less than atmospheric pressure) can be decided by methodology of sealing of tiny cavity.
- A complete theoretical detail regarding aspects of designing and fabrication, and experimental results before and after each step of fabrication.

MEMS Pressure Sensors: Fabrication and Process Optimization will greatly benefit undergraduate and postgraduate students of MEMS and NEMS courses. Process engineers and technologists in the microelectronics industry including MEMS-based sensors manufacturers.

Hardcover: ISBN 978-84-616-2207-8
e-Book: ISBN 978-84-616-2438-6

Order: http://www.sensorsportal.com/HTML/BOOKSTORE/MEMS_Pressure_Sensors.htm