International Journal of Advance Research in Science and Engineering
Vol. No.6, Issue No. 08, August 2017
www.ijarse.com
IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Investigation on Various Diaphragm Designs For Low Pressure MEMS Piezoresistive Sensor

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ABSTRACT

The paper focuses on the modeling and analysis of MEMS piezoresistive pressure sensors based on design and performance parameters of square diaphragm. The simulations performed using the Finite Element Method software Intellisuite® proved that the better shape for the design of a piezoresistive pressure sensor is one with the square shaped diaphragm. The square shaped diaphragm with different design of ring embossed is simulated and tested for low pressure from 0 kpa to 5 kpa. The work is then highlighted on the modeling of MEMS piezoresistive pressure sensors with three different square shaped diaphragms, one diaphragm with rings have equal width and equal spacing and one corner opened, and the second and third designs are the diaphragm with rings have unequal width progressively increasing and progressively decreasing with equal spacing respectively. Based on these three methods, the sensitivity of the bulk micromachined silicon low pressure sensor is improved remarkably, which is verified by the experiment and comparing the performance parameters of the three sensors. The diaphragm deflection in first pressure sensor was found to be more when compared to other pressure sensors, and the first pressure sensor is capable of giving more output voltage and exhibits more voltage sensitivity. The open in the corner of the layer plays an integral part of sensor design. The results show that the sensitivity is measured to be 0.433 mV/kpa/V at the pressure 5 kpa, achieving improvement of about 234%, compared with that of the traditional flat diaphragm pressure sensor.

Keywords— Deflection, Finite Element Method, Intellisuite,MEMS, Piezoresistive Pressure Sensor, Stress , Voltage Sensitivity,

I. INTRODUCTION

In recent years sufficient research has been carried out on micro machined pressure sensors. These sensors are fabricated by new manufacturing technologies such as bulk micromachining or surface micromachining [1]. Pressure sensors have profound applications in medical field, automobile industry, household applications, oceanography etc, [8]. Conventional transducers are bulkier and consume more power. They are not suitable for compact and standalone systems. MEMS pressure sensors have the advantages of small size, low cost, low energy consumption and high resolution when compared to conventional transducers. Moreover MEMS technology allows more electronics to be fabricated on the same chip along with transducer to be compact and less noise design and more built-in intelligence features. Diaphragms are one of most important mechanical parts for many of MEMS sensors and actuators. A thin membrane serves as the sensing element in MEMS pressure sensors. Pressure applied on the diaphragm deflects the membrane and this deflection is limited until

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346
the elastic force is balanced by pressure [6]. The different shapes play a key role in the design of pressure sensors for various applications. The purpose of this paper is to analyze different shapes of diaphragms, based on the parameters namely deflection and stress using FEM software Intellisuite 8.7v [9].

The different MEMS materials and fabrication techniques have been under research to improve the sensitivity of piezo resistive pressure sensors. Hence the work in this paper also high light to model, compare and analyze different performance parameters like deflection, stress, output voltage and voltage sensitivity for a piezoresistive pressure sensor with the two different types of diaphragms. The diaphragm under consideration is one with conventional silicon diaphragm and other one with ring embossed diaphragm. The corner of the ring embossed diaphragm is opened and the effect is studied in this work. The work also extended to establish that changing dimensions of the embossed ring in the diaphragm. For pressure ranges, 0 kpa to 5 kpa the analysis was carried out and the results were obtained.

In this paper, first the working principles of a silicon piezoresistive pressure sensor have explained [13]. Then the specifications and design parameters of a proposed pressure sensor, based on different design and fabrication is considered. Finally, the outcome of simulation of various structures of pressure sensor using Intellisuite-8.7V software is presented.

II. PIEZO RESISTIVE PRESSURE SENSOR

Pressure sensor fabricated in this work is based on the piezoresistors[4,5]. These piezoresistors undergo a change in resistance due to the applied pressure. The resistance change is converted into voltage signal by means of a Wheatstone bridge and by applying known pressures on the diaphragm and recording the output voltages the sensor can be calibrated.

A piezoresistive pressure sensor consists of three major active components namely, a diaphragm, Wheatstone bridge and the piezoresistors. These three components, responsible for the sensitivity of the device, are shown in fig1.

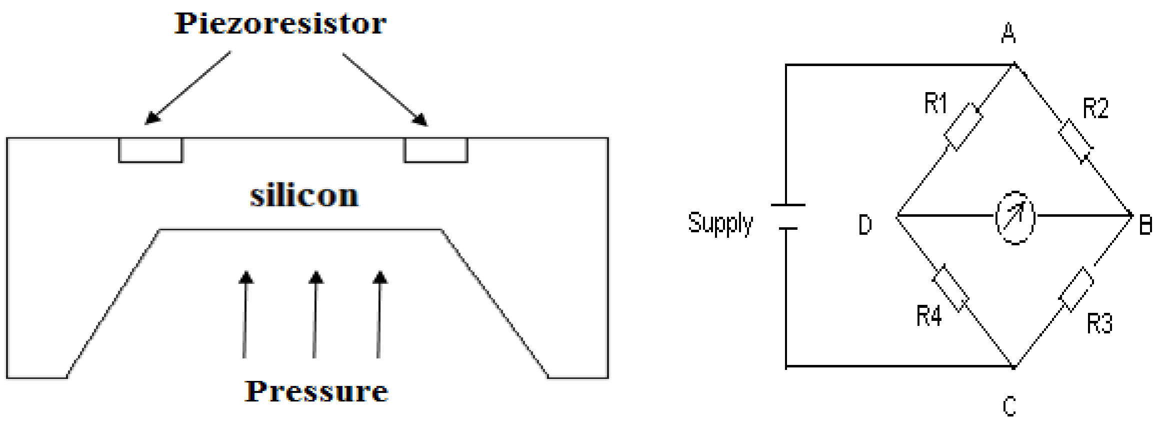

Figure 1. Diaphragm,Piezoresistors and Wheatstone bridge configuration

The change in resistance of a piezoresistive material under stress in given by Equation (1)

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta p}{p} \quad (1)$$

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

The first two terms correspond to geometrical deformation in length and cross section of the resistors, respectively. For piezoresistors under stress, these terms are very small compared to the last term [6] which corresponds to change in resistivity. Hence, the equation reduces to, Equation (2)

$$\frac{\Delta R}{R} = \frac{\Delta p}{p} = \pi_l \sigma_l + \pi_t \sigma_t \quad (2)$$

Where σl and σt are the longitudinal and transverse stresses acting on the piezoresistor.

In equation (3), where, πl and πt correspond to longitudinal and transverse piezoresistive coefficients. In the present design, the piezoresistors are oriented along [110] directions on (100) wafer in order to maximize the piezoresistive effect. For this orientation, Equation (3)

$$\pi_{l,110} = \frac{1}{2}(\pi_{11} + \pi_{12} + \pi_{44})$$

$$\pi_{t,110} = \frac{1}{2}(\pi_{11} + \pi_{12} - \pi_{44}) \quad (3)$$

Where, π_{11}, π_{12} and π_{44} are the three independent nonzero piezoresistive coefficients of silicon. Two piezoresistors are subjected to longitudinal stress and their resistance increases, whereas the other two resistors are subject to transverse stress and their resistance decreases [13]. Thus, the balanced Wheatstone bridge becomes unbalanced and the sensor gives a voltage output by using equation (4)

$$V_1 = \frac{R_3}{R_3 + R_4} X\, V_{cc}$$

$$V_2 = \frac{R_2}{R_2 + R_1} X\, V_{cc}$$

$$\Delta V = V_1 - V_2 \quad (4)$$

R_1, R_2, R_3 and R_4 are wheat stone bridge arm resistances.

III.DESIGN OF VARIOUS DIAPHRAGM STRUCTURES

We have conducted simulations and experiments for four different diaphragm structures of piezoresistive pressure sensors and evaluate their performance [7,10]. The design parameters of the diaphragms have been selected within the specified pressure range to maximize the sensitivity.

The different diaphragm designs are:

- Standard Flat Diaphragm(SFD)
- Unequal Rings Progressively Increasing Embossed Diaphragm(URPIED)
- Unequal Rings Progressively Decreasing Embossed Diaphragm(URPDED)
- Equal Rings With One Corner Open Embossed Diaphragm(ERCOED)

A. Standard Flat Diaphragm (SFD) Design

The standard flat diaphragm piezoresistive pressure sensors sensitivity primarily depends on the dimensions of the diaphragm. To increase the sensitivity, a/h ratio must be as high as possible ("a" is the radius of the diaphragm and "h" is the thickness of the diaphragm). For the specified pressure range, we have selected the

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ISSN (P) 2319 - 8346

dimensions of the diaphragm to be 288 μm by 288 μm with thickness of 2 μm to withstand the fracture stress. The schematics of the diaphragm structure for a thickness of 2 μm are shown in Fig. 2.In this structure 0.185 mv/Kpa/V sensitivity is obtained.

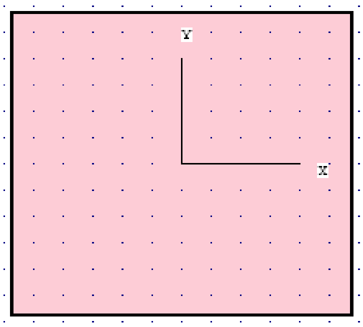

Fig. 2.flat diaphragm (top view)

B. Unequal Rings Progressively Increasing Embossed Diaphragm (URPIED) Design

It has been observed that in unequal width and equally spaced ring embossed diaphragm, the sensitivity is higher than flat diaphragm.The highest sensitivity achieved with this diaphragm thickness of 2 μm and thickness of ring is 1 μm is about 0.424 mV/Kpa/V. In the proposed structure we designed the rings with different thickness of 8, 16, 24 and 28 micro meters respectively and equally spaced at the distance of 16 micro meters as shown in Fig.3.

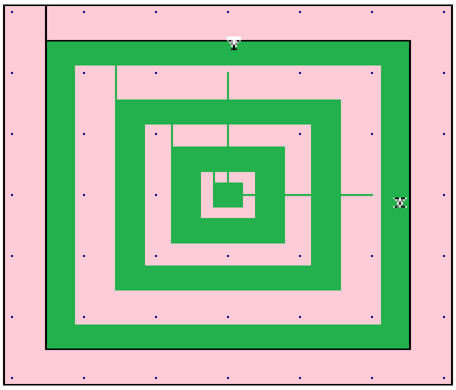

Fig.3. URPIED (top view)

C. Unequal Rings Progressively Decreasing Embossed Diaphragm (URPDED) Design

It has been observed that in unequal width progressively decreasing and equally spaced ring embossed diaphragm the sensitivity is higher than SFD and URPIED. The highest sensitivity achieved with this diaphragm thickness of 2 μm and thickness of ring is 1 μm is about .428 mV/Kpa/V. In the proposed structure we designed the rings with different thickness of 32, 24, 16 and 8 micro meters respectively and equally spaced at the distance of 16 micro meters as shown in Fig.4.

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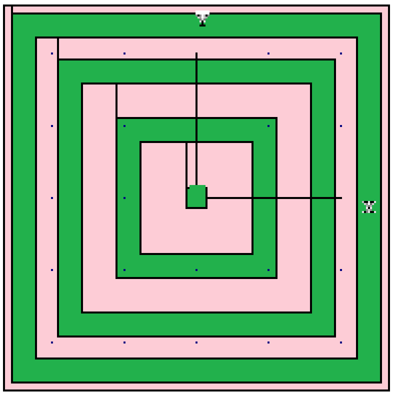

Fig.4. URPDED (top view)

D. Equal Rings with One Corner Open Embossed Diaphragm (ERCOED) Design

It has been experiential that in equal rings embossed with one corner open diaphragm the sensitivity is higher than other diaphragm designs.The highest sensitivity achieved with this diaphragm thickness of 2 µm and thickness of ring is 1 µm is about .433 mV/Kpa/V. In the proposed structure we designed the rings with equal thickness of 8 micro meters and equally spaced at the distance of 16 micro meters and made open at the leftmost corner as shown in Fig.5.

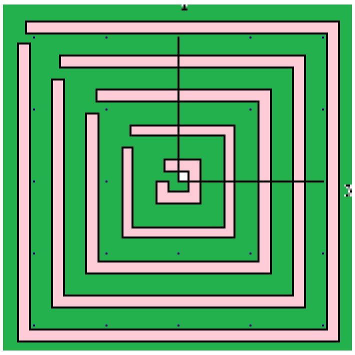

Fig.5. ERCOED(top view).

The design of this pressure sensor entail determination of various geometries like side length of the diaphragm, thickness of the diaphragm, cantilever beam length, width and thickness to achieve the maximum sensitivity and the least non-linearity[3]. The diaphragm design must concentrate on improving the deflection sensitivity, still maintaining high burst pressure (Pb). In this approach, thickness of the diaphragm should be minimum that yields the maximum deflection for the given side length is obtained. The minimum optimal burst pressure (P_{bmin}) can be calculated for given maximum operating pressure (P_{max}) of the device using Equation (5)

$$P_{B\,min} = \frac{\sigma_{elestic}}{0.39}\left[\frac{P_{max}(1-\gamma^3)}{0.84\,E}\right]^{\frac{1}{2}} \tag{5}$$

Where E is the Young's modulus of the silicon, γ is its Poisson's ratio , σ is the silicon film pre-stress.

IV. PERFORMANCE OF RINGS EMBOSSED DIAPHRAGM EMPLOYED PRESSURE SENSOR.

In order to obtain the various performance factors of this pressure sensor, the authors have used FEM analysis using IntelliSuite MEMS design software[14]. Using IntelliFab module the structure is created by clearly specifying the various process steps starting from cleaning of silicon wafer[15]. The required boundary conditions are specified before the simulation and the pressure load is applied at the bottom surface of the diaphragm. The structure was created for simulation in the Intellisuite environment [16].

A. Deflection studies

The structure of the designed pressure sensor for the geometries listed in Table 1 is created for FEM analysis .

Table 1 Material parameters used for the FEM simulation

Parameters	**Value**
Material	**Silicon**
Side length (2a) in µm	288
Young's modulus in GPa	160
Poisson's ratio	0.34
Diaphragm thickness in µm	2
Ring Thickness in µm	1
Piezo resistors dimensions in µm	8 µm *4 µm

The pressure is applied at the bottom surface of the diaphragm. The piezo resistors arrangement is shown in Fig.6.

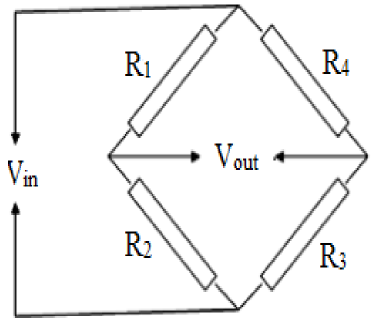

Fig.6.Piezo resistors arrangement

The design of piezoresistive pressure sensor consists of piezoresistive element placed on a top of the diaphragm[4,8]. Placement of piezoresistive element on the square diaphragm is very important design consideration to attain the required sensitivity. The best possible location to place the piezoresistive

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ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

material would be in the region of high stress on the diaphragm[17-18] Then these resistors are connected in the form of Whetstone's bridge as shown in Fig.6. The application of pressure under the sensor causes a deflection of the membrane and this causes a change in resistance of the piezoresistive elements. The deflection at the centre of the diaphragm for the specified pressure range (0–5 kPa) was obtained is plotted as shown in Fig.7. It is obvious from the deflection results that the maximum deflection at 5 kPa is 2.36 µm. The deflection curve shows that better linearity is ensured in this structure. The deflection sensitivity is anticipated to be 0.472 µm/kPa. As a result, the calculation of stress distribution and deflection in accordance with the applied pressure becomes essential.

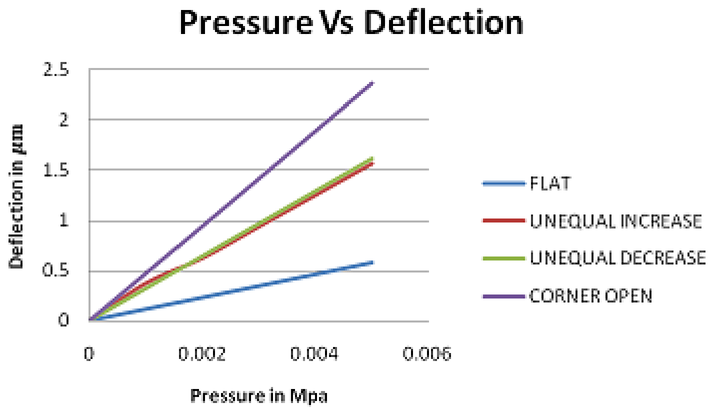
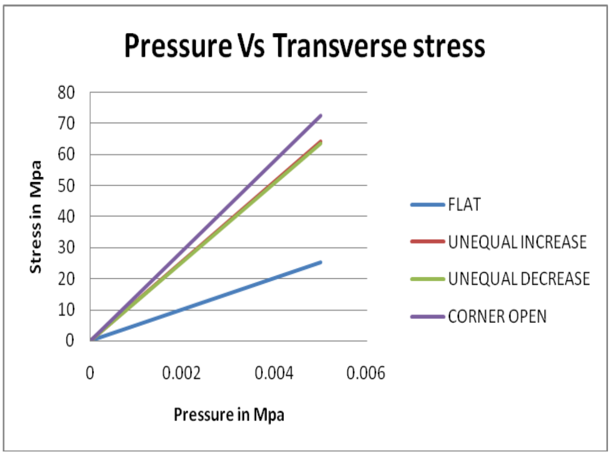


Fig.7 Pressure Versus Deflection of the diaphragm

B. Stress and Piezoresistive analysis

The stress in the diaphragm plays an important role in determining the performance of the diaphragm. [11].The resistance change and the sensitivity of the sensors are actually controlled by the magnitude of the stress difference between the longitudinal and transverse direction. The maximum stress is seen at the middle point of the square diaphragm and at the middle of the edges [12]. The corners of the diaphragm have no stress. Hence, the maximum longitudinal and transverse stresses are measured. The stress distribution is very high in the equal rings with one corner open embossed diaphragm. is shown in Fig. 8.



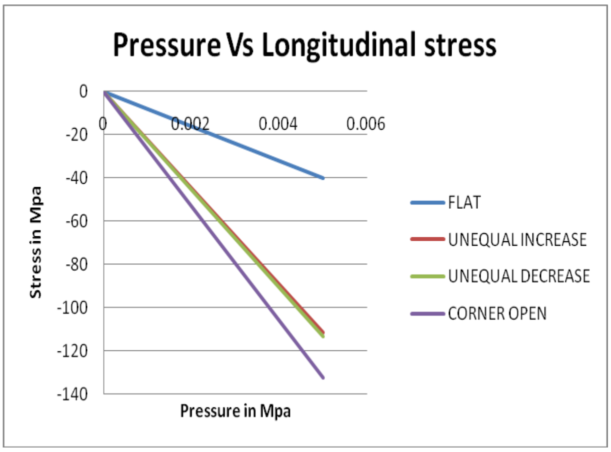


Fig.8. Pressure versus Stress distribution

Consequently, piezoresistive analysis was carried out using IntelliSuite simulation and to obtain the resistances at various pressure levels. Fig.9 shows the resistances of R1, R2, R3 and R4 at different pressures.

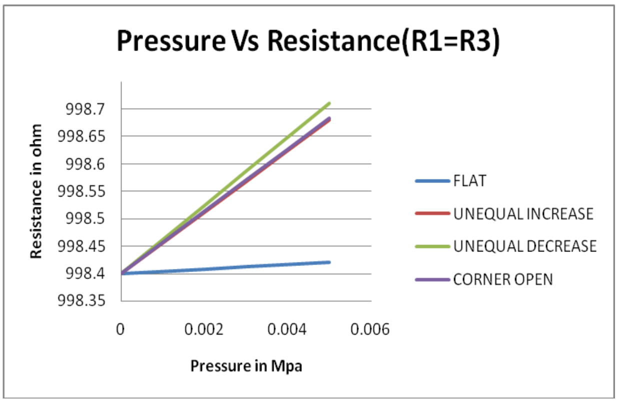


Fig.9. Resistances measured by simulation at different pressures

C. Voltage studies

The resistance values obtained at different pressure are used to calculate the differential voltage output of the bridge using equation (4) The voltage values calculated are plotted against pressure as shown in Fig.10.

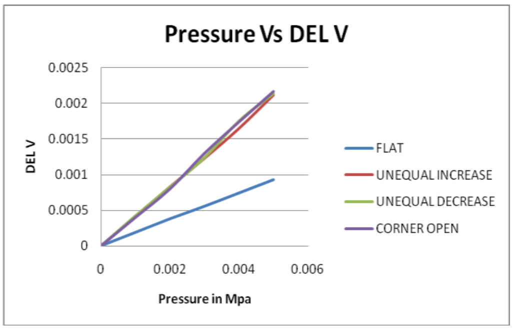


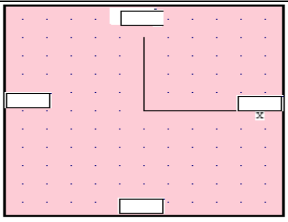
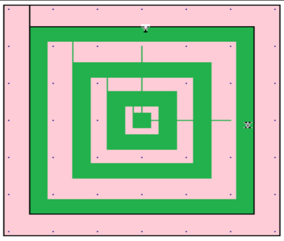
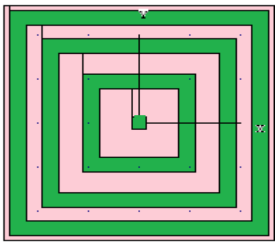
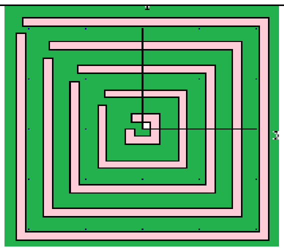
Fig.10.Bridge output voltages estimated between(0-5) kPa

International Journal of Advance Research in Science and Engineering
Vol. No.6, Issue No. 08, August 2017
www.ijarse.com
IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

IV. COMPARISON WITH OTHER STRUCTURES

Now, it is essential to check if this structure is able to give better sensitivity than the other structures for low pressure sensing. The authors have produced these structures and have estimated the sensitivity and non-linearity for various structures. The various dimensions of these structures have been optimized to give the maximum sensitivity. The resistances of the resistors forming the bridge are predictable through piezoresistive analysis conducted using IntelliSuite simulation. The sensitivities obtained for the various cases are listed in Table 2 . The results clearly show that the proposed equally spaced and equal width rings with one corner open embossed structure can enhance the stress induced considerably for any given pressure and therefore can help one to achieved better sensitivity than the other three structures reported in this study.

Table 2 comparison with other structures

Diaphragm type	Top View of the Diaphragm	Sensitivity (μV/kPa/V)
Flat Diaphragm (2μm)		185
Rings embossed with equal width and unequal spacing (Progressively increasing)		424
Rings embossed with equal width and unequal spacing (Progressively decreasing)		428
Equal Rings with one corner open embossed diaphragm		433

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V. CONCLUSION

An investigation has been made of the ring embossed diaphragm with square shapes for low pressure measurement in the range of 0 to 5KPa. This is done using analytical equations and Intellisuite MEMS CAD simulation tool.The flat, Rings embossed with unequal width of diaphragms and Rings embossed with equal width one corner open diaphragm of a pressure sensor was taken for analysis. It was found that the rings embossed diaphragm gave good performance than the flat diaphragm. For low pressure range the equally spaced rings with equal width one corner open diaphragm is best suited.

VI. ACKNOWLEDGEMENTS

Authors would like to acknowledge the generous support of the Co ordinator,NpaMass , Annamalai university.

REFERENCES

[1] Bhat K. N. "Silicon Micro machined Pressure Sensors" Journal of the Indian Institute of Science Vol 87:1 Jan–Mar 2007 journal.library.iisc.ernet.in

[2] Alvi P. A. , Akhtar J. , Lal K. M., Naqvi S. A. H. and Azam A."Design and Fabrication of Micromachined Absolute Micro Pressure Sensor" Sensors & Transducers ,,Volume 96 :Issue 9 :September 2008

[3] Xiaodong Wanga, Baoqing Lia, Onofrio L. Russoa, Harry T. Romanb, Ken K. China, Kenneth R. Farmera "Diaphragm design guidelines and an optical pressure sensor based on MEMS technique" Microelectronics Journal 37 ,50–56, 2006

[4] Y. H. Zhang, C. Yang, Z. H. Zhang, H. W. Lin, L. T. Liu, T. L.Ren, A Novel Pressure Microsensor With 30- μm-Thick Diaphragm and Meander-Shaped Piezoresistors Partially Distributed on High-Stress Bulk Silicon Region, IEEE Sensors Journal. 7 (2007) 1742.

[5] A. Barlian, W.-T. Park, J. R. Mallon, Jr., A. J.Rastegar, B. L. Pruitt, Review: Semiconductor piezoresistance for microsystems, Proc. IEEE.97 (2009) 513.

[6] S. Guo, H. Eriksen, K. Childress, A. Fink, M. Hoffman, High temperature smart-cut SOI pressure sensor, Sens. Actuators A. 154 (2009) 255.

[7] Huiyang Yu,; Jianqiu Huang ,; "Design and application of a High sensitivity Piezoresistive Pressure sensor for Low Pressure Conditions", Sensors Journal. 15, pp.22692-22704, 2015.

[8] Shwetha Meti*, Kirankumar B. Balavald*, B. G. Sheeparmatti " MEMS piezoresistive pressure sensor: a survey" *Int. Journal of Engineering Research and Applications ISSN: 2248-9622, Vol. 6, Issue 4, (Part - 1) April 2016, pp.23-31*

[9] A. Nallathambi, T. Shanmuganantham "Design of Diaphragm Based MEMS Pressure Sensor with Sensitivity Analysis for Environmental Applications"*Sensors & Transducers, Vol. 188, Issue 5, May 2015, pp. 48-54*

[10] Pramanik C., Saha H., "Low Pressure Piezoresistive Sensors for Medical Electronics Applications", Journal Materials and Manufacturing Process published on 07 Feb 2007.

[11] Shwetha Meti, Kriankumar B, Balavalad, B.G. Sheeparmatti, "Sensitivity Analysis of Silicon Based Micro Pressure Sensors Using Different Configurations of Meander Shape Piezoresistors", International Journal of Engineering Science and Computing, pp.6241-6245, May 2016.

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

[12] Analysis of Square and Circular Diaphragms for a MEMS Pressure Sensor Using a Data Mining Tool,Madhavi, Sumithradevi, Krishna, Vijayalakshmi, Communication systems and Network Technologies, June 2011

[13] K.J.Suja, G.S.Kumar, A.Nisanth, Rama Komaragiri, "Dimension and doping concentration based noise and performance optimization of a piezoresistive MEMS pressure sensor", Microsyst Techno-Springer, Feb.2014.

[14] M. Narayanaswamy, R. Joseph Daniel, K. Sumangala and C. Antony Jeyasehar, "Computer Aided Modelling and Diaphragm Design Approach for High Sensitivity Silicon-On-Insulator Pressure Sensors", Measurement, Vol. 44, No. 10, pp. 1924-1936, 2011.

[15] M. Narayanaswamy, R. Joseph Daniel and K. Sumangala, "Peizoresistor Size and Placement Effect on Sensitivity of Silicon-On-Insulator Piezoresistive Pressure Sensor", Journal of Instrument Society of India, Vol. 43, No. 3, pp. 208-211, 2013.

[16] M. Rajavelu, D. Sivakumar, R. Joseph Daniel and K. Sumangala, "Perforated Diaphragms Employed Piezoresistive MEMS Pressure Sensor for Sensitivity Enhancement in Gas Flow Measurement", Flow Measurement and Instrumentation, Vol. 35, pp. 63-75, 2014.

[17] D. Sindhanaiselvi, R. Ananda Natarajan and T. Shanmuganantham, "Performance Analysis of Sculptured Diaphragm for Low Pressure MEMS Sensors", Applied Mechanics and Materials, Vol. 592-594, pp. 2193-2198, 2014.

[18] D. Sindhanaiselvi, R. Ananda Natarajan and T. Shanmuganantham, "Design and Optimization of Low Pressure Sculptured Diaphragm with Burst Pressure, Stress Analysis and its Enhancement", International Journal of Applied Engineering Research, Vol. 10, No.24, pp. 21075-21081, 2015.