SENSITIVITY ENRICHMENT BY EQUALLY SPACED RINGS EMBOSSED SILICON DIAPHRAGM IN LOW PRESSURE MEMS PIEZORESISTIVE PRESSURE SENSORS

[1] M.Latha, [2] Dr. R. Ananda Natarajan,
[1]Research Scholar, Department of EEE, Pondicherry Engineering College, Puducherry, India
[2] Professor, Department of E&I, Pondicherry Engineering College, Puducherry, India.

Abstract: In this paper a MEMS pressure sensor for low pressure measurement in the range (0-5) kPa is proposed. Based on the burst pressure calculation the diaphragm dimensions are considered and four piezoresistors are placed on the diaphragm to sense deflection. To improve the sensitivity, further two modified ring embossed structures are proposed. Structure one has equally spaced and equal width rings. In the second structure the rings are equally spaced and one corner opened. The intellisuite MEMS CAD tool has been used to develop and analyze the performance of the two structures with standard flat diaphragm. The diaphragm side length is taken as 288 micro meter. The results show that deflection sensitivity improves 350% and voltage sensitivity improves 259%.Improvement of stress generation is 250%.Analytical results are compared with simulation results. These results conclude that the ring embossed diaphragm has better sensitivity and linearity than flat diaphragm.

Keywords: Piezoresistive, Pressure sensor, Stress, Sensitivity, Low pressure, Intellisuite.

1. INTRODUCTION

MEMS (Micro Electro Mechanical Systems) are process technology used to create very small devices or systems. MEMS devices are more precise and basically smaller, faster, lighter than their solid state devices [1]. Miniaturization of complex systems are done by micro fabrication technology and integrating the sensing, controlling and actuating functions on a single chip [2]. The differential and absolute micro pressure sensors based on different transduction principles on the variety of materials have been developed using MEMS technology in the wide range [3]. By using the micromachining technique in MEMS Silicon pressure sensors are first fabricated [4, 5]. Pressure sensors extensively used for aerospace, biomedical, automobile and defense applications [6]. For pressure measurement various sensing principles can be used. These comprise of piezoresistive, capacitive, resonant, piezoelectric sensing [7]. Out of these different sensing principles, the piezoresistive sensing is preferred in pressure sensors because of ease of fabrication, high reliability, excellent linearity and repeatability. Piezoresistive sensors have better sensitivity than the metal strain gauges. These pressure sensors use silicon as a piezoresistive element and they are very popular due to high sensitivity and repeatability [8, 3]. The presence of an insulating layer under the polysilicon piezoresistors has the advantage in high temperature applications [9, 10]. There are many structures in the design of low pressure sensor. The factors for designing the pressure sensor are thickness of the diaphragm and also the depth of the piezo resistors. Membranes with center boss structures have been used to linearise the sensor signal. But a large memberane is required to achieve a reasonable output signal.

In the sensor employed peninsular structure diaphragm, the sensitivity is increased by 11.4% and the nonlinearity is reduced by 60% when compared with flat diaphragm[11]. In low pressure sensing the stability, linearity and sensitivity are the major issues. To improve the sensitivity with allowable linearity different types of diaphragms were fabricated for low pressure sensing. The diaphragms with center bosses have more stiffness than flat diaphragm. This method also helpful to reduce the nonlinearity error. The non linearity was reduced by either improve the sensitivity (or) reduce the size of the sensor. Due to this additional center mass, the acceleration sensitivity of the diaphragm was increased. [12, 13]. The peninsula structure has more sensitivity than center boss diaphragm [11]. Pramanik and Saha denoted that the complementary bossed diaphragm has more sensitivity than that of a standard flat diaphragm, but the nonlinearity increases. By providing nano crystalline silicon piezoresistors the sensitivity is improved with a slight increase in nonlinearity [14]. Kinnell developed a new structure named as hollow stiffing structure that replace the solid center boss and obtained better sensitivity and linearity [15]. To increase the performance of the sensor Mackowiak offered partly-structured thicker membranes. When the sensor being structured the sensitivity become increased to 300% compared with unstructured sensors. The stability is lesser in the structure if the diaphragm is more thinner [16] .The sensors fabricated with MOSFET, its performance is improved and lower in power consumption [17].

In this proposed work, design and simulation of pressure sensor with silicon diaphragm and poly silicon piezoresistors is considered. To improve the sensitivity of low pressure sensor, rings embossed diaphragm pressure sensor is proposed. The proposed ring embossed structure could have the advantages of low fabrication cost, high sensitivity and good linearity over other existing structures. The performances of proposed structures are compared with simple standard flat diaphragm structure to demonstrate the superiority of the proposed structures.

The paper is organized as follows, first the working principle of a silicon piezoresistive pressure sensor is presented. Then the design and specifications of a proposed pressure sensor are presented. Finally, simulated values of proposed pressure sensor using Intellisuite MEMS CAD Tool are compared with analytical value.

1.1. MEMS Silicon Pressure Sensor

A piezoresistive pressure sensor has a diaphragm with piezoresistors on top of it are connected in a Wheatstone bridge arrangement [18]. This is illustrated in Fig.1. The diaphragm is generally fabricated by dry etching or though wet bulk micromachining [13, 19]. The back side of the diaphragm is sealed using anodic bonding in vacuum, to measure the absolute value of pressure. The pressure applied on the diaphragm causes deflection and stress, which is sensed by the piezoresistors on top of the diaphragm [20-22]. The piezoresistors are subjected to stress when a pressure is applied [23, 24]. The important factors of the diaphragm are size, shape and thickness and placement of piezoresistors which are function of output of the pressure sensor [14].

When the piezoresistors are subjected to stress, the change in the electrical resistance is

$$\frac{\Delta R}{R} = \frac{\Delta l}{l} - \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \qquad (1)$$

The first and second terms are very small compared to the third term [15]

So the above equation can be approximated to

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

Where σ_l and σ_t are the longitudinal and transverse stresses acting on the piezoresistor. There will be increase in resistance when the piezoresistors are subjected to longitudinal stress whereas there will be a decrease in resistance when they are subject to transverse stress [24]. Due to this fact, the Wheatstone bridge becomes unbalanced and the output voltage of the sensor is given by the equation (3)

$$\Delta V = V_1 - V_2 \qquad (3)$$

Where

$$V_1 = \frac{R_3}{R_3+R_2} V_{cc} \quad , \quad V_2 = \frac{R_4}{R_1+R_4} V_{cc}$$

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

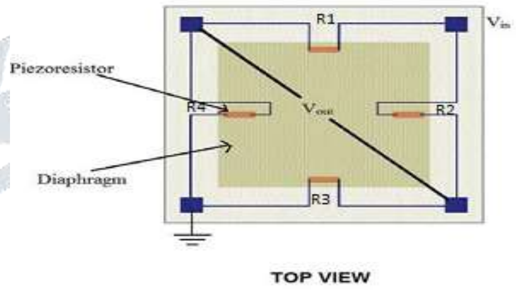

Fig. 1. Piezoresistive pressure sensor

2. PROPOSED DIAPHRAGMS

In this work, two types of silicon piezoresistive diaphragms are proposed and their outputs are compared with Standard Flat Diaphragm (SFD) [14]. For maximum sensitivity the thickness of the diaphragm has been selected as thin as possible. However the thickness cannot be decreased further beyond certain value due to burst pressure capacity. Therefore, to improve the sensitivity three different structures are proposed. They are (i) Equal Width Rings Embossed Diaphragm (EWRED), (ii) Equal

Rings with One Corner Open Embossed Diaphragm (ERCOED)

2.1. Standard Flat Diaphragm (SFD)

The 2 μm thick standard flat diaphragm structure with piezoresistors is considered as shown in Fig. 2. In general, the sensitivity of the sensor depends upon the thickness, width and shape. The sensitivity is directly proportional to the side length "a" and inversely proportional to thickness "h". Selections of dimension of the proposed sensors are presented in section 3.

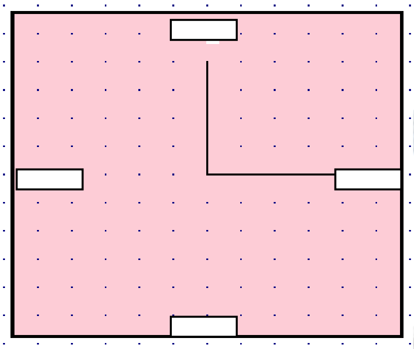

Fig. 2. Standard Flat Diaphragm (top view)

2.2. Equal Width Rings Embossed Diaphragm (EWRED) Design

In the proposed EWRED structure, equally spaced equal width rings are embossed on the flat diaphragm base as shown in Fig.3. Such that the thickness of the flat diaphragm base is 1 μm and the thickness of embossed rings are 1 μm. The rings are acting reinforcement to withstand the burst pressure. In the proposed embossed diaphragm five rings with 8 μm width and spaced equally at the distance of 16 μm are considered. In EWRED the piezoresistors are placed at outside the outer most ring to have maximum stress and to improve the sensitivity.

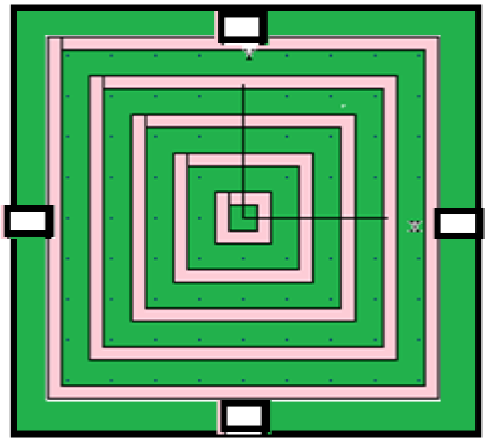

Fig.3. Top view of Equal Width Rings Embossed Diaphragm (EWRED)

2.3. 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.4.

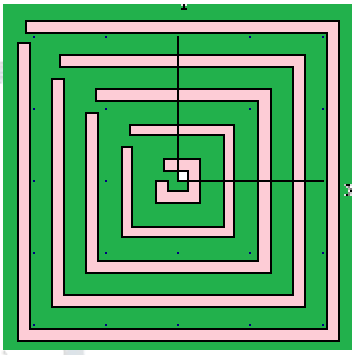

Fig.4. Top view of Equal Rings with One Corner Open Embossed Diaphragm (ERCOED)

3.DESIGN PARAMETRS OF PROPOSED PRESSURE SENSOR

The square diaphragm should have the maximum induced stress for a given pressure. The design parameters of the proposed pressure sensor are listed in Table 1

Table 1 Design parameters used for the FEM simulation

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

The relation for minimum burst pressure [25] is

$$P_{B\,min} = \frac{\sigma_{elestic}}{0.39}\left[\frac{P_{max}\left(1-\gamma^{3}\right)}{0.84\,E}\right]^{\frac{1}{2}} \quad (4)$$

Where E is the Young’s modulus of the silicon=160Gpa, γ is its Poisson’s ratio =0.3, σ is the silicon film pre-stress=7GPa, P_{max} =5 kPa.

Using Equation (4), the Burst pressure P_{Bmin}=3.414MPa. This value is very well above design range.

Another relation between the thickness and minimum burst pressure [23] is

$$h_{min} = \left[\frac{0.39\,P_{B\,min}}{\sigma_{elastic}}\right]^{\frac{1}{2}} a \quad (5)$$

For a diaphragm thickness of 2 µm and side length of 288 µm, the proposed embossed diaphragm has a minimum burst pressure of 3.46 MPa. This burst pressure is very well above the measurement range of (0-5) kPa with a factor of safety equal to 680kPa.

3. SIMULATION STUDIES OF PROPOSED DIAPHARMS

Using Intellisuite MEMS CAD tool, the various performance of this pressure sensor was determined [25]. The SFD and Rings embossed diaphragm designs were created using IntelliFab module [25]. Bulk micromachining technique was used to create the substrate. The wafer is silicon Oxide of 50 micrometer is deposited. Using KOH wet etching 2 micrometer silicon diaphragm was created and the ring structures are embossed with 1 micrometer thickness. The diaphragm size is approximately 82000 micrometer ^{2} .Then Poly silicon thin film is deposited by LPCVD method on the top of SiO_2 layer for piezo resistor arrangement. The size of the piezoresistor is optimized to get better sensitivity. To increase the sensitivity, the piezoresistors are implant with boron. They are placed in the middle of the each edge, where the stress is more. The pressure load is applied at the bottom surface of the diaphragm [26-28]. The below structure is created for simulation in the Intellisuite environment is shown in Fig.5.

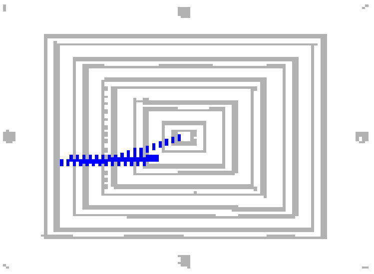

Fig.5. Ring embossed diaphragm created for simulation

4.1. Deflection analysis

In all the proposed pressure sensor structures, the pressure is applied from the bottom of the diaphragm. The simulated variation of deflection for the applied pressure of 2 kPa of the sensor is shown in Fig.6. The variation of deflection varies from a minimum of 0.0816144 µm to maximum of 0.897768 µm. Note that the maximum deflection is at the centre of the diaphragm.

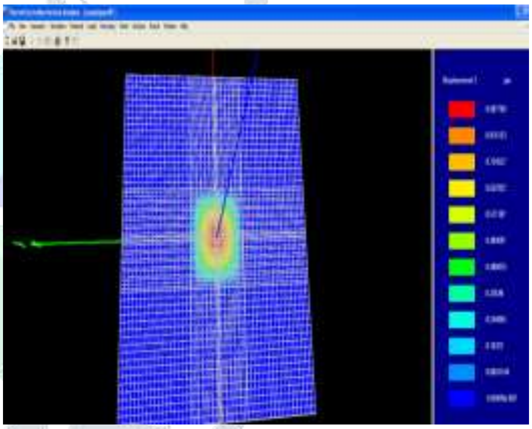

Fig.6.Simulation result of deflection for 2 kPa

The plot between applied pressure and the corresponding maximum deflection of proposed sensors is shown in Fig. 7.It can be noted that the maximum deflection occur for EWRED. The maximum deflection of EWRED is 2.25 µm for an applied pressure of 5 kPa.

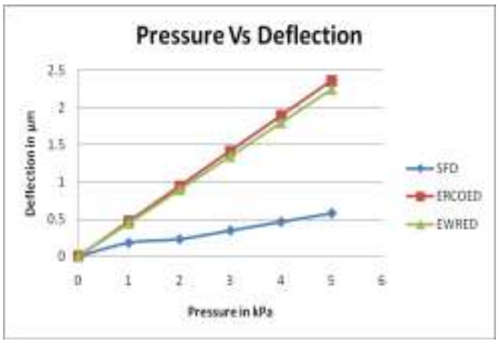

Fig.7. Pressure Versus Deflection of the diaphragm

The analytical results of all structures are compared with simulated results for correctness. The analytical value is calculated using the formula [27] ,for flat diaphragm

$$Y = \frac{\propto PL^4}{h^3 E} \qquad (6)$$

Where α=0.0138, P=applied pressure, E=160GPa

L is length of the diaphragm=288 µm ,h is thickness of the diaphragm=2 µm
for ring embossed diaphragm using the formula[27]

$$Y = \frac{\propto PG^4}{h^3 E} \qquad (7)$$

Where G is effective length of the diaphragm=280 µm,
h is thickness of the diaphragm=1 µm
The Comparison of analytical and simulation results of one of the proposed structure (EWRED) is present in table 2 and the graphical comparison of the same is presented in Figure 8.

Table 2 Comparison of Analytical and Simulated results for deflection of SFD and EWRED diaphragms.

Pressure in KPa	Analytical Results		Simulated Results	
	Deflection in Flat diaphragm(µm)	Deflection in Ring diaphragm (µm)	Deflection in Flat diaphragm(µm)	Deflection in Ring diaphragm (µm)
0	0	0	0	0
1	0.1065	0.53	0.116906	0.44884
2	0.14834	1.06028	0.233811	0.897768
3	0.22251	1.59042	0.350717	1.34665
4	0.29669	2.12056	0.467630	1.79554
5	0.37085	2.65069	0.584528	2.24442

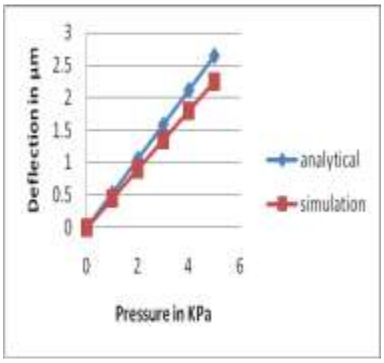

Fig .8. Comparison of Analytical and simulated result of EWRED

4.2. Stress analysis

The resistors are placed at which maximum stress occurs. The applied pressure and the corresponding maximum stresses of the proposed sensors are tabulated as shown in the table 3. It can be noted that the EWRED has the maximum stress and the corresponding graphical representation are shown in Fig. 9 . The simulated stress distribution for EWRED is shown in Fig. 10.

Table 3 Measured stresses at different pressure

Pressure in kPa	Stress at R1(=R3) MPa			Stress at R2(=R4) MPa		
	SFD	ERCOED	EWRED	SFD	ERCOED	EWRED
0	0	0	0	0	0	0
1	5.07	14.505	**14.20**	8.06	26.521	**25.55**
2	10.14	29.01006	**28.40**	16.12	53.043	**51.10**
3	15.22	43.515	**42.60**	24.18	79.565	**76.65**
4	20.29	58.02	**56.80**	32.24	106.0368	**102.2**
5	25.36	72.5253	**70.99**	40.30	132.608	**127.7**

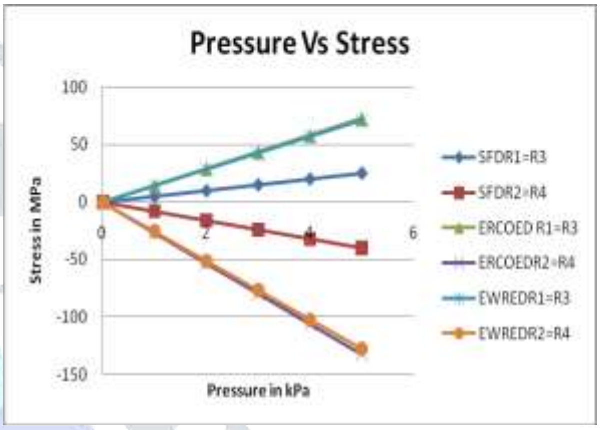

Fig.9.Stress distribution versus Pressure measured

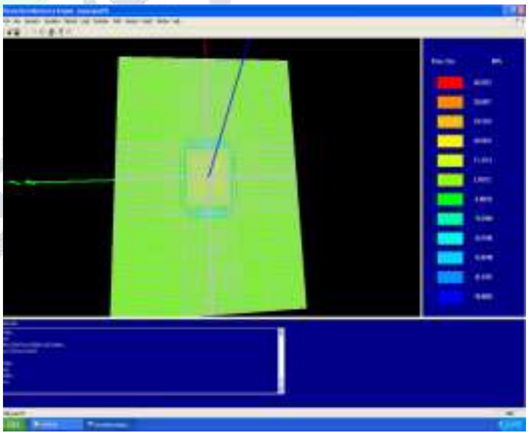

Fig.10.Stress distribution for 2 kPa

4.3. Voltage analysis

It is obvious that the change in resistance for the applied pressure will be maximum for proposed EWRED structure. The differential voltage output of the bridge is calculated by the simulated resistance values obtained for the pressures range (0-5 kPa) using equation (3) as shown in Fig. 11. It shows that EWRED gives better output voltage than all other proposed and standard structures.

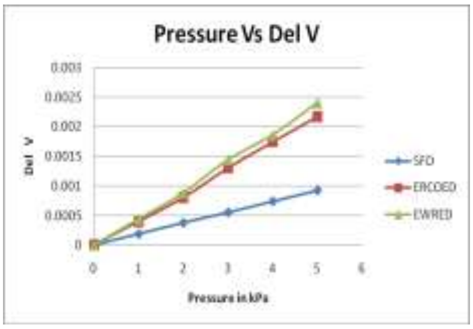

Fig.11.Bridge output voltages estimated between (0-5) kPa

The percentage non-linearity produced by each sensor configuration was calculated. The % non-linearity was estimated using the technique adopted by Sundari et.al [29].The results are presented in Fig.12. The results clearly show that the present design is capable of maintaining high degree linearity at its output.

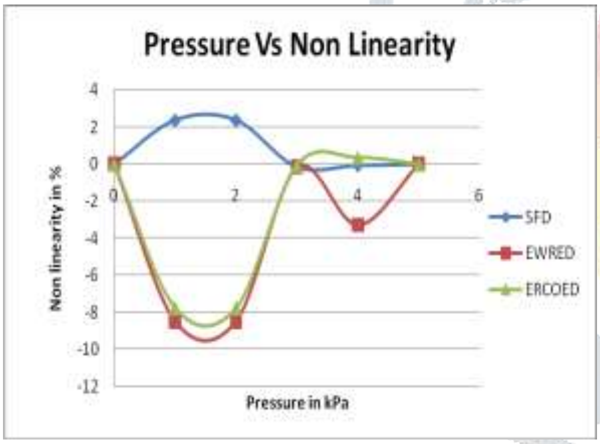

Fig.12.pressure Vs non linearity (0-5) kPa

5. RESULTS AND DISCUSSION

The sensitivity, maximum stress, maximum deflection and maximum resistance are determined for the different structures are tabulated in Table 4.The results obviously show that the proposed Equal Width Ring Embossed Diaphragm (EWRED) Structure gives maximum resistance for any given pressure and used to achieve better sensitivity than the all other structures reported in this work. The simulation results show that this proposed EWRED structure has sensitivity of 0.480mv/kPa/V. The proposed structure has sensitivity of 0.433mv/kPa/V .

Table 4 comparison between structures at 5kPa

S. No	Type	Sensitivity µV/kPa/V	Maximum Stress MPa at R1=R3	Maximum Stress MPa at R2=R4	Maximum deflection µm	Maximum Resistance in ?	%Non Linearity
1	SFD	185.6	25.357	40.303	0.585	R1=998.42 R2=996.57	1.14
2	E WRE D	**480**	**70.993**	**127.75**	**2.25**	**R1=998.68** **R2=993.89**	5.106
3	E RCO E D	433	72.523	132.608	2.3637	R1=998.68 R2=994.34	3.8

6.CONCLUSION

In this work, three MEMS silicon pressure sensor diaphragm structures are proposed. FEM analysis is performed on the elastic element of the pressure sensor. The pressure sensorswith Standard Flat Diaphragm (SFD), Equal Width Embossed Ring Diaphragm (EWRED), Equal Rings with One Corner Open Embossed Diaphragm (ERCOED) out performs other diaphragms. For low pressure range the EWRED is best suited and it has maximum sensitivity.

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