VLSI Layout Based Design Optimization of a Piezoresistive MEMS Pressure Sensors Using COMSOL

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Abstract: This paper focuses on the diaphragm design and optimization of a piezoresistive Micro Electro Mechanical System (MEMS) pressure sensor by considering Very Large Scale Integration (VLSI) layout schemes. The aim of these studies is to find an optimal diaphragm shape by Finite Element Method (FEM) using COMSOL®, which is most suitable for VLSI layout. Optimal diaphragm shape is a diaphragm shape that results in reasonable output stimuli with minimal deflection and stress. Three different shapes of diaphragms are considered in this study are circular, square and rectangular. Not only form the VLSI layout aspect, but also from the pressure, stress and sensor output considerations, square shaped diaphragms are preferred.

Keywords: MEMS piezoresistive pressure sensor, VLSI design, Wheatstone bridge, diaphragm shape

1. Introduction

Pressure sensors have profound applications in medical field, automobile industry, household applications and becoming a common sensor element in many applications [1, 2]. One of the most important features of Micro Electro Mechanical System (MEMS) is that, the sensors are compatible with Very Large Scale Integration (VLSI) silicon process. Integration with VLSI process enables not only miniaturization but also building various circuits that are used in sensing, storing the collected data on memories (for data collection, where no communication is possible) and wireless/remote communication. One of the main hurdles in the VLSI design is layout. As the layout (through mask generation) decides the cost of the sensor and the variations in the sensor, the layout aspects need to be studied in detail. In this work, various diaphragm shapes, namely square, rectangle and circular shapes are studied both from the sensor perspective (output voltage, sensitivity and linearity) and layout perspective.

In this work, it is assumed that Wheatstone bridge configuration is used to sense the stress developed in a diaphragm. The stress is sensed by measuring change in piezoresistors which are connected in Wheatstone bridge configuration that are situated on a pressure sensor diaphragm. Three different diaphragms that are in circular, square and rectangular shapes are compared for stress, deflection, sensor output voltage and sensitivity.

The diaphragm shapes that used in these simulation studies are shown in fig. 1. The dimensions of the diaphragm are such that the area is same in all the three cases.

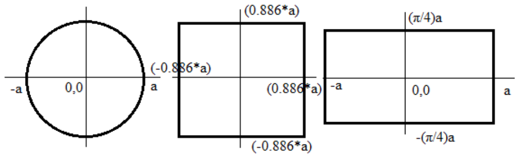


Figure 1. Circular, square and rectangular diaphragms and their relative dimensions used in simulations

2. Sensor Diaphragm Design

To model the silicon pressure sensor diaphragm, it is assumed that the diaphragm has a uniform thickness, with perfectly clamped edges. In the steady state, the diaphragm deflection is governed by the Lagrange equation as in eqn. (1) which allows to calculate the out-of-plane membrane deflection *w(x,y)* as a function of position [3]. In this case, Cartesian coordinates are chosen for analysis as the diaphragm is rectangular in shape.

$$\frac{\partial^4 w(x,y)}{\partial x^4} + 2\alpha_{si}\frac{\partial^4 w(x,y)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y)}{\partial y^4} = \frac{P}{D.h^3} \qquad (1)$$

P represents the differential pressure applied on the membrane of thickness *h*; *D* is a rigidity parameter which depends on material properties given by eqn. (2)

$$D = \frac{Eh^3}{12(1-\vartheta^2)} \qquad (2)$$

The anisotropy coefficient α_{si}, depends on the crystallographic orientation. E is the Young's modulus whereas ϑ is the Poisson's ratio. The factor G is called the shear modulus or Coulomb modulus and it describes the reaction of the material to the shear stress. α_{si} can be calculated using eqn. (3) and eqn. (4).

$$G = \frac{E}{2(1+\vartheta)} \quad (3)$$

$$\alpha_{si} = \vartheta + \frac{2G(1-\vartheta^2)}{E} \quad (4)$$

However the exact solution of eqn. (1) does not exist and one of the approaches used to analyze the basic shapes is the Polynomial approximation [5-6]. This approach is used to analyze the deflection and stress for the different shapes of diaphragms.

2.1 Circular Diaphragm

When considering the isotropic circular membrane which has its radius a as shown in Fig. 1, is characterized by the axial symmetry. So in order to simplify calculations, the out-of-plane deformation $w(r)$ is considered to be dependent only on the distance from its center r and is given by eqn. (5)[7].

$$w(r) = \frac{Pa^4}{64D}\left(1 - \frac{r^2}{a^2}\right)^2 \quad (5)$$

2.2 Square Diaphragm

The solution to eqn. (1) for a square diaphragm with side length $\sqrt{\pi}a$ as shown in Fig.1(a) is $w(x,y)$, with appropriate approximations and simplification yields the displacement of a square diaphragm which changes with uniform pressure (P), given by eqn. (5) [7].

The solution to eqn. (1) for a square diaphragm with side length 2a as shown in Fig.1 is $w(x,y)$ with appropriate approximations and simplification yields the displacement of a square diaphragm which changes with uniform pressure (P), given by eqn. (7) [7].

$$w(x,y) = \frac{1}{47}\frac{Pa^4}{D}\left(\frac{1-x^2}{\pi a^2}\right)^2\left(\frac{1-y^2}{\pi a^2}\right)^2 \quad (7)$$

2.3 Rectangular Diaphragm

In case of a rectangular diaphragm the deflection in the diaphragm can be simplified as in eqn. (8) [7]. The width of rectangular diaphragm is 0.5πa and a length is 2a as shown in Fig. 1.

$$w(x,y) = \frac{P(1-\vartheta^2)}{2Eh^3}\left(\frac{\frac{\pi^2 a^2}{16} - x^2}{\frac{\pi^4 a^4}{256} + a^4}\right)^2 \left(a^2 - y^2\right)^2 \quad (8)$$

2.4 Sensor Design

A Pressure sensor is designed to measure a pressure from 1MPa to 100 MPa. The diaphragm thickness (h) is estimated as 30µm and made on [100] plane of single crystalline silicon. For the rectangular diaphragm design, a length to width ratio of 1.25 is assumed. Various diaphragm dimensions are shown in table I. The Young's modulus (E) of Si is 2×10^{11} Pa and Poisson's ratio (ϑ) is 0.28.

Table I. Dimensions of various diaphragms in the design

Diaphragm type	Dimensions (µm)
Circular	250 (radius)
Square	443 (side)
Rectangular	396×500(length × width)

2.5 Sensor Circuit Design

(6) A Wheatstone bridge circuit as shown in fig. 2 is used for sensing the output voltage [8]. Four piezoresistors namely R_1, R_2, R_3 and R_4 form the bridge circuit.

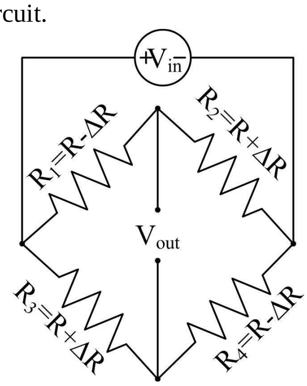


Figure 2. Wheatstone bridge configuration to measure output voltage due to change in resistances on the sensors.

The length, width and thickness of the piezo resistors are 200µm, 10µm and 10µm respectively. The piezo resistors are placed with an offset (dis-

tance from the edge of the diaphragm) of 13µm in the longitudinal direction and 10µm in the transverse direction. The electrical resistivity of each piezo resistor is 0.5×10^{-4} Ωm.
When no pressure is applied, the bridge is under balance and ΔR is zero and the output voltage of the sensor is zero. When a pressure is applied, the resistance of the piezo resistors change thus the bridge is not balanced which results in a voltage at the output. As the applied pressure results in more diaphragm deflection, that causes more stress and more output voltage. Thus the bridge output voltage is a direct indication of the applied pressure.

3. Application Mode Using COMSOL

The structural mechanics and conductive media DC modules are used in the FEM studies. The structural mechanics module is used for the structural design of the model which includes pre-setting subdomain consists of silicon as substrate/diaphragm and polysilicon as piezoresistor. The material system uses anisotropic models that include local and global coordinate systems respectively. The deflection and stress that are resulted due to application of pressure are studied using the structural mechanics module. The conductive DC module is used to investigate the changes in electrical connectivity when the piezoresistors are arranged in a Wheatstone bridge configuration. Constants and different variable are used in subdomain expression according to the required theories.

4. Results and Discussion

In this section, deflection and stress are compared in mechanical analysis and in electrical analysis; the sensor output voltage and sensitivity are compared for all the three diaphragms under consideration.

4.1 Mechanical Analysis

All the three diaphragms are simulated using COMSOL and various results are compared. Fig. 3 shows a comparison of the maximum deflection in various diaphragm shapes as the applied pressure is changed. It can be observed from fig. 3 that the deflection is more in circular diaphragm. The maximum deflection in various diaphragms is shown in fig. 4.

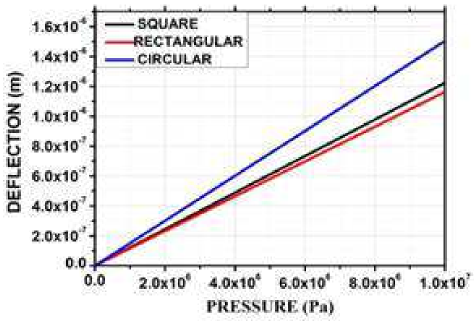


Figure 3. Comparison of deflection Vs. pressure in various diaphragm.

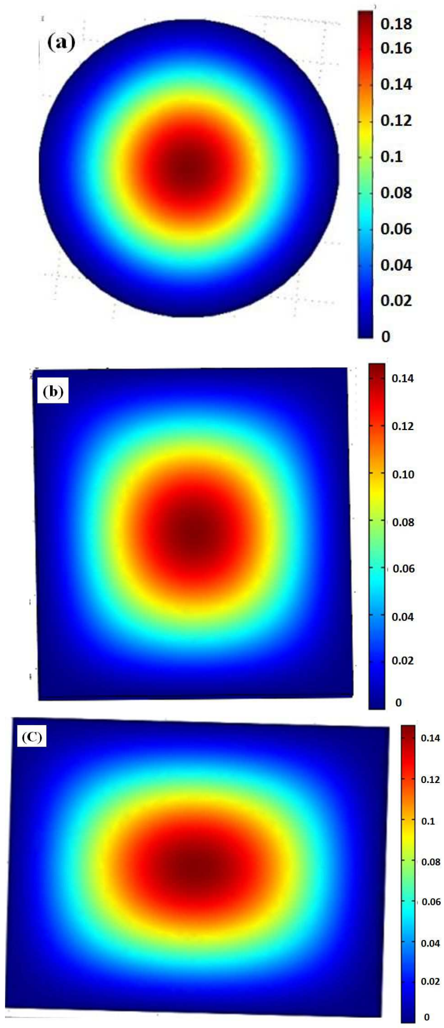


Figure 4. Comparison of deflection in (a) circular (b) square (c) rectangular diaphragms at an applied pressure of 1MPa.

As observed from the fig. 4, the maximum deflection is more in case of circular diaphragm when compared to the square and rectangular diaphragms. The deflection is maximum at the center of the diaphragm and minimum at edges. Table II provides a comparison between the maximum deflections in all the three different diaphragms at an applied pressure of 1MPa.

Table II. Comparison of maximum deflection and maximum stress between various diaphragms

Diaphragm type	Deflection (μm)	Stress (N/m^2)
Circular	0.181	5.254×10^7
Square	0.146	1.325×10^7
Rectangular	0.139	17.095×10^7

Fig. 5 shows a comparison of the maximum stress in various diaphragm shapes as the applied pressure is changed. It can be observed from fig. 5 that the stress is more in rectangular shaped diaphragm.

The stress distribution in various diaphragms is compared in fig. 6. Generally, the maximum stress position is at the edge of the diaphragm.

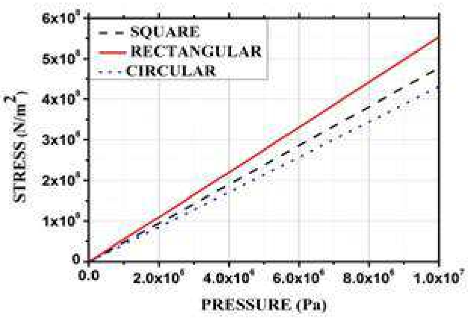
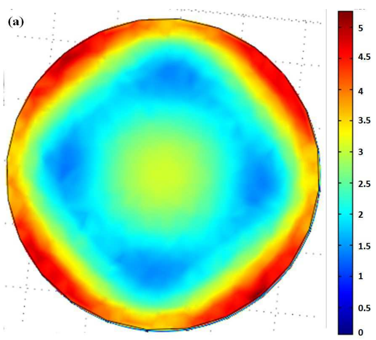


Figure 5. Comparison of Stress vs. Pressure in various diaphragms.



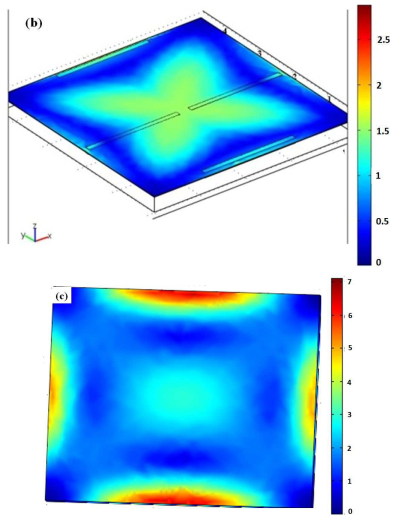


Figure 6. Comparison of stress in (a) circular (b) square (c) rectangular diaphragms at an applied pressure of 1MPa.

Table II provides a comparison between the maximum deflections in all the three different diaphragms at an applied pressure of 1MPa.
It can be noted that in a rectangular diaphragm, the stress is much larger compared to other diaphragm shapes. This is due to the fact that, the diaphragm structure is more asymmetric.

4.2 Electrical Analysis

Piezoresistors are arranged in Wheatstone bridge configuration and the potential distribution (in arbitrary units) across the piezoresistors is shown in fig. 7. The output voltage of the pressure sensor as a function of applied pressure is shown in fig. 8. The output sensor voltage is smaller in the case of circular diaphragm. For the square and rectangular diaphragms, the output voltage is almost comparable.

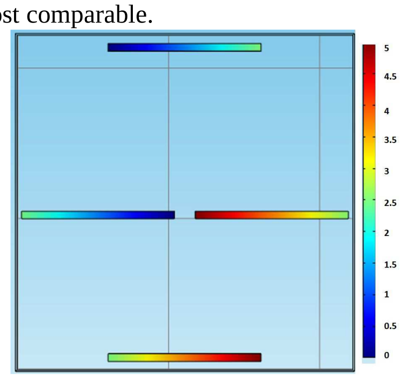


Figure 7. Potential distribution in a piezoresistor.

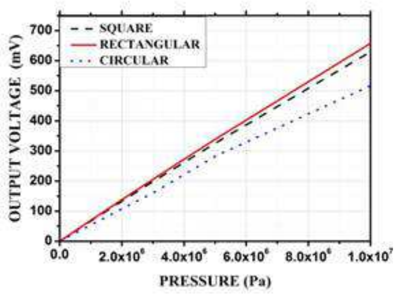


Figure 8. Output voltage of the pressure sensor.

The sensitivity of the pressure sensor as a function of applied pressure is plotted in fig. 9. It can be observed that, the sensitivity of the circular diaphragm is less. As the deflection in a circular diaphragm increases, the sensor output becomes nonlinear, thus resulting in a close to zero sensitivity when applied pressure is high.

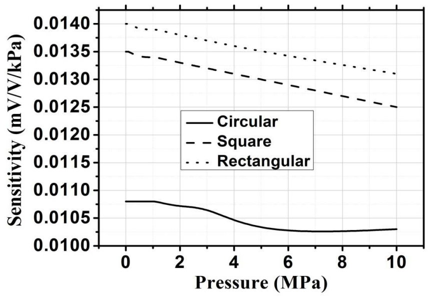


Figure 9. Sensitivity of the pressure sensor.

5. Conclusions

Thus form the sensor output voltage, it can be concluded that the rectangular and square diaphragms are better. However, when the stress in the diaphragm is considered, the rectangular diaphragm feels more stress compared to the square diaphragm. Thus, the probability for the sensor breakdown is more in the rectangular diaphragm when compared to the square diaphragm. To reduce stress, one can increase the diaphragm thickness. However, increasing diaphragm thickness reduces the deflection which in turn reduces the output voltage. In addition, it is well established that square and rectangular masks are more suitable for design in VLSI industry. Thus, from the stress and output sensitivity considerations, square typed diaphragms are more preferred than the other two shapes, namely circular and rectangular diaphragms.

6. References

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7. Acknowledgements

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