Piezoresistive MEMS Pressure Sensors using Si, Ge, and SiC Diaphragms: A VLSI Layout Optimization

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***Abstract*-- The work presented in this paper relates to optimizing the VLSI layout geometry of a Piezoresistive MEMS Pressure Sensors. MEMS is the technology of miniaturizing mechanical devices with the aid of Electrical support. The study is conducted through the analysis of diaphragms made out of semiconductor and insulator materials. The Piezoresistive property of materials are used here where the resistivity of the material changes on application of pressure. The optimal diaphragm shape is decided by studying the deflection, stress, and output voltage. Three different shapes are considered for the studies, Circular, Square, and Rectangular. The stress, deflection, and output voltage are analyzed using COMSOL Multiphysics software and the observed results are included in the paper.**

***Index Terms*-- MEMS, Piezoresistivity, Diaphragm, Pressure, Stress, Deflection**

I. Introduction

A pressure sensor is used for the measurement of pressure of gases and liquids. Pressure can be defined as a force required to stop a fluid from expanding, and is usually force per unit area. A pressure sensor usually acts as a transducer; it generates a signal as a function of the applied pressure. Pressure sensors have a lot of applications in medical, automobile and marine field.

The VLSI fabrication process involves a lot of unit steps like Oxidation, Deposition, Lithography, Etching etc. The Lithography process makes use of a mask which transfers the pattern on to the wafer surface. The mask should possess precise and accurate dimension of the feature to be transferred. The layout is an important material in fabrication process. It is optimized considering various parameters.

In this paper, we are trying to optimize the shape which is best suited from VLSI point of view. This optimized layout can be used as for the construction of the MEMS Pressure Sensor. The optimization is done by analyzing the parameters like Deflection, Stress, and Output Voltage [9]. Three different shapes of diaphragms are considered, Square, Rectangular, and Circular. Pressure is applied on the Diaphragm and the stress and deflection is measured. Materials like Silicon, Germanium, and Silicon Carbide are used as the diaphragm material. From the mechanical analysis itself, an optimization is made and hence Silicon alone is opted for the electrical analysis, Output voltage. The diaphragm design is done first. Then the simulations are performed in COMSOL Multiphysics software. The different results are included towards the end of the paper.

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II. Motivation and Problem Statement

Pressure sensors have immense applications in our day to day life. Diaphragm is the simplest pressure sensor, which is nothing but a stretched membrane which is hinged at its four edges. The pressure is being applied at the top surface of the diaphragm. Because of the immense technological advancements, the pressure sensors can be fabricated using the MEMS technology which involves all the unit steps in VLSI fabrication [1]. Among the various unit processes Lithography is a challenging one. It is Lithographic technique that helps one to transfer the required pattern to the wafer. Since this requires a very accurate mask to transfer the features on to the wafer during fabrication, the process faces lot of problems.

In VLSI technology, MEMS device fabrication faces the usual problems since there is tremendous reduction in technology node as part of miniaturization. It is Lithographic techniques that face lot of problems where there is a need of very accurate mask to transfer the features on to the wafer during fabrication. The layout used for this process should be compatible in such a way that it results in an accurate pattern. The layout is so chosen such that it is compatible from the VLSI point of view.

III. Elated Works

Silicon is a material which have piezoresistivity (Piezo: Greek peizin, to press) which is the property of change in resistance with stress. In the paper [1], the authors the reason for piezoresistivity as, when pressure is applied the inter atomic positions are changed which results in a change in the amount of conduction. The most important one is to measure the deflection of the diaphragm.

Many studies have been carried out to optimize the shape of diaphragms. In the paper [2] the static response of miniature capacitor pressure sensors with thin square and rectangular diaphragms is studied. Analytical comparison of different shapes of diaphragms based on Displacement, Stress and Vibration analysis are provided in paper [3]. The simulation results show that the circular diaphragm generates larger deflection and has the lowest stress on its edges compared to other shapes. In paper [4] a simulation program is developed in order to calculate the output responses of Piezoresistive

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pressure sensors. The sensitivity and linearity of Piezoresistive pressure sensors are studied.

In paper [5] the various sensing principles of pressure sensors like piezoresistivity, capacitive, resonant etc, are considered. Among the various principles the piezoresistive property is the best used due to its higher sensitivity, linearity and repeatability and also bulk production possibilities. An analytical study of the diaphragms (square) is done in paper [6]. It is carried out to identify the location for the placement of piezoresistive sensors. It is identified that the piezoresistors can be placed at the regions where there is maximum stress experienced.

Pressure sensors can be used for low pressure bio-medical applications. Timoshenko model and FEM model are used to predict the electromechanical behavior of (square diaphragm) piezoresistive pressure sensors[7].

IV. System Modeling and Description

The main console is the COMSOL Multiphysics software in which where there are several modules present which will help in the construction of the diaphragm of required dimensions and material. Since the software allows to add suitable physics to the model, a load, pressure can be applied with the diaphragm edges hinged. The responses of the load stress and deflection are obtained. The Structural Mechanics module is used to design diaphragm, which includes the setting of dimensions, shape, material, Pressure range etc.

V. Sensor Design Modeling

A diaphragm of uniform thickness of 30µm and 20 µm is made out of Semiconductor materials like Si, Ge and SiC. The diaphragm is perfectly clamped at edges. The diaphragm deflection is governed by the Legrange's Equation, which allows to calculate the out of plane membrane deflection as a function of position [3].

$$\frac{\partial^4 w(x,y)}{\partial x^4} + 2\alpha_{si}\frac{\partial^4 w(x,y)}{\partial x^2 \partial y^2} + \frac{\partial^4 w(x,y)}{\partial y^4} = \frac{P}{Dh^3} \quad (1)$$

where P is the Pressure applied on the membrane with a thickness of 'h' and D is the Rigidity Parameter.

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

α_{si} is the anisotropy coefficient, E is the Young's Modulus and ϑ is the Poisson's Ratio.

A. Circular Diaphragm

The deformation w(r) for the circular diaphragm is given by the equation [4]

$$w(r) = \frac{Pa^4}{64D}\left(1 - \frac{r^2}{a^2}\right)^2 \quad (3)$$

where a is the radius of the circular diaphragm and r is the distance from its center.

B. Square Diaphragm

The displacement resulted by the applied pressure is given as

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

C. Rectangular Diaphragm

In rectangular diaphragm the deflection is simplified as:

$$w(x,y) = \frac{P(1-\vartheta^2)}{2Eh^3}\left(\frac{\frac{\pi^2 a^2}{16}-x^2}{\frac{\pi^4 a^4}{256}+a^4}\right)^2 (a^2-y^2)^2 \quad (5)$$

VI. Sensor Design

For the accurate analysis the total area of the three diaphragms taken are kept equal. For that the circular diaphragm of radius ‘a’ is taken and the side length of the square is taken as √πa. For the same area as that the width of the rectangular diaphragm is taken as 0.5πa and the length as 2a.

Table I
Diaphragm shapes and their dimensions

Diaphragm Type	Dimensions(µm)
Circular	250(radius)
Square	443(side length)
Rectangular	500x393(length x width)

The materials chosen are Silicon, Germanium and Silicon Carbide. The three different shapes are as shown.

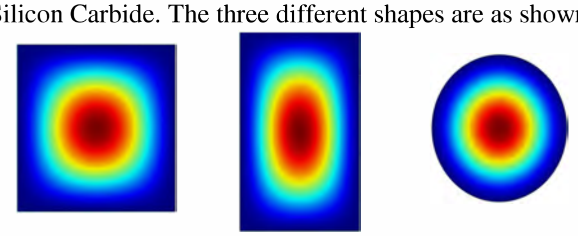

Fig 1. The three diaphragm shapes

The fig 1. depicts the deflection of the diaphragm on application of pressure. The region in red indicates that the maximum deflection is at the center, and it reduces towards the edges. The Piezoresistive material taken is n-Si (poly) lightly doped with dimensions 200µm x 10µm x 10µm.

VII. Experiments

The COMSOL Multiphysics software is used to perform the simulation. The space dimension is selected as 3D for the diaphragm. To add the physics to the model the Structural Mechanics Module is used. The study type is chosen as Stationary. The required dimensions are entered as Global Definitions. The geometry is selected and the material is selected. The materials used are Silicon, Germanium and Silicon Carbide. With each material three different shapes of diaphragms.

The edges of the diaphragm are fixed and a boundary load, Pressure is applied. The Pressure applied range from 1MPa to 100MPa. The deflection and stress is obtained for each pressure for each thickness values for each diaphragm.

The diaphragms are analyzed as such and later incorporated the piezoresistor and the simulations are conducted.

The electrical analysis is then performed with the Silicon diaphragm. For that a terminal voltage of 5V is applied to piezoresistors connected in Wheatstone Bridge Configuration.

VIII. RESULTS

The mechanical analysis of the diaphragm is done. The three diaphragms made of Silicon material are simulated and the deflection and stress responses are obtained..

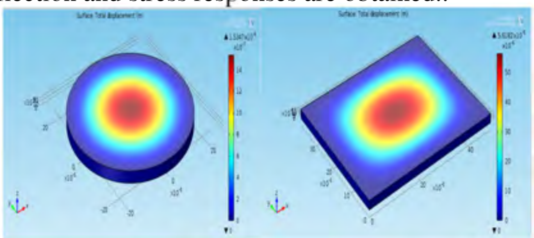

Fig 2. Displacement for Circular and rectangular Diaphragm(t=30µm)

The Fig 2. shows the diaphragm response on pressure. For the circular diaphragm maximum deflection is found at the center of the diaphragm. For the rectangular diaphragm maximum deflection is obtained at the center and minimum towards the edges.

For diaphragms, when the thickness is increased the deflection will decrease. The Circular and rectangular diaphragms are of thickness of 30µm. Among the both, circular diaphragm is having the maximum deflection.

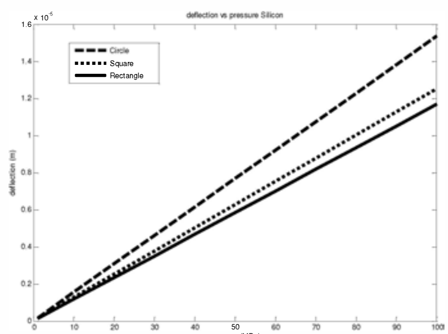

Fig 3. Deflection (m) Vs Pressure(MPa) plot for Silicon diaphragm

In Fig 3. the plot shows that the circular diaphragm has the maximum deflection. Both Square and rectangular have comparable values of deflection.

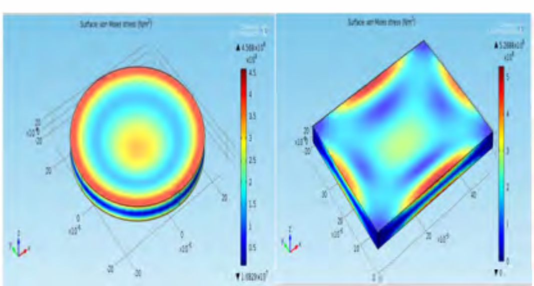

Fig 4. Stress for Circular diaphragm and Rectangular diaphragm(t=30µm)

In Fig 4. the stress response of circular diaphragm is shown. The edges have the maximum stress which is due to the hinged edges..

The stress experienced by the rectangular diaphragm is shown in Fig 4. The edges which are hinged experience the maximum stress.

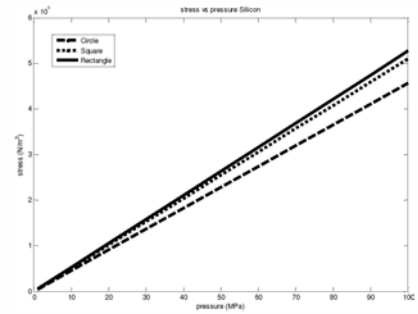

Fig 5. Stress(N/m^2) Vs Pressure(MPa) plot for Silicon diaphragm

From Fig 5. we can see that stress is maximum for the rectangular diaphragm where the maximum stress is at the hinged edges. The increased stress value for rectangular diaphragm is due to its asymmetric structure.

Stress is increased when the thickness is reduced. But thickness cannot be decreased beyond a limit, as this will lead to non linear effects. Thin diaphragms will give better sensitivity also [4].

The Diaphragm material is then changed to Germanium and Silicon Carbide.

A similar study carried out with Silicon and Silicon dioxide diaphragms, resulted in an increased stress at edges suffered by Silicon than Silicon dioxide, whereas the Silicon dioxide diaphragm was capable of operating at large pressure ranges [11].

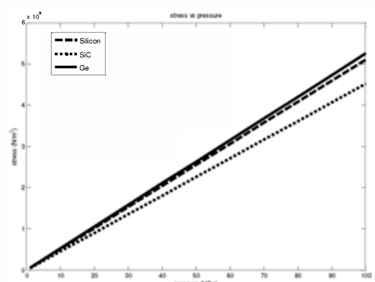

Fig 6. Stress Vs Pressure plot for different materials of Square diaphragm.

Fig. 6 shows the sterss- pressure plot for different materials for square diaphragm. While analyzing with different materials, it can be seen that for the same value of thickness Germanium is having the maximum stress and deflection, whereas the minimum values of stress and deflection is for SiC.

After the diaphragm is mechanically analyzed, the Piezoresistive material can be incorporated onto the diaphragm.

After incorporating the piezoresistive material the diaphragm is applied with the same range of pressure and the deflection and stress is noted.

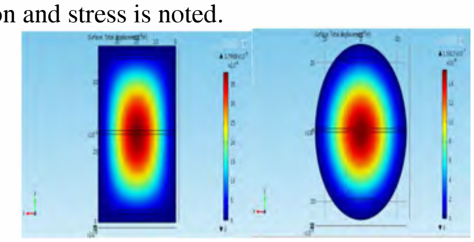

Fig 7. Deflection for rectangular and circular with Piezoresistors placed.

Table II
Displacement values for Silicon Diaphragms of different shapes

Silicon (Displacement)						
Pressure	Thickness =20µm			Thickness =30µm		
	Circular	Rectangular	Square	Circular	Rectangular	Square
1MPa	$4.9888\text{x}10^{-7}$	$3.7305\text{x}10^{-7}$	$4.0133\text{x}10^{-7}$	$1.5347\text{x}10^{-7}$	$1.1662\text{x}10^{-7}$	$1.2505\text{x}10^{-7}$
20MPa	$9.9776\text{x}10^{-6}$	$7.4610\text{x}10^{-6}$	$8.0265\text{x}10^{-6}$	$3.0694\text{x}10^{-6}$	$2.3324\text{x}10^{-6}$	$2.5010\text{x}10^{-6}$
40MPa	$1.9955\text{x}10^{-5}$	$1.4922\text{x}10^{-5}$	$1.6053\text{x}10^{-5}$	$6.1387\text{x}10^{-6}$	$4.6649\text{x}10^{-6}$	$5.0019\text{x}10^{-6}$
60MPa	$2.9933\text{x}10^{-5}$	$2.2383\text{x}10^{-5}$	$2.4080\text{x}10^{-5}$	$9.2081\text{x}10^{-6}$	$6.9973\text{x}10^{-6}$	$7.5029\text{x}10^{-6}$
80MPa	$3.9910\text{x}10^{-5}$	$2.9844\text{x}10^{-5}$	$3.2106\text{x}10^{-5}$	$1.2277\text{x}10^{-5}$	$9.3297\text{x}10^{-6}$	$1.0004\text{x}10^{-5}$
100MPa	$4.9888\text{x}10^{-5}$	$3.7305\text{x}10^{-5}$	$4.0133\text{x}10^{-5}$	$1.5347\text{x}10^{-5}$	$1.1662\text{x}10^{-5}$	$1.2505\text{x}10^{-5}$

Even when the piezoresistors are placed the mechanical properties remain more or less the same.

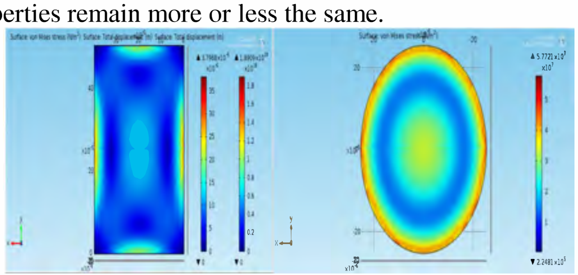

Fig 8. Stress for rectangular and circular with Piezoresistors placed.

Fig. 8 shows the stress response of rectangular and circular diaphragms with the piezoresistors placed. For the electrical analysis we have considered only the Silicon diaphragm. The terminal voltage applied is 5V.

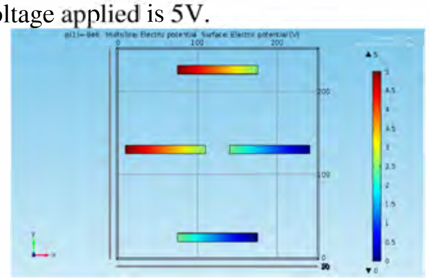

Fig 9. Potential Distribution in a Piezoresistor

Fig.9 shows the potential distribution on a square diaphragm. Fig. 10 shows the output voltage Vs Applied Pressure .

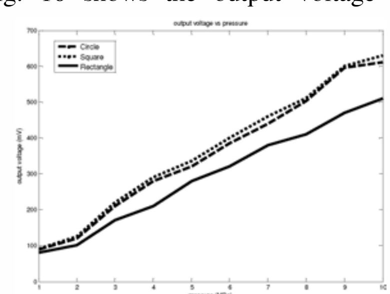

Fig 10. Output voltage Vs Applied Pressure.

IX. ANALYSIS

By analyzing the results, for a particular thickness the Circular diaphragm have the maximum displacement (Deflection) and the maximum deflection value is found at the center of the diaphragm. Both rectangular and square diaphragms have almost comparable values of deflection. When the thickness of the diaphragm is increased the deflection values for each diaphragm shapes got considerably reduced.

The Stress is found to be maximum for the rectangular diaphragm. The Circular diaphragm has the minimum stress value. The square diaphragm also have a comparable stress value as that of the rectangular diaphragm. When the thickness is increased the stress value gets reduced. Since stress is more for rectangular diaphragm, the probability of sensor breakdown is more. So if the thickness is reduced, the stress value can be increased and can be used for those applications where maximum stress is experienced.

So among the three diaphragms, we can optimize that the square diaphragm is optimal since it has neither high stress values nor deflection values. Under harsh conditions, SiC is used since it doesn't get stressed out at higher pressure values compared to Si [8].

When the piezoresistive material is placed, there is no considerable change in stress and deflection values. So mechanical wise, square is optimized as better diaphragm layout.

Only square diaphragm is used for the electrical analysis, output voltage. It is seen from the plot Fig 10, that the output voltage for both square and rectangular diaphragms are comparable and that the circular diaphragm have the minimum value. For low pressure applications, a Full Scale Output Voltage of 61.7mV/V is obtained analytically and through simulation for a square diaphragm of length 1000µm and thickness 10µm [6].

A fabricated Pressure sensor, tested under a range of pressure 100hPa to 1012hPa showed a result of increasing output voltage with applied pressure. The output voltage shows linear variation only for thickness value less than 1000µm [5].

Table III
Comparison of the parameters in different shapes of layout.

Shape	Stress	Deflection	Output voltage
Square	Maximum	Minimum	Maximum
Rectangle	Maximum	Minimum	Maximum
Circle	Minimum	Maximum	Minimum

X. INFERENCES

When compared the pressure sensor with the existing Piezoresistive Pressure sensor ICs it is seen that this study have found that mechanical wise both the sensor has a pressure withstanding limit of 100kPa as that of the LPS331AP IC. The output voltage is also having a comparable value. When compared with the works with another literature, the result was found almost comparable, except for output voltage the plot in this study is not a smooth one [9].

The proper selection of geometry of diaphragm will help in the proper placement of piezoresistors for better sensitivity. The mechanical analysis will also help in determining the operating ranges of the pressure sensors [10].

XI. FUTURE WORKS

In this study only three parameters are considered. Again the study can be extended for the analysis of Sensitivity, Linearity etc. There are different materials that can be used as MEMS materials including polymers, insulators, ceramics etc. By using each material we can simulate and obtain the parameters and make an optimization. Similarly the Piezoelectric property can also be studied.

XII. CONCLUSION

In conclusion this paper has demonstrated the mechanical analysis and electrical analysis of the various diaphragms to study the parameters like deflection, stress and output voltage with respect to a range of applied pressure. Using the COMSOL Multiphysics software the diaphragm model is simulated and stress and deflection distribution is obtained. While considering the deflection value the circular diaphragm is better than the square and rectangular. But when stress is considered rectangular is better. But higher values of stress will make the sensor breakdown probability high. Output voltage is maximum for rectangular and square diaphragms. An increase in thickness will reduce deflection and in turn output voltage. Hence every parameters are dependent on each other. So we can conclude that from the mechanical and electrical point of view the square diaphragm is better than the other two diaphragm shapes. And from the VLSI aspect the square masks are more suitable.

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