DESIGN AND DEFORMATION ANALYSIS OF MEMS BASED PIEZORESISTIVE PRESSURE SENSOR

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ABSTRACT
The present work reports about the design and simulation analysis of MEMS based piezoresistive pressure sensor. The design includes diaphragm using n-silicon material and piezoresistor using p-silicon material those are integrated on to diaphragm. Specifically, the proposed design has been simulated to get maximum deformation of diaphragm for small input of pressure. The design has been simulated for different crystallographic forms of silicon for different inputs Using COMSOL Multiphysics v 4.3b., the study is extended and analyses has been done such that flexibility of measuring pressure for polysilicon material has best performance compared to single crystal silicon and interchanged p-type, n-type of single crystal silicon.

KEYWORDS: *MEMS, Piezoresistivity, Tolerance value, Polycrystalline.*

I. INTRODUCTION

With the emerging MEMS technology [1], recent advancements in its innovation gives rise to achieve rapid progress in high resolution and accuracy which mainly involves extension in its range depending on its application. The development of extremely small sensors came in to existence,which were replaced by bulky sensors. Dynamic characterstics like pressure, acceleration and force etc are measured accurately. Microsensors are designed and tested for its reliability using comsol multiphysics. Recent researches has been transferred to micromachined sensors [2] which promises robustness, accuracy, low power consumption, high efficiency. These are widely used in the fields like biomedical [3] optoelectronics [4], automotive [5] and industrial applictions [6]. Recent days, the major attention has been focused on investigating new materials for improved performance,relibility, lower production cost and new applications. The pressure sensors are of different types like piezoelectric, optical, elctromagnetic, potentiometric, capacitive. For micromachined sensors, piezoresistivity is a common sensing principle. Among all known piezoresistive materials, silicon in particular, exhibits remarkable piezoresistive [7, 8] response characteristics. Apart from pressure measurement piezoresistive pressure sensors are classified as acceleration, vibration and velocity sensors. Piezoresistive pressure sensors are one of the very first products. The first Piezoresistive pressure sensor designed to reduce fuel consumption by a tight control of the ratio between air and fuel. These sensors are used commonly for repeatability measurements. This sensor uses piezoresistive effect explained by change in resistance of sensing material when they are subjected to stress usually associated with semiconductor materials that allows conduction. Resistivity of semiconductor changes by applying pressure as band structure of material varies with conduction. It uses wheatstone bridge [9] principle for measuring resistance of material. The resistivity depends on force applied on the wafer. The conduction flows as usual when there is no force. Change in applied force causes in change in conduction that associated with change in resistivity.The related work has many changes that optimized the performance of sensor [10-15]. The application of piezoresistive pressure sensor is to measure pressure more accurately. The study gives the importance of tolerance value which shows performance of the proposed pressure sensor design. The paper presents details of design work, geometry, required physical interfaces, simulation, results & analyses, conclusion along with future scope of the work.

II. DESIGN WORK

Comsol multiphysics software is a good tool to create models. The design work uses the materials, p-type silicon for piezoresistors and n-type silicon for the entire diaphragm [16]. The Finite Element Method(FEM) is adopted to optimize the pressure sensor for parameters like sensitivity and linearity. This is achieved by choosing the proper shape of piezoresistor, thickness of diaphraghm and the position of piezoresistor on the pressure sensor. It consists of various material properties in built that can be used to design required device. The model builder of comsol software can be used to solve models and allows to access required functionality. The software is a powerful tool as it creates environment for multiphysics for creating, analyzing, visualizing models when different physics are coupled which are predefined on software. Geometric values can be given using geometry tool of comsol software which consists of in built geometric figures. For any design the following steps are required in comsol software defining geometry that is constructing model using geometry tool, addition of physical interface that adds physics equations to model automatically, giving materials to model that adds material properties which are predefined in materials library, meshing for proper distribution for inputs provided.

III. GEOMETRY DETAILS

The diaphraghm with a square membrane of side1 mm and thickness 20µm around its edge by region 0.1mm wide is designed. The piezoresistor as in wheatstone bridge is constructed using various predefined structures in geometry [17] as shown in Fig. 1.

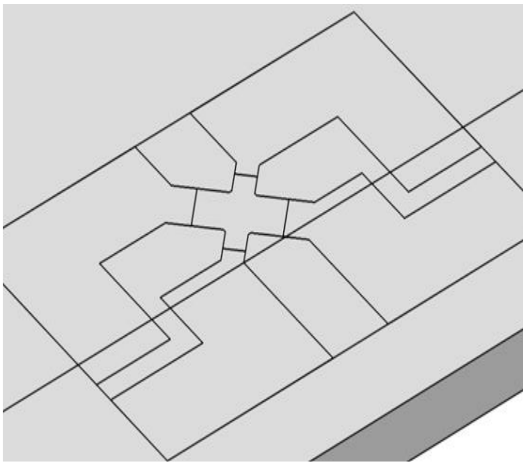

Figure 1. Geometry of piezoresistor.

The upper surface, lower surface and membrane lower are defined using geometry tool. The area of membrane lower surface is subtracted from upper surface using comsol and is fixed. The fixed area doesnot experience any change, whereas the remaining area experiences, when force is applied on the pressure sensor.

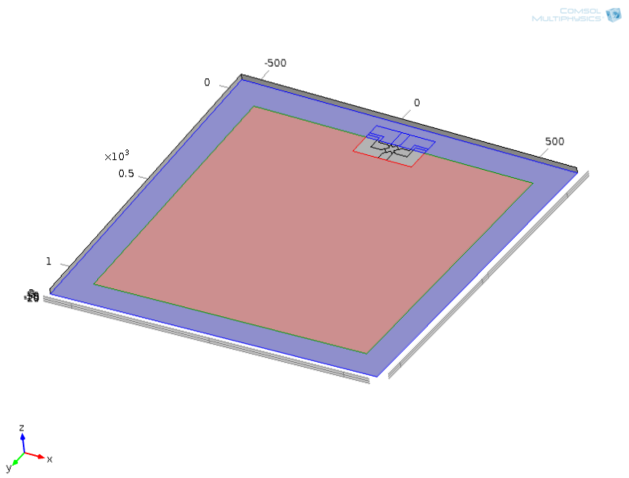

Figure 2. Fixed area of lower surface diaphragm

The lower membarane is fixed on boundary of it. The inner portion is set free which is represented as pink colour in Fig. 2 . The blue coloured portion is fixed. The input pressure is applied on the upper surface which transforms to piezoresistor.

IV. Physical Interface

The propose design works on the principle of piezoresistive effect [18], with increase in applied pressure, change in resistivity is measured with change in deformation. The physics used is piezoresistive boundary currents that is applied to the device that automatically facilitates with definitions of linear elastic material, thin conducting layer and piezoresistive layer for model. The linear elasticity ensures the property of material that stress is linear function of strain and acts as reversible process. It automatically includes thermal expansion property to material. Thus thermal properties are coupled with existent physics to model. The piezoresistive material library consists of single crystal and polycrystalline p,n-typed doped silicon.

The applied stress on diaphragm changes the band structure that induces strain in it, which is the result of piezoresistance effect. The electric field in the vicinity of surface of diaphragm with applied stress is given as equation.

$$E = \rho . J + \Delta\rho . J \quad \ldots\ldots\ldots\ldots \quad (1)$$

Where 'ρ' is resistivity, J is current in piezoresistors, '$\Delta\rho$' is induced change in resistivity. It is given as function of stress by the equation.

$$\Delta\rho = \Pi . \sigma \quad \ldots\ldots\ldots\ldots \quad (2)$$

Where 'π' is piezoresistance tensor, a material property. 'σ' is shear stress. '$\Delta\rho'$ is induced change in resistivity that couples current in one direction, electric field perpendicular to current direction.

V. Simulation

After defining the geometry of the proposed model, materials are added, which givesa solid design. Later, meshing is done in-order to distribute the applied pressure equally on the device. The sizes of meshing are as follows, for the entire wafer maximum meshing size is 60 µm, and minimum is 0.5µm. For piezoresistor maximum is 2 µm, minimum is 0.1 µm, for connectors maximum is 6 µm and for edges maximum is 0.4 µm. Terminal and ground are defined on the connectors of the piezoresistor, so that it forms an electrode [18] to measure voltage as a measure of pressure [17]. The terminal voltage is given as 3 volts as bias. Simulation has been carried out for the proposed design with the inputs ranging from 100 kPa to till the tolerance value and results are noticed as deformations of diaphraghm are shown below.

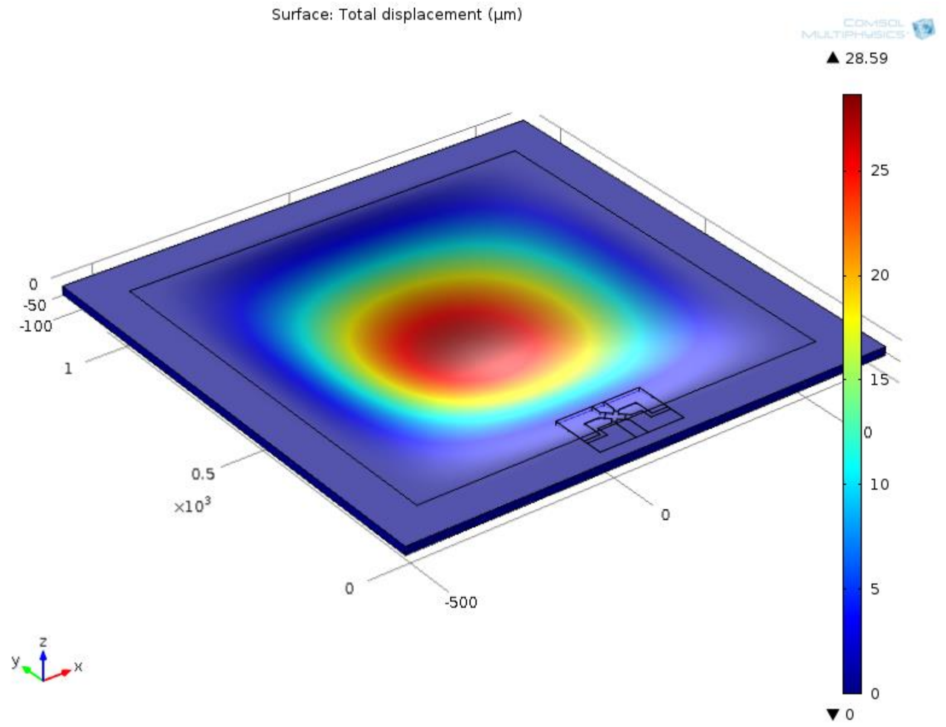

Figure 3. The deformation of the pressure sensor at the applied pressure of 2277 kPa of single crystal silicon(n,p type).

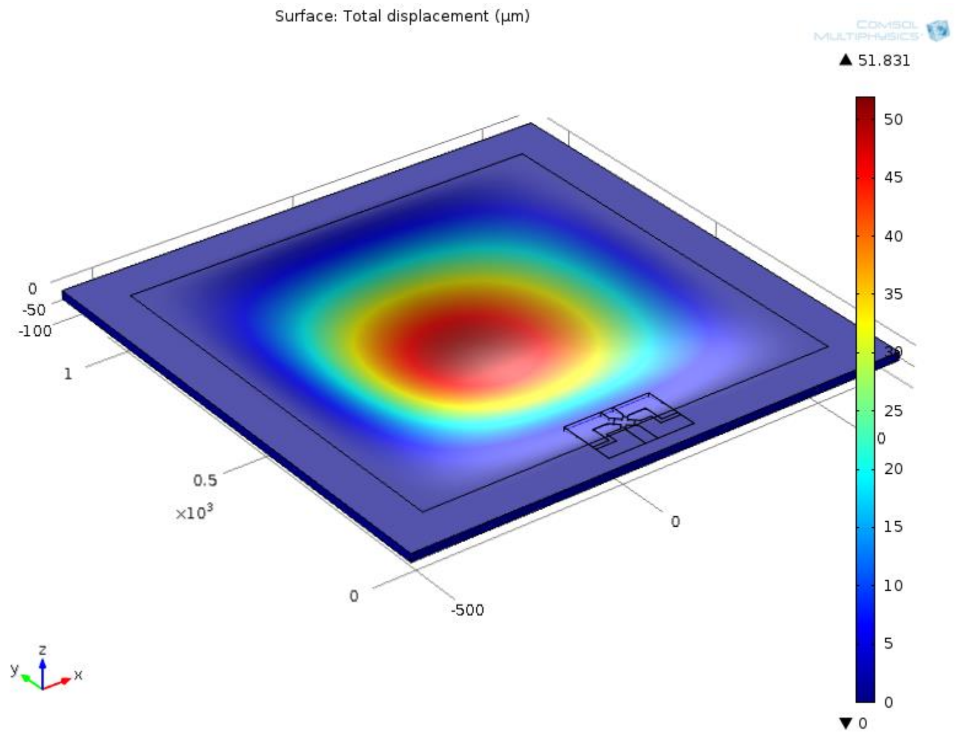

Figure 4. The deformation of the pressure sensor at the applied pressure of 4128 kPa of single crystal silicon interchanged (p,n type).

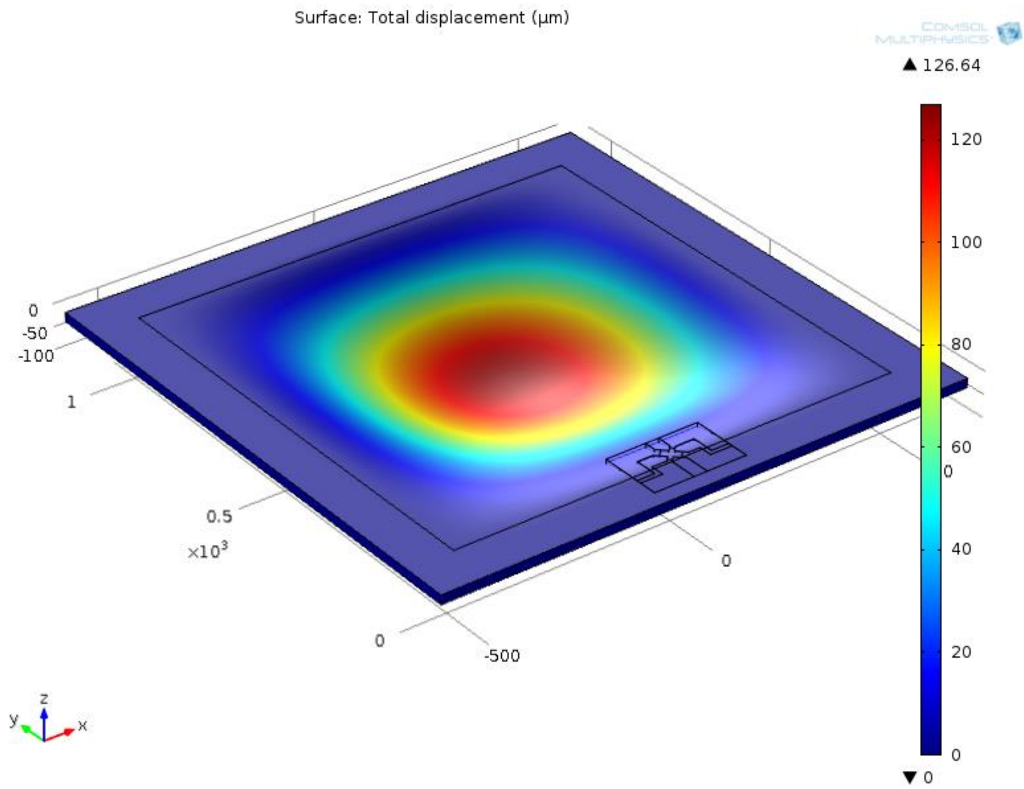

Figure 5. The deformation of the pressure sensor at the applied pressure of 10752 kPa of poly crystal silicon (n,p) type.

5.1. Single crystal material (n,p type)

Comparison of maximum deformation of single crystal silicon(n,p) [16] at 2277kPa pressure (Fig. 3), single crystal silicon interchaned (p,n) at 4128 kPa pressure (Fig. 4) and polycrystal silicon (n,p) at 10752 kPa pressure (Fig. 5). The maximum deformation for interchanged n, p type single crystal silicon material is found to be 51.831µm. It can be noted that the maximum deformation for p, n-types single crystal silicon was 28.59 µm. Thus maximum sensing capability has been observed from the proposed design with interchanging of n and p-type silicon. It can be concluded that the performance of pressure sensor enhanced approximately double the given design that can be seen from the above Fig. 4 . The maximum deformation for polycrystalline silicion material is found to be 126.64 µm. which can be seen from Fig. 5 . Thus the maximum deformation is enhanced [17] to 126.64 µm, when compared to single crystalline silicon materials. Thus the optimised sensing action has been noticed with the polysilicon material. The maximum deformations (µm) at the center for various loads applied to different forms of materials of silicon of proposed pressure sensor are tabulated and shown in Table I.

VI. RESULTS AND ANALYSIS

Simulation is carried out in three steps. Firstly, using single crystalline form of silicon material, next interchanging p,n-type single crystal silicon and finally poly crystal silicon form. The below equation explains about the shear stress at the mid-point of the diaphragm [16].

$$\sigma^{l,12} = 014\left(\frac{L}{H}\right)^{2} \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, P is the applied pressure, L is the length of the diaphragm edge and H is the diaphragm thickness.

Table 1. The maximum deformation values at center of diaphragm for different applied pressures.

Applied Pressure (kPa)	Deformation (µm)		
	Singlecrystal Silicon (n,p type)	Singlecrystal Silicon Interchanged (p,n type)	Polycrystal silicon (n,p type)
1000	12.556	12.556	11.778
2000	25.112	25.112	23.556
3000	-	37.668	35.334
4000	-	50.224	47.112
5000	-	-	58.89
6000	-	-	70.668
7000	-	-	82.446
8000	-	-	94.224
9000	-	-	106
10000	-	-	117.78

6.1. Single crystal material (n, p type)

As mentioned above, simulation of pressure sensor has been carried out for the single crystal solid design. Deformation of diaphragm in response of applied pressrue ranging from 100 kPa [17] to 2277 kPa has been studied and same can be seen from the figure 3. It is important to note that the design cannot hold the pressure beyond 2277 kPa. From this analysis, it is clear that the single crystal solid design [16] exhibits maximum deformation of 28.59 µm with the maximum applied pressure of 2277 kPa. The shear stress distribution of device at 2277 kPa pressure is studied as shown in Fig. 6. The second piola kirchoff's law is also given as graph of arc length v/s shear stress in Fig. 7.

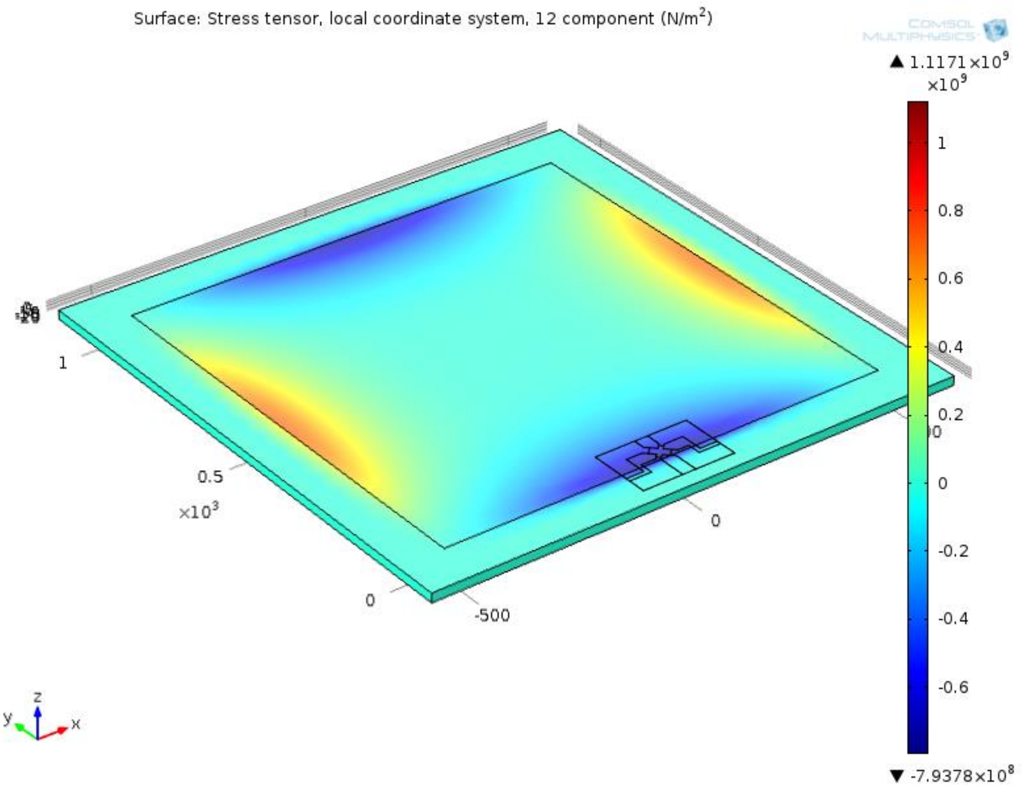

Figure 6. Shear stress tensor for single crystal silicon at the applied pressure 2277kPa.

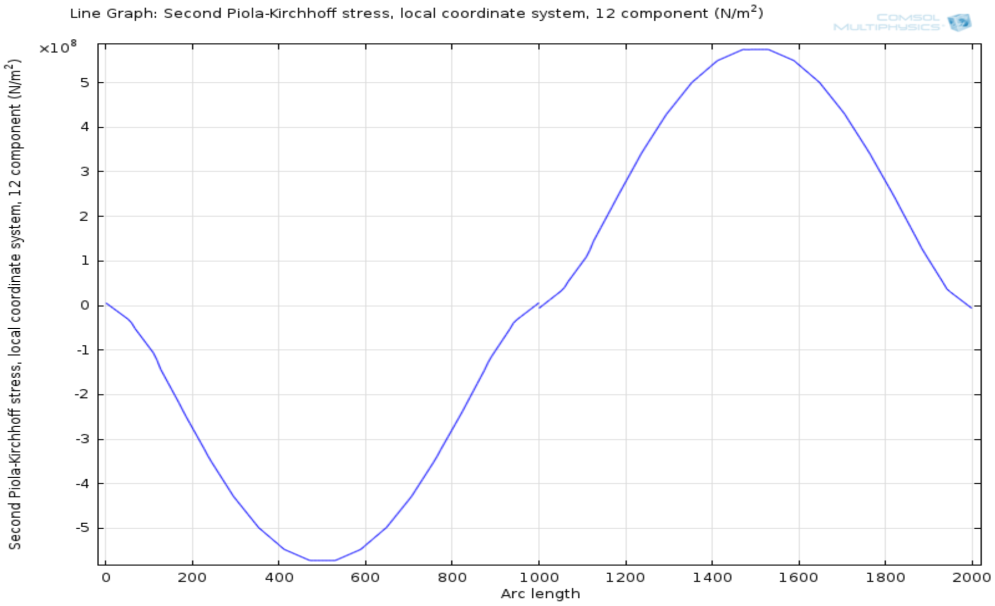

Figure 7. Arc lenght v/s shear stress tensor at the applied pressure 2277 kPa.

6.2. Single crystal material interchanged (p, n type)

The next analysis done on interchanging of n-type and p-type single crystal silion and the response of deformation in diaphragm is noticed for different applied pressure ranging from 100 kPa to 4128 kPa as it cannot tolerate beyond that value. The result shows the maximum deformation as 51.831 µm at the pressure of 4128 kPa. Hence by using the same material, the performance has been optimized from the maximum deformation 28.59 µm to 51.831 µm. Thus the design is extended [16] to improve results. The shear stress distribution and second Piola kirchoff's law are given in Fig. 8, 9 respectively.

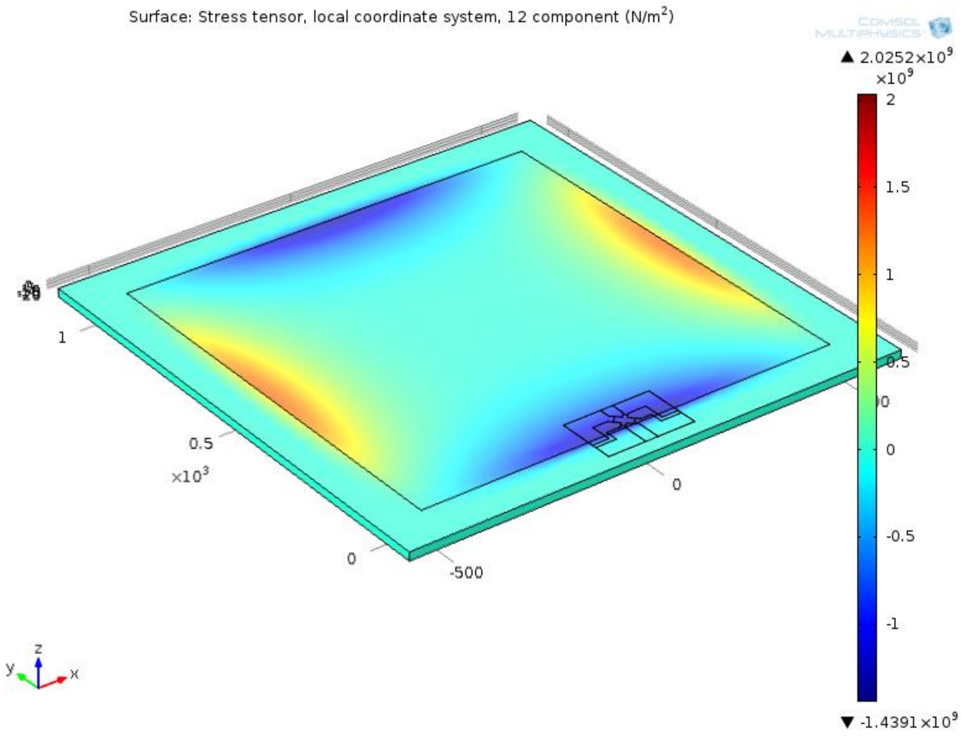

Figure 8. Shear stress tensor for single crystal silicon at the applied pressure of 4128 kPa.

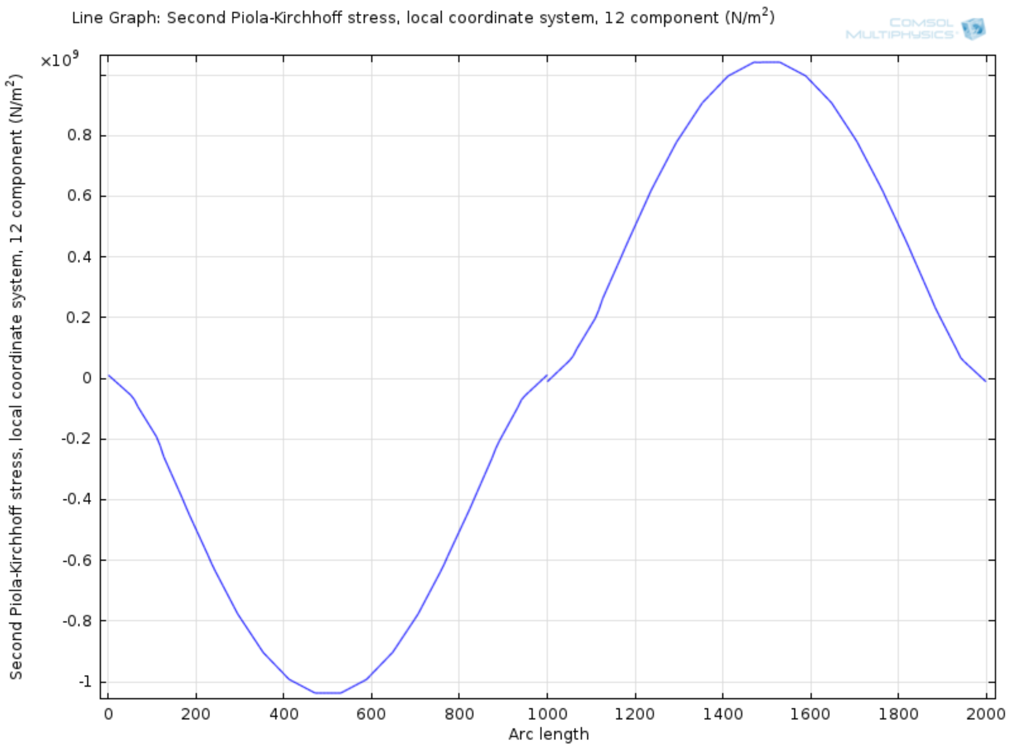

Figure 9. Arc lenght v/s shear stress tensor at the applied pressure of 4128 kPa.

6.2. Poly crystal silicon material (n, p type)

The final step includes the study of polycristalline silicon as material and sensing action is reported same as above steps. It gives the tolerance value of 126.64µm to the applied pressure of 10752 kPa. Thus the performance increased to great extent is noticed when compared to singlecrystal silicon material [17]. The shear stress and the second Piola Kirchoff's law i.e., arc length v/s stress are given in Fig. 10, 11 respectively.

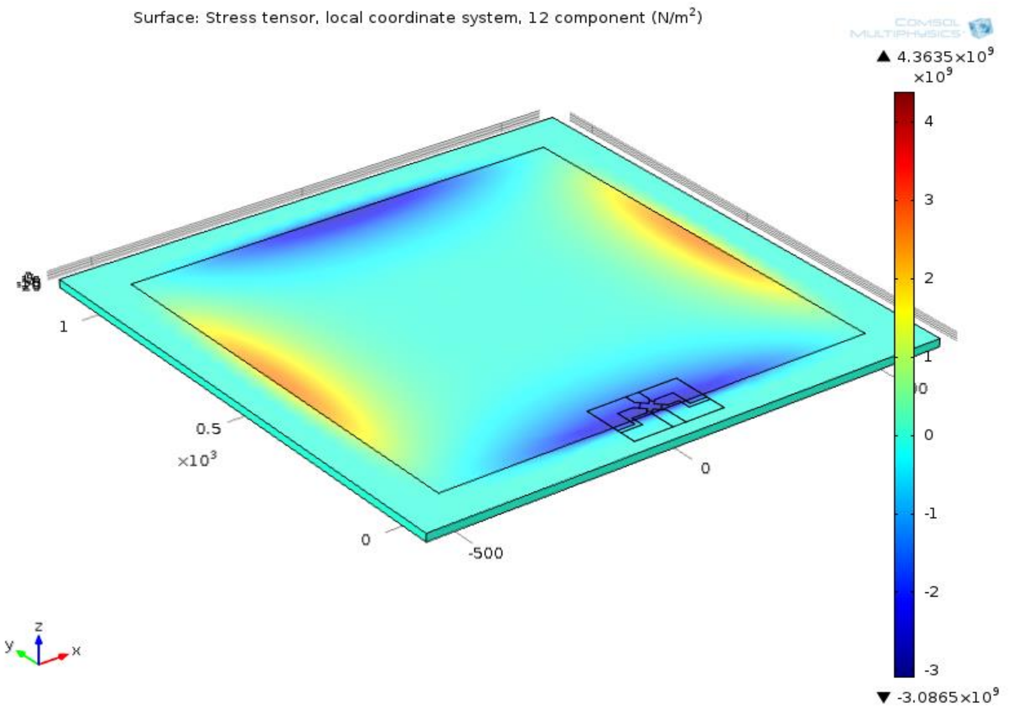

Figure 10.Shear stress tensor for polycrystal silicon at the applied pressure 10752 kPa .

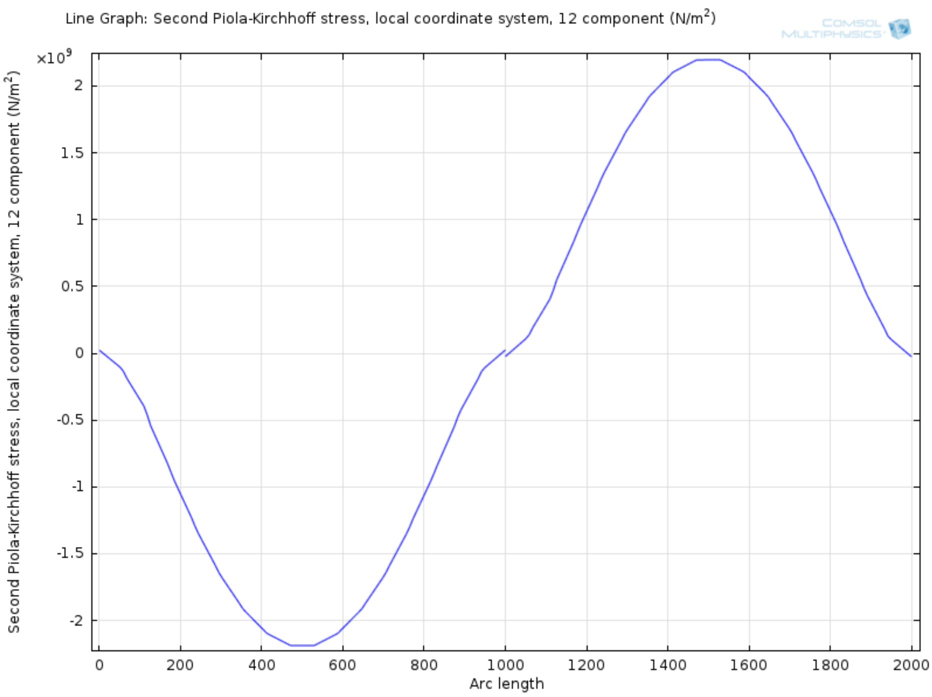

Figure 11. Arc lenght v/s shear stress tensor at the applied pressure 10752 kPa.

Hence the study has been extended which gives polycrystalline form of silicon as it shows maximum optimizated results as pressure sensor.

Table 2. The following comparison table briefly explains about the maximum deformation, shear stress and stess sensor respectively.

Material	**Maximum Deformation (µm)**	**Maximum Shear Stress (MPa)**	**Maximum Stress Tensor (MPa)**
Single crystalline silicon (n,p type)	28.59	1171.1	500
Single crystalline silicon (p,n type)	51.831	2025.2	800
Polycrystalline silicon (n,p type)	126.64	4363.5	2000

Thus, the proposed forms will be useful in making devices for producing desired deformations of pressure sensor using the different forms of materials providing the optimized results as tolerance.

VII. CONCLUSION

MEMS based piezoresistive pressure sensor is designed using COMSOL MultiPhysics v. 4.3b. The sensor has been studied with different forms of silicon materials for diaphragm with different applied pressures and corresponding results are compared. From the analyses of simulation results, it can be concluded that the proposed piezoresistive pressure sensor design provided with polysilicon material for diaphragm found to exhibit optimum deformation in turn beter sensing action for given input of applied pressure in comparision with designs [16] of other p & n type material interchanges for the wafer and piezoresistors.

VIII. FUTURE WORK

The proposed design can be extended by making changes in the geometry of diaphragm, applied inputs and meshing inturn to get better sensing mechanism. Further, there will be lot of scope to add other semiconducting materials those are to be assigned to diaphragm to get optimum output from the proposed solid pressure sensor design for small applied inputs.

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