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# Design and Simulation of Silicon on Insulator Based Piezoresistive Pressure Sensor

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**Abstract:**
In this paper we designed Piezoresistive pressure sensor using silicon on insulator based diaphragm. The silicon on insulator material is used to improve the sensitivity and also used to archive high reliability. The main aim of this SOI technology is silicon does not withstand high temperature in many applications so we use SOI instead of silicon and it will also act as an oxide layer between, piezoresistor and the substrate providing insulation. Piezoresistive pressure sensor employs a change in resistance values of piezoresistive elements placed on the surface of the diaphragm. The simulation and modeling of proposed pressure sensors is done using COMSOL Multiphysics. Based on simulation results, SOI based Piezoresistive pressure sensor provides high linearity and better sensitivity.

**Keywords:** Pressure, Piezoresistive pressure sensor, SOI based pressure sensor, Linearity, Sensitivity

## I. INTRODUCTION

Micro Electro Mechanical System (MEMS) is one of the important techniques to integrating both the electric and mechanical components together to form a small or tiny structure of miniaturized dimensions. Various types of the pressure sensors are designed using the MEMS technology. Among these pressure sensor is widely used for various domains [1]. Because, of its high gain factor, high reliability and high sensitivity which can exhibit a good linear relationship between, the resistance changes in output and stress applied.

Pressure sensor is used in many industrial and day to day life applications. There is always increasing need for pressure measurement techniques. MEMS based Pressure sensors are highly popular in the domain of pressure measurement due to their reliable and accurate measurements. Pressure (P) is defined as the force applied per unit area which is given by,

$$P = F / A \quad \text{------ (1)}$$

Where F is force applied and A is the area where the force is applied. MEMS pressure sensor converts mechanical into electrical signal based on particular transduction mechanism.

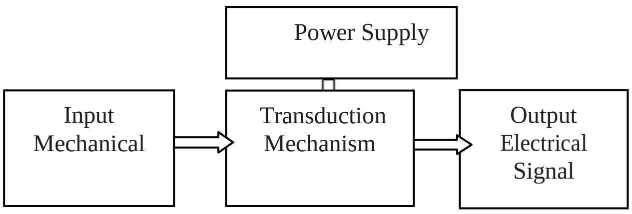


**Fig 1**: A typical Pressure sensor

The figure 1 shows the basic block diagram of a typical pressure sensor. The pressure sensors have their wider application in the field of automotive industry, bio-medical and weather forecasting. Many MEMS instruments were manufactured and commercialized from several years and have reached consumer. Piezoresistive pressure sensor use silicon, poly silicon as a piezoresistive material because of its high sensitivity and repeatability. Pressure sensors employing the use of other materials like sic, and diamond for the piezoresistor are not very popular for the commercial usage because the fabrication technology is not mature for such materials [3]. Also silicon based piezoresistive pressure sensor can be easily fabricated using ion implantation and the sheet resistance of the resistors can also be carefully controlled using ion implantation. Temperature is the main factor in the efficiency of the MEMS pressure sensor where these have to be used in many applications like aerospace and harsh environment. Consequently, for this kind of environment special sensing devices are refusing to adapt a high temperature and high pressure environment. Among all types of MEMS pressure sensor a piezoresistive pressure sensor are widely used, because these sensors provides a high sensitivity and high linear operation over a wide range of pressure. Piezoresistive pressure sensors are the one of the very first product of MEMS technology. Those products are broadly used in many applications such as biomedical, aerospace and house hold applications. The piezoresistive pressure sensor mainly been studied and commercialized because of their high yield and wide dynamic range.

A silicon based pressure sensor is one of the major applications of the piezoresistive pressure sensor. Recently MEMS situated technologies includes silicon, silicon on insulator, silicon on sapphire, silicon on carbide, steel, carbon nanotubes and diamond has been observed to be in a position to furnish the critical ruggedness to be capable to adapt and provide the better performance in harsh environment. This paper manly focus on the designing and simulation of silicon on insulator based piezoresistive pressure sensor, because the silicon does not withstand in the high temperature applications, so instead of silicon we are using an oxide layer this layer between, piezoresistor and substrate providing insulation. This will helps to piezoresistive pressure sensor to makes an operate at high temperature applications.

U.Sampath Kumar et.al [1] describes about the sensitivity of the pressure sensor can be considering or selecting the proper geometry and the position of the piezoresistor and the effective use of its deflection area. And that will increases the sensitivity and linearity of the sensor. Kanda. Y et al [2] describes the calculation of Piezoresistive coefficients as a function of temperature and also, he observes that Piezoresistive coefficient plays as important role while designing the model of pressure sensor. M.Z.Shaik et.al [3] explains about Piezoresistive pressure sensor for low pressure ranges sensors and also for high temperature environment using SOI. This type of the pressure sensors are widely intended for extreme environment conditions and also for high operating temperature ranges. K.Y.Madhavi et.al [4] describe about the silicon based Piezoresistive pressure sensors for high sensitivity using a FEM. The simulate and analyze the parameters like side length, thickness and all the piezoresistor to determine the sensitivity of the sensor for the pressure from 0 to 2 MPa. Nurul Amziah Md Yunus et al [5] explain about the different types of the pressure sensors and their theory of operation. The fabrication processes of pressure sensor are discussed. The device application of pressure sensor such as pressure monitoring of tire are explained. Xin Li, Qin liu [6], Discussed about the temperature analysis of piezoresistive pressure sensor. The top layer of silicon is used as energy boosting material due to its single crystalline properties and also discussed about the high temperature application. The silicon on insulator material is used for high temperature application, manly SOI is used for extremely high environment conditions and high temperature up to 300 degC .Square Diaphragm is used because of high sensitivity, the negative bounding process can be used to solve the packaging problems. With the help of literature survey we come to know that the importance of Piezoresistive pressure sensor and their use in pressure sensing applications. As compare to other pressure sensor models this type of model will gives high sensitivity and linearity.

## II. DESIGN OF SOI PRESSURE SENSOR

The objective of the work is to design and simulate silicon on insulator based piezoresistive pressure sensor. To with stand at high temperature applications so, we use instead silicon the SOI is used as shown in below figures.

### a) *Piezoresistive pressure sensor*

The proposed pressure sensor employs a piezoresistive transduction mechanism, where piezoresistive elements are placed on the surface of the square diaphragm at the maximum stress region. In the proposed work terminal voltage and applied pressure are the inputs. Deformation and change in the output voltage are the outputs which give linear response with respect to applied pressure. The interconnection of the piezoresistor is done using connectors as shown in the Figure 2.1

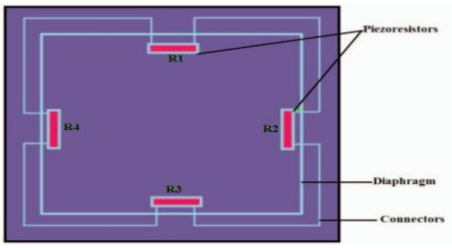


**Fig 2.1**: Proposed model of piezoresistive pressure sensor.

In this proposed work the silicon on insulator (SOI) based Piezoresistive process sensor is designed and simulated. The proposed module is shown in fig 3.2. The top view shows the four registers R1,R2,R3 and R4 these are implemented on the surface of the silicon diaphragms .The silicon diaphragms by the applied pressure in to change of electronic resistance, which will converted in to output voltage . A proposed pressure sensor model consist of a substrate of length 500µm, width 500 µm and thickness 10 µm, with in the substrate a diaphragm of length 400 µm, width 400 µm and thickness 10 µm is embedded on the substrate. Above the diaphragm a four piezoresistor of length 100 µm, width 10 µm are placed in the Wheatstone bridge configuration. These piezoresistor are connected with the help of double line connectors of width 1 µm and space between the connectors are 10 µm is modeled. And also the dimension of the silicon diaphragm is (500 µm*500 µm*10 µm) and dimension of $SiO_2$ insulating material is (500 µm*500 µm*3µm).The sensor exhibit a high sensitivity and linearity over a pressure range 0 to 2MPa. The simulation is done for the micro pressure sensor of the form by using a COMSOL Multiphysics.

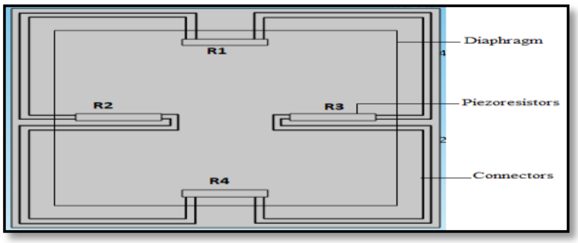


Fig 2.2 Proposed Model of SI PZR.

In this proposed model the diminution of the diaphragm model is 400um*400um with the 10um thickness and upper and bottom layer is 3um thickness for middle insulator layer as shown in fig 3.2. In this model three materials are used n-type silicon for piezoresistor and p-type silicon for the bottom of the layer between, these layers the middle silicon dioxide is used for middle insulator layer with 3um thickness.

### b) *SOI Based Piezoresistive pressure sensor*

Silicon on insulator is similar to the silicon based Piezoresistive pressure sensor. But, only changes in this model is within the silicon diaphragm a silicon dioxide insulator layer is placed and within this layers a p-type piezoresistor are placed with the help of connectors. And the connectors are made with the help of p-type metal. The dimension of the silicon diaphragm is (500 µm*500 µm*10 µm) and dimension of $SiO_2$ insulating material is (500 µm*500 µm*3µm).The below fig 4.3 shows the geometry of SOI Piezoresistive pressure sensor.

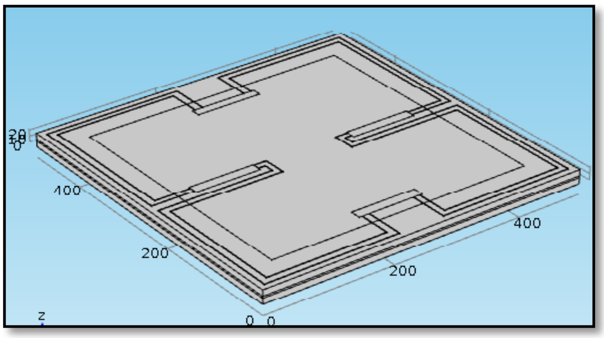


Fig 2.3 Proposed Model of SOI PZR

## III. Material and Performance Parameters

When pressure is applied to the diaphragm the deformation is take place at the center. Because, of the deformation the displacement can be obtained by simulation and also analytically by using equation 1.

$$D = \frac{0.01512\,(1-V^2)\,Pa^4}{Eh^3} \qquad (2)$$

Where, P= Applied pressure
a= Side length of the diaphragm
E= Young's modulus of silicon
h= Thickness of the diaphragm
v= Poisson's ratio of silicon

The output voltage is depends on the input voltage and applied pressure. We can measure the output voltage by using following equation 2.

$$V_{out} = \frac{Pa^2\,(1\text{-}V2)}{h^2}\,\pi_L\,V_{in} \qquad (3)$$

Where, $\pi_t$ = Piezoresistive coefficient for inverse position.

The common material used for Piezoresistive pressure sensor is silicon, however relying upon the application, the different categories of silicon materials can be used as a piezoresistive component, for example p-type and n-type silicon. However the mechanism is same for the pressure sensing. The material are choose at outline of the diaphragm on which the piezoresistor are put performs a vital part in choosing the application of the pressure sensor and the scope of the pressure sensor can sense and also the Piezoresistive materials play a pivotal part in deciding the resistivity of the material and the associating arms of the piezoresistor are build by using aluminum metal because the metal will not share to the effect of piezoresistivity.

*a) Piezoresistive pressure sensor*

**TABLE 3.1**: Specifications of the model

| ***Parameter*** | ***Depth (μm)*** | ***Width (μm)*** | ***Height (μm)*** |
|---|---|---|---|
| Substrate | 500 | 500 | 10 |
| Diaphragm | 400 | 400 | 10 |
| Piezoresistors | - | 100 | 10 |

**TABLE 3.2**: Material Properties for Si

| ***Name*** | ***n-type silicon*** | ***p-type silicon*** |
|---|---|---|
| Density | 2330 kg/m$^3$ | 2330 kg/m$^3$ |
| Young's modulus | 160 GPa | 160 GPa |
| Poisson's ratio | 0.22 | 0.22 |
| Used | Substrate, diaphragm, Piezoresistors, connecting wires | Connector arms |

*b) SOI Based Piezoresistive pressure sensor*

The material used for SOI Based Piezoresistive pressure sensor is silicon and sio2, however relying upon the application, the different categories of silicon materials can be used as a piezoresistive component, for example p-type and n-type silicon. However the mechanism is same for the pressure sensing. The material are choose at outline of the diaphragm on which the piezoresistor are put performs a vital part in choosing the application of the pressure sensor and the scope of the pressure sensor can sense and also the Piezoresistive materials play a pivotal part in deciding the resistivity of the material and the associating arms of the piezoresistor are build by using aluminum metal because the metal will not share to the effect of piezoresistivity

TABLE 3.3:- Material Properties for Soi

| Materials | n-type silicon | p-type silicon | Silicon | $SiO_2$ |
|---|---|---|---|---|
| Young's modulus (GPa) | 160 | 160 | 170e9 | 170e9 |
| Poisson's ratio | 0.22 | 0.22 | 0.28 | 0.17 |
| Density (Kg/m$^3$) | 2330 | 2330 | 2329 | 2200 |
| Relative permittivity | 4.5 | 4.5 | 1 | 4.5 |

IV.DESIGN OF SOI SENSOR

In Silicon on insulator based model we are considering six blocks and all together form SOI as shown in fig 4.1.

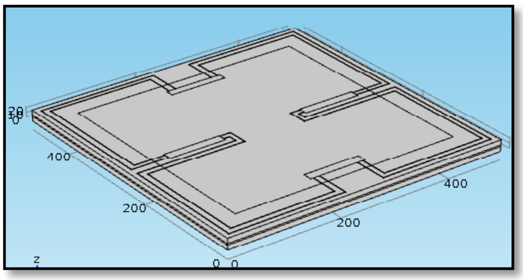


Fig 4.1 Square Diaphragms

According to deflection theory, the piezoresistor are placed in maximum stress regions as shown in figure. The thickness and length is selected as 100um and 3um respectively.

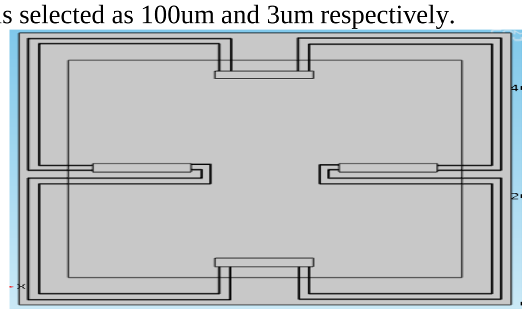

Fig 4.2 Connectors connected to piezoresistor

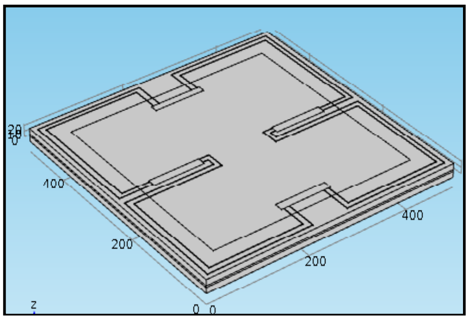


Fig 4.3 Operation of SOI based Piezoresistive pressure sensors

The above figure 4.2 and 4.3 shows the connectors are connected to the piezoresistors. And the pressure is applied at the bottom of the surface. For the bottom surface the silicon material is used and insulator material is at the middle layer. N-type silicon for piezoresistor. P-type silicon is used for upper substrate and diaphragm. Thin Piezoresistive layer and thin conductive layer are used by selecting all piezoresistors and connectors respectively. The pressure is applied with suitable value by selecting the proper diaphragm area. In the edges selection select the connector where the voltage is applied and select the terminal type as voltage VIN=5V. And select the connectors to be grounded.

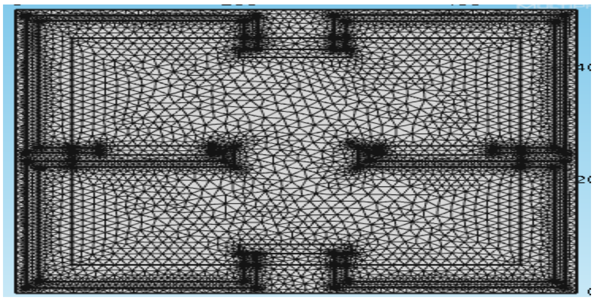

Fig 4.4 Meshing the model

Meshing is to reduce the complexity of the computation to the entire model is disinterested into contiguous smaller units whose different equations can be solved easily. The meshed model is shown in figure 4.4.

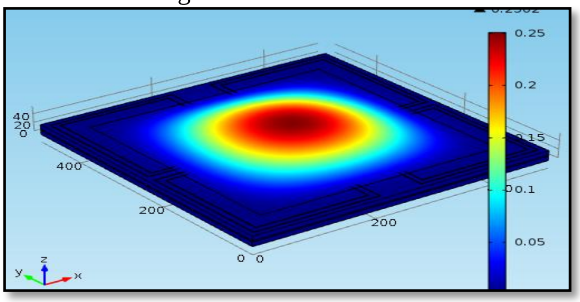

Fig 4.5 Deformed Piezoresistive pressure sensors

Output voltage is to be measured and evaluate by taking two point evaluation methods.

## V.RESULTS AND DISCUSSION

This section deals with the simulated results and discussion of silicon based piezoresistive and SOI based piezoresistive pressure sensor. All the three pressure sensors considered are designed in the pressure range of 0 to 2MPa. Parameters such as Total displacement, output voltage, and Electric potential are considered also with different temperature ranges.

**TABLE 5.1**: Simulated displacement and electric potential values of Silicon Based Piezoresistive pressure sensor

| **Applied pressure (kPa)** | **Displacement (μm)** | **Electric potential (mV)** | **Stress (MPa)** |
|---|---|---|---|
| 0 | 0 | 449.2 | 0 |
| 200 | 0.5244 | 500.95 | 199.17 |
| 400 | 1.0487 | 551.73 | 398.33 |
| 600 | 1.5731 | 601.6 | 597.5 |
| 800 | 2.0975 | 650.58 | 796.67 |
| 1000 | 2.6218 | 698.7 | 995.84 |
| 1200 | 3.1462 | 746 | 1195 |
| 1400 | 3.6705 | 792.47 | 1394.2 |
| 1600 | 4.1949 | 838.17 | 1593.3 |
| 1800 | 4.7193 | 883.08 | 1792.5 |
| 2000 | 5.2436 | 927.23 | 1991.7 |

**TABLE 5.2**: Simulated displacement and electric potential values of SOI Based Piezoresistive pressure sensor

| **Applied pressure (kPa)** | **Displacement (μm)** | **Electric potential (mV)** | **Stress (MPa)** |
|---|---|---|---|
| 0 | 0 | 371.52 | 0 |
| 200 | 0.2617 | 419.32 | 127.81 |
| 400 | 0.5235 | 466.4 | 255.63 |
| 600 | 0.7852 | 512.82 | 383.44 |
| 800 | 1.0496 | 558.61 | 511.25 |
| 1000 | 1.3087 | 603.77 | 639.06 |
| 1200 | 1.5704 | 648.33 | 766.08 |
| 1400 | 1.8321 | 692.3 | 894.69 |
| 1600 | 2.0939 | 735.69 | 1022.5 |
| 1800 | 2.3556 | 778.52 | 1150.3 |
| 2000 | 2.6173 | 820.81 | 1278.1 |

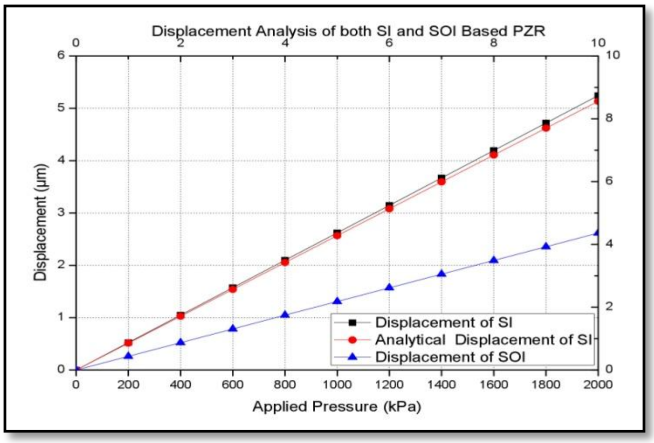


**Fig 5.a**: Total displacement v/s applied pressure

Shows the displacement values from 0 and 5.2436 μm for silicon based Piezoresistive pressure sensor and also from 0 and 2.6173 μm for SOI based Piezoresistive pressure sensor when a pressure ranges from 0 to 2 MPa is applied on it respectively. Fig 5.a shows the graph of deformation values vs. applied pressure for silicon based Piezoresistive pressure sensor and SOI Based piezoresistive pressure sensor. The overall graph shows that as the pressure increases the deformation also increases

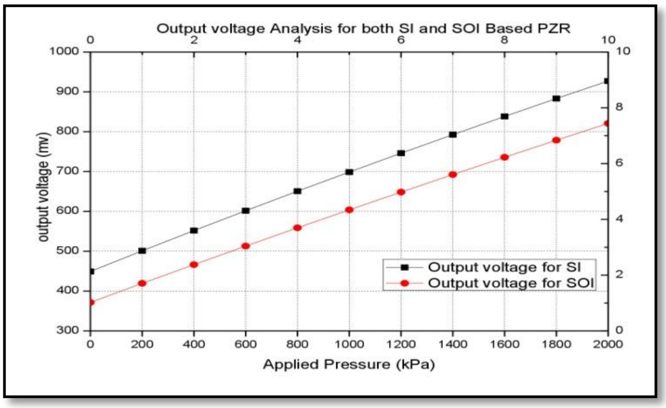


**Fig 5.b:** Output voltage v/s applied pressure

The output voltage of 449.2mV to 927.23mV for silicon based Piezoresistive pressure sensor and also of 371.57mV to 9820.81mV for SOI based Piezoresistive pressure sensor, when pressure is applied from 0 to 2MPa respectively. Fig 5.b shows the graph of the output voltage versus applied pressure for silicon based Piezoresistive pressure sensor. From the graphs we can depict that as the pressure increases the output voltage also increases linearly.

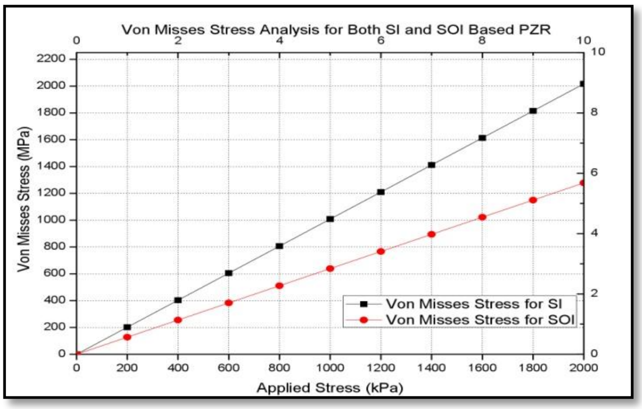


**Fig 5.c:** Von Misses Stress v/s applied pressure

The von misses stress value of 0 and 1991.7 MPa for the silicon based Piezoresistive pressure sensor and also of 0 and 1278.1MPa for silicon on insulator based piezoresistive pressure sensor when a pressure is applied in the ranges from 0 and 2MPa is applied on it respectively. Fig 7.10 shows the graph of von misses stress versus applied pressure for silicon and SOI Based Piezoresistive pressure sensor. The graph shows that as the pressure is increases the stress also increases

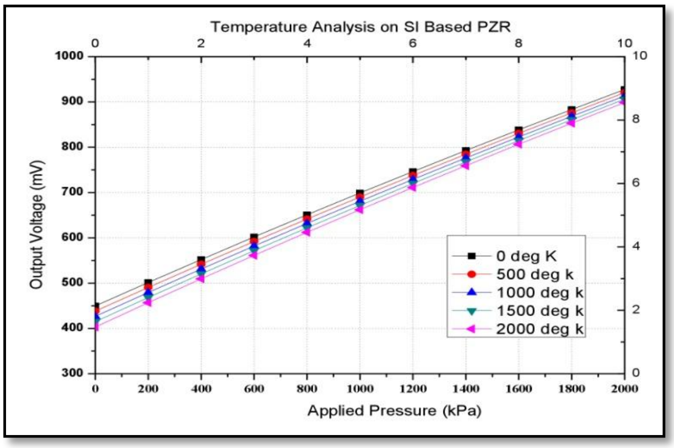


**Fig 5.d**: output voltage v/s applied pressure

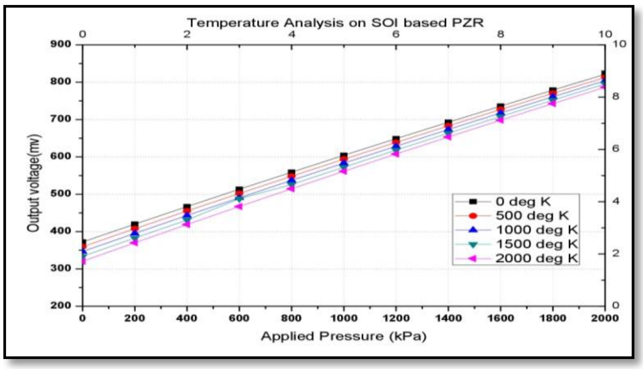


**Fig 5.e**: output voltage v/s applied pressure.

The graph of the output voltage generated by the both the sensors for every temperature under different pressure values is plotted in the fig 5.g and 5.h. Since both piezoresistive coefficients of the piezoresistive material decreases as the temperature decreases, the output voltage generated by the sensors also decreases. Hence, silicon cannot withstand at high temperature in many applications so we use SOI instead of silicon and it will also act oxide layer between, piezoresistor and substrate providing insulation under the high temperature.

Sensitivity analysis

The sensitivity of the Piezoresistive pressure sensor is the ratio of output voltage change to the change in the applied pressure. The sensitivity of any kind of sensor indicates the amount of change in the output for corresponding change in input.

$$S = \frac{\Delta V}{\Delta P} \frac{1}{Vin}$$

Where, Vin is the supply voltage. As comparing AnthonyD.Kurtz1, Alexander A," *Ultra High Temperature, Miniature, SOI Sensors for Extreme Environments*", the results of this paper the silicon based sensitivity is 35mv/Map and SOI Based PZR having 40mv/Map and the calculated sensitivity of the silicon based piezoresistive pressure sensor and Silicon on insulator (SOI) Based piezoresistive pressure sensor are shown in the table 5.4.

**TABLE 5.4:** Sensitivity analysis of Silicon based PZR and SOI Based PZR Sensors

| ***Pressure sensor*** | ***Sensitivity(mV/MPa)*** |
|---|---|
| Silicon Based PZR | 47.58 |
| SOI Based PZR | 51 |

From the table 5.4 it clearly knows that the silicon based piezoresistive pressure sensor achieves low sensitivity as compared to Silicon On insulator based Piezoresistive pressure sensor. Because, of the high sensitivity the Silicon On insulator based Piezoresistive pressure sensor is widely used in high temperature applications [14].

## VI.CONCLUSION

Based on the simulation results we can found that silicon based piezoresistive pressure sensor and SOI based piezoresistive pressure sensor provide a good linearity as well as better sensitivity. A SOI based piezoresistive pressure sensor provides a high sensitivity. Hence silicon on insulator based piezoresistive pressure sensor is used in high sensitivity applications as well as in high temperature applications.

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