Sensitivity Analysis of Different Models of Piezoresistive Micro Pressure Sensors

By

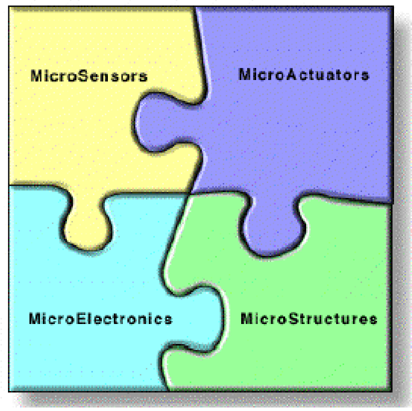
S. MEENATCHISUNDARAM
Assistant Professor (Selection Grade),
Dept. of Instrumentation and Control Engineering
Manipal Institute of Technology, Manipal

Content

Micro Electro Mechanical Systems (MEMS)

MEMS are systems that integrate…

- sensing
- actuation
- computation
- control
- communication
- power



They are…

smaller

more functional

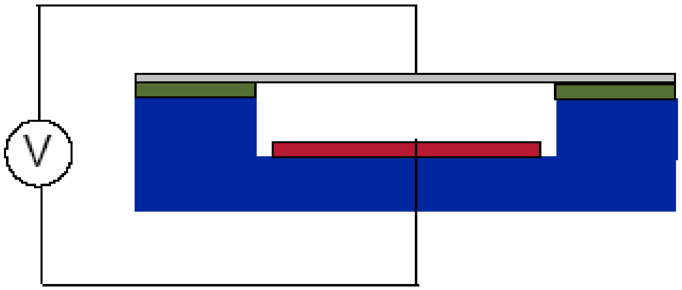
faster

less power-consuming

and cheaper!

Micro Electro Mechanical Systems (MEMS)

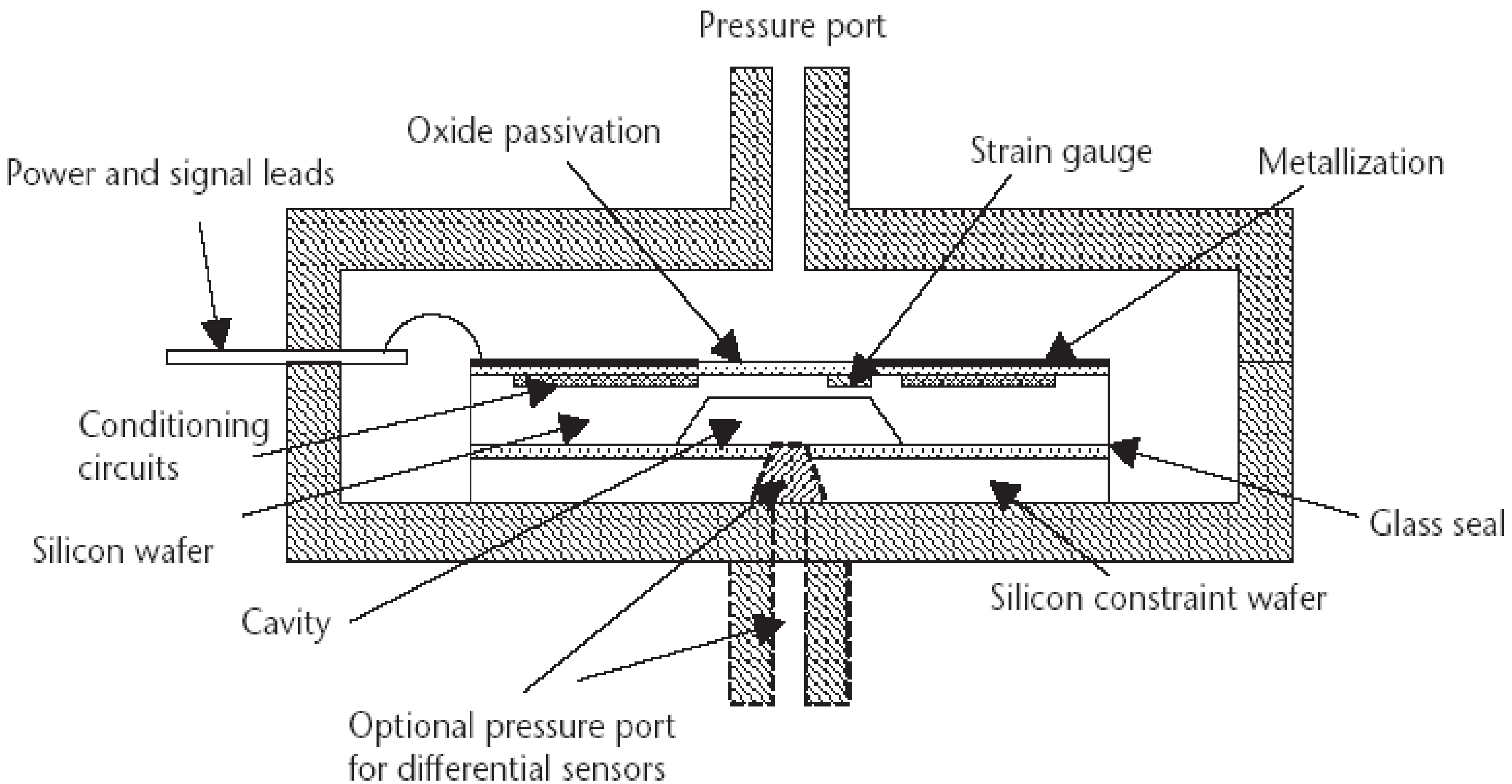
Pressure sensor



Capacitive sensing

Piezoresistive sensing

MEMS Based Pressure Sensors

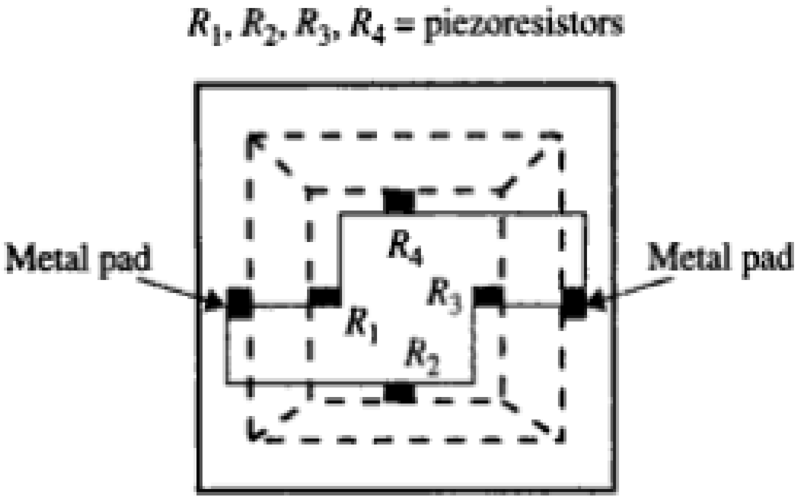


Piezoresistive Pressure Sensors

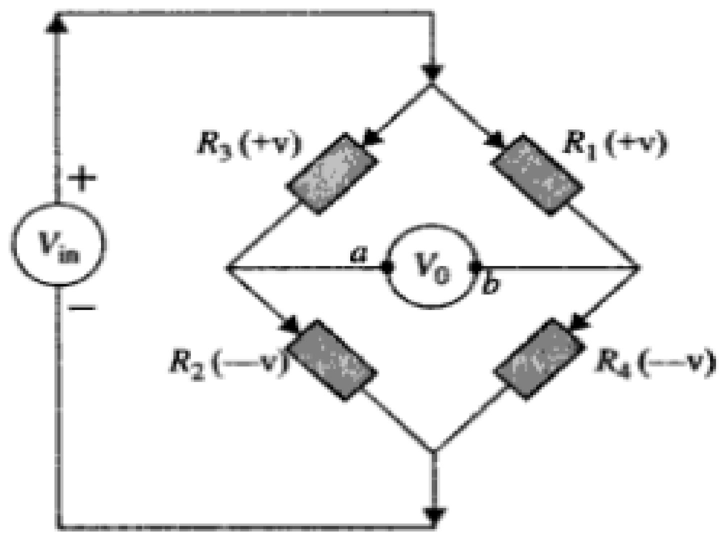
- ❖ Piezoresistance is defined as a change in electrical resistance of solids when subjected to stress fields.
- ❖ Piezoresistors have high gain and exhibit a good linear relationship between the applied stress and the resistance change output.
- ❖ But these sensors suffer on account of temperature dependence of the piezoresistive coefficients.
- ❖ This piezoresistive nature of silicon makes the use of diffused or implanted resistors an obvious and straightforward technique for measuring the strain in a micromachined silicon diaphragm [Tai-Ran Hsu 2002, Beebey 2004].

Piezoresistive Pressure Sensors

The schematic of a packaged pressure sensor is shown in figure. These piezoresistors convert the stresses induced in the silicon diaphragm by the applied pressure into a change of electrical resistance, which is then converted into voltage output by a Wheatstone bridge circuit.



Top view of silicon die



Circuit

Piezoresistive Pressure Sensors

The equations for maximum deflection and stress in a square diaphragm are given by [Warren C Young 2002]

$$W_{\max} = \frac{0.0151(1-\gamma^2)}{Eh^3} Pa^4 \tag{1.1}$$

$$\sigma_{\max} = \frac{0.308}{h^2} Pa^2 \tag{1.2}$$

The change of electric resistance in a silicon piezoresistance gage can thus be expressed as:

$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_T \sigma_T \tag{1.3}$$

where the value of π_l and π_T in the <100> orientation are equal to $0.02\pi_{44}$, σ_l is the stress in the longitudinal direction and σ_T is stress in tangent direction. R can be calculated by the length l, the cross-sectional area A and resistivity (ρ) of the material as

$$R = \frac{\rho l}{A} = \frac{\rho l}{wt} \tag{1.4}$$

The output of a wheatstone bridge can be given as

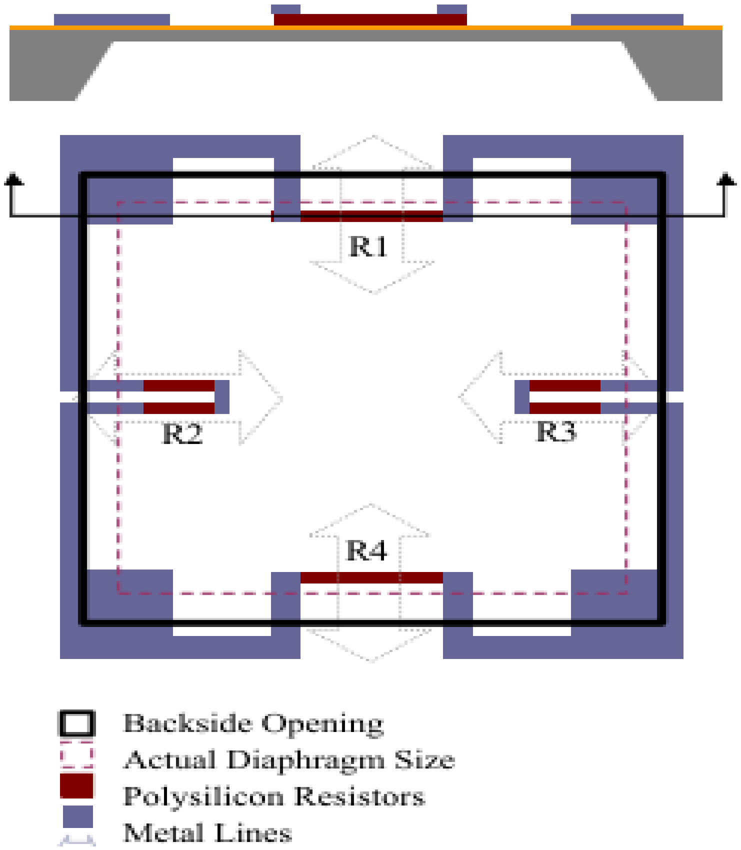
$$V_0 = V_s \left(\frac{R3}{R3+R4} - \frac{R2}{R1+R2} \right) \tag{1.5}$$

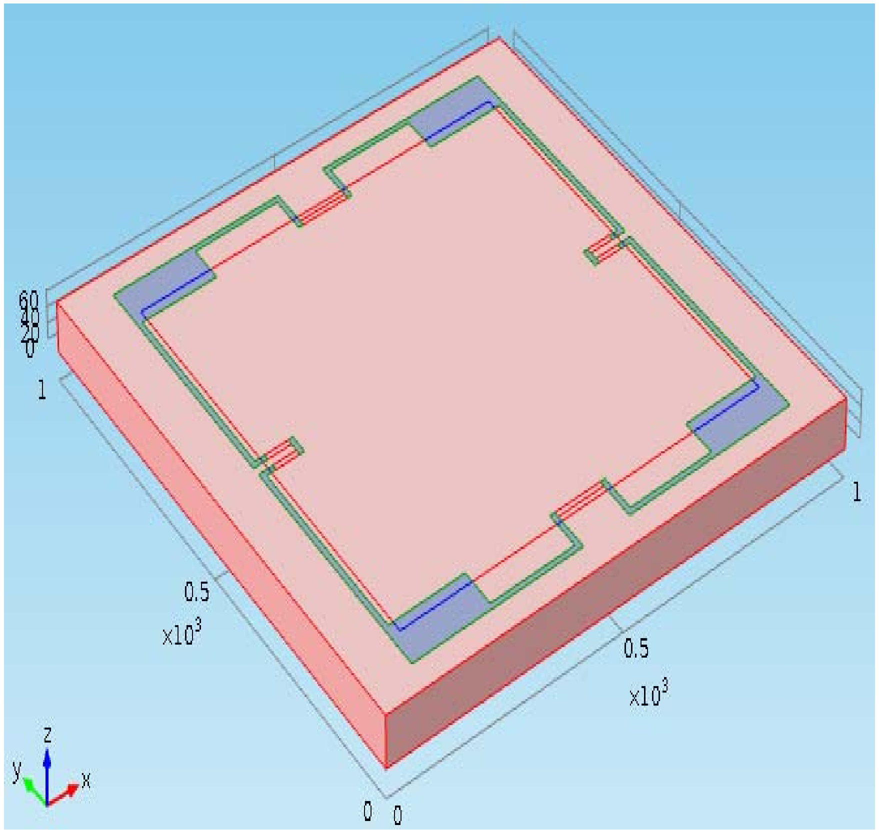
Modeling of Piezoresistive Pressure Sensors

Parameters	Values
Side of the square diaphragm (a)	783um
Thickness of the diaphragm (h)	63um
Max. pressure (P_{max})	100MPa
Poisson's ratio(ν)	0.27
Young's modulus (E)	131.9GPa
Density (p)	2330kg/m^3
Diaphragm	single crystal, lightly doped n-silicon
Piezoresistive Material	p-silicon

Sensor Models

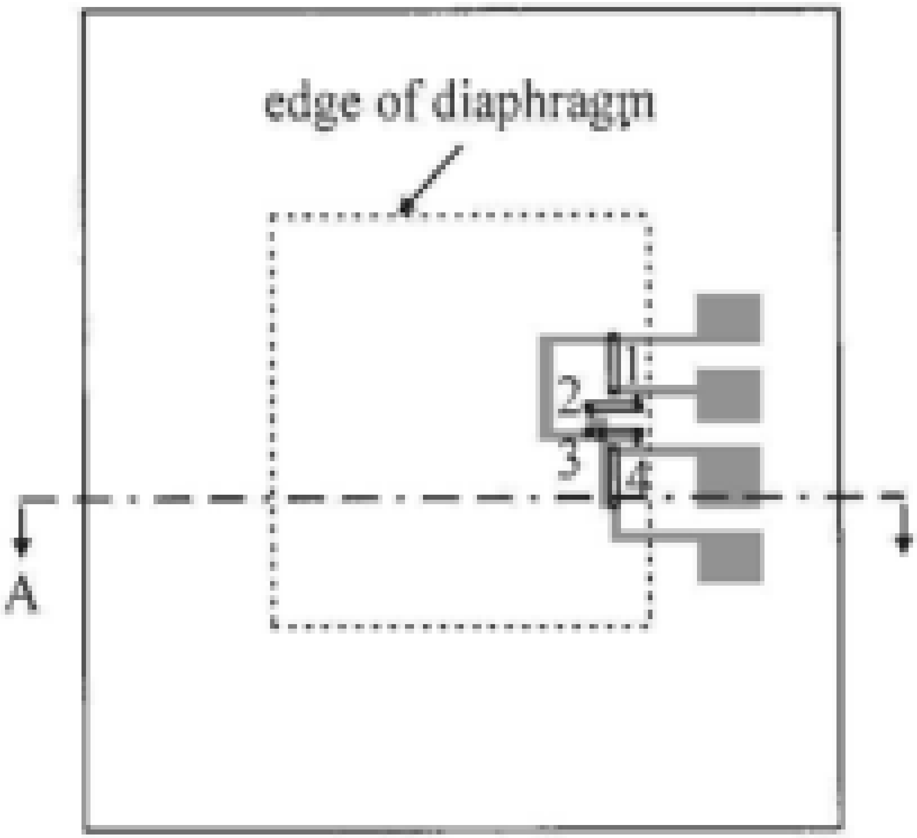
Model 1: Piezoresistive Sensors by Lynn Fuller:

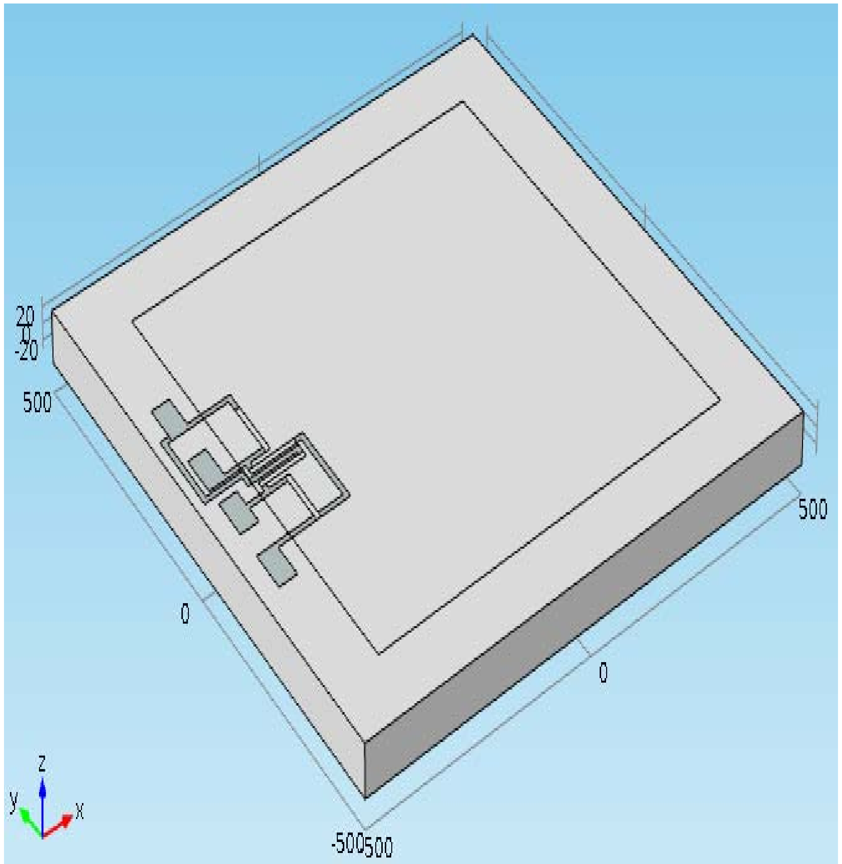




Sensor Models

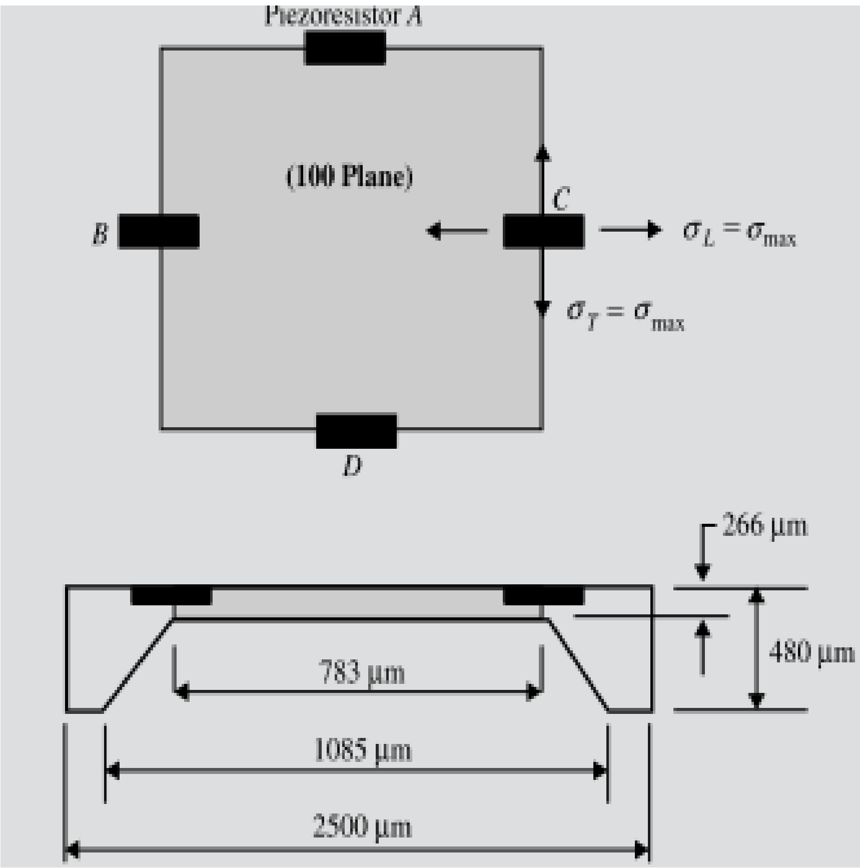
Model 2 - Silicon pressure transducer by M Bao:

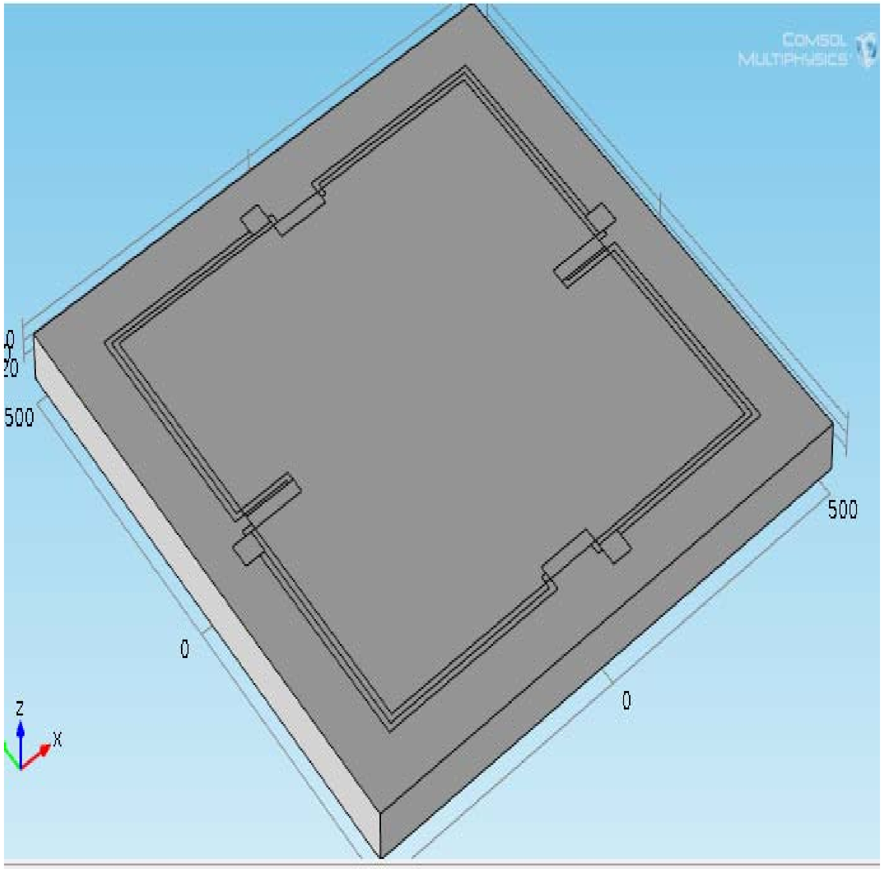




Sensor Models

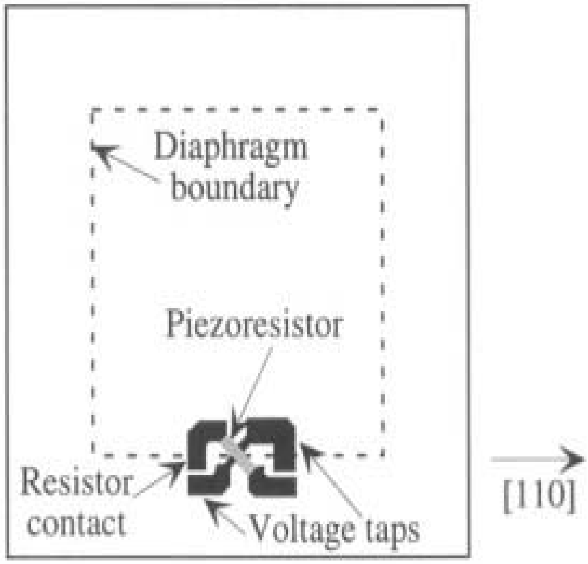
Model 3 - Pressure sensor die by Tai-Ran Hsu:

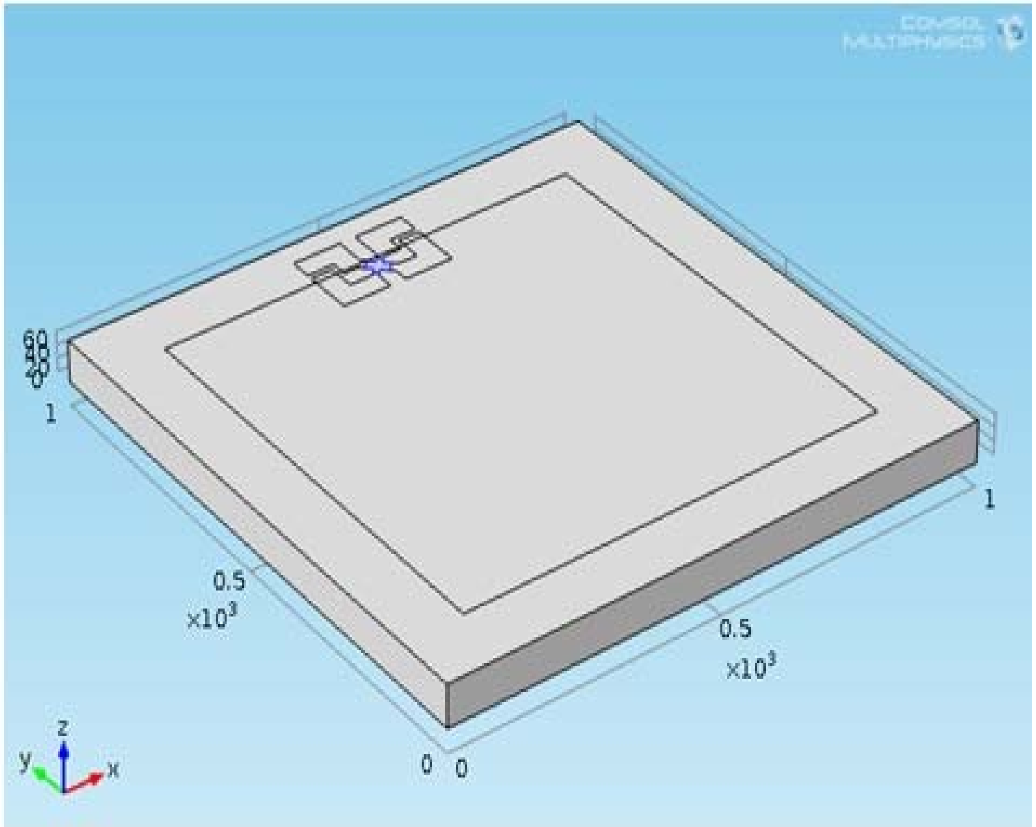




Sensor Models

Model 4 - Motorola Xducer piezoresistor:





Modelling Using Comsol Multiphysics

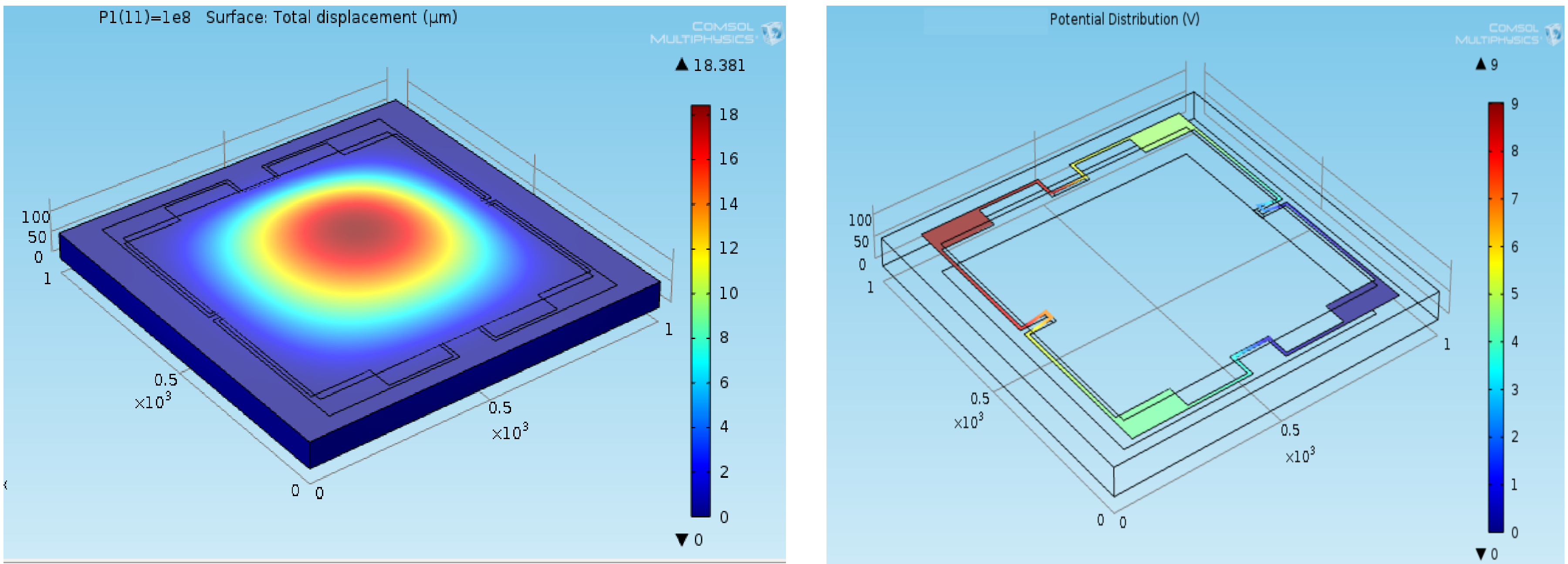
- Piezoresistive physics for boundary currents is chosen as the environment for the analysis.
- The geometry is created using a block (the diaphragm) with the given values for width, depth and height.
- Two work planes are defined on the top and bottom side of the block. The next step is to define the boarders of the membrane on the work planes. This also defines the frame at the same time.
- Afterwards, the remaining geometry of the sensor is defined, hence the dimensions of the resistors and the connections, is defined by a 2D drawing on the upper work plane.
- The material of the whole diaphragm (membrane and frame) is single crystal, lightly doped n-silicon. The piezoresistance is of lightly doped p-silicon. Aluminium is used as metal strip to connect between resistors.

Modelling Using Comsol Multiphysics

- After this, the structural, electrical and piezoresistive properties of the model were defined. The lower and upper side of the *frame* is defined as fixed and a pressure is applied on the upper side of the *membrane*.
- The areas within the boundaries of the connections are determined as thin conductive layers with a thickness of 400nm and the areas bordered by the geometry of the resistors are defined as thin piezoresistive layers, also with a thickness of 400nm.
- The electrical properties are determined by defining a ground and a terminal at the edges of two connection pads for each sensor and the voltage is applied between them.
- An average of terminal current has to be defined over these edges as well as over the relevant edges or boundaries at the remaining connection pads where the voltage for the device output is supposed to be measured. The element size is defined as "finer".

RESULTS AND DISCUSSION

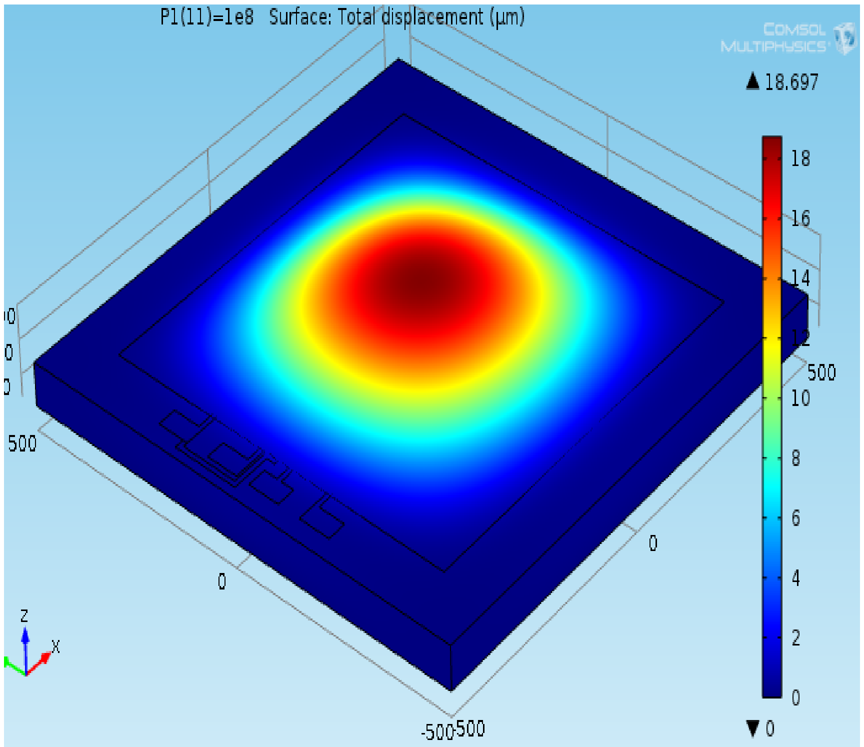
After modelling, a range of pressures from 0MPa to 100MPa, in steps of 10MPa is applied and simulated using parametric sweep of Comsol Multiphysics. The displacement profile and potential distribution of the sensors are shown in figure.

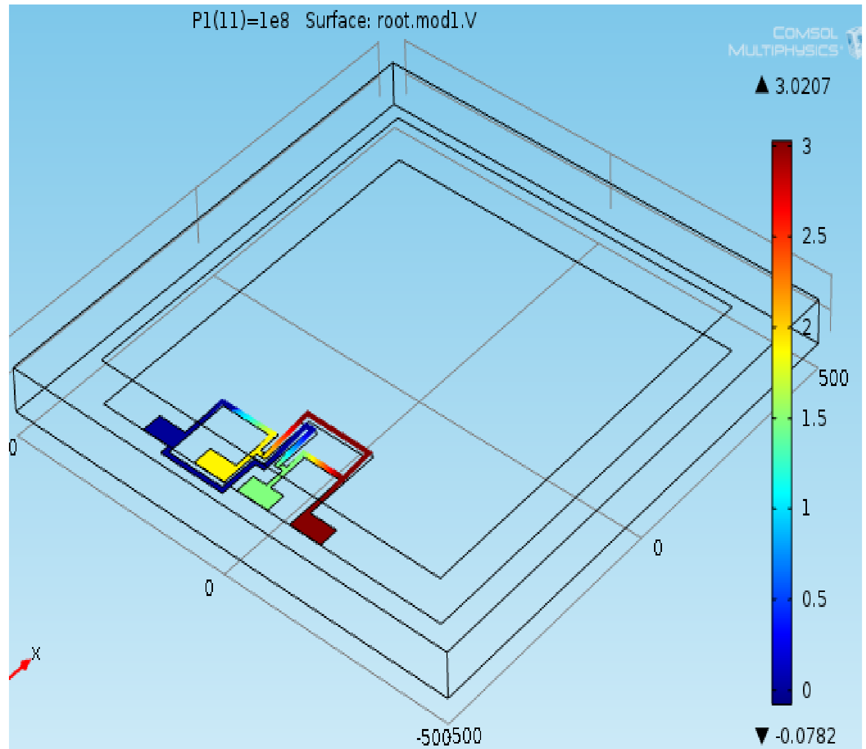


Displacement Profile and Potential Distribution of Model 1 [Lynn Fuller]

RESULTS AND DISCUSSION

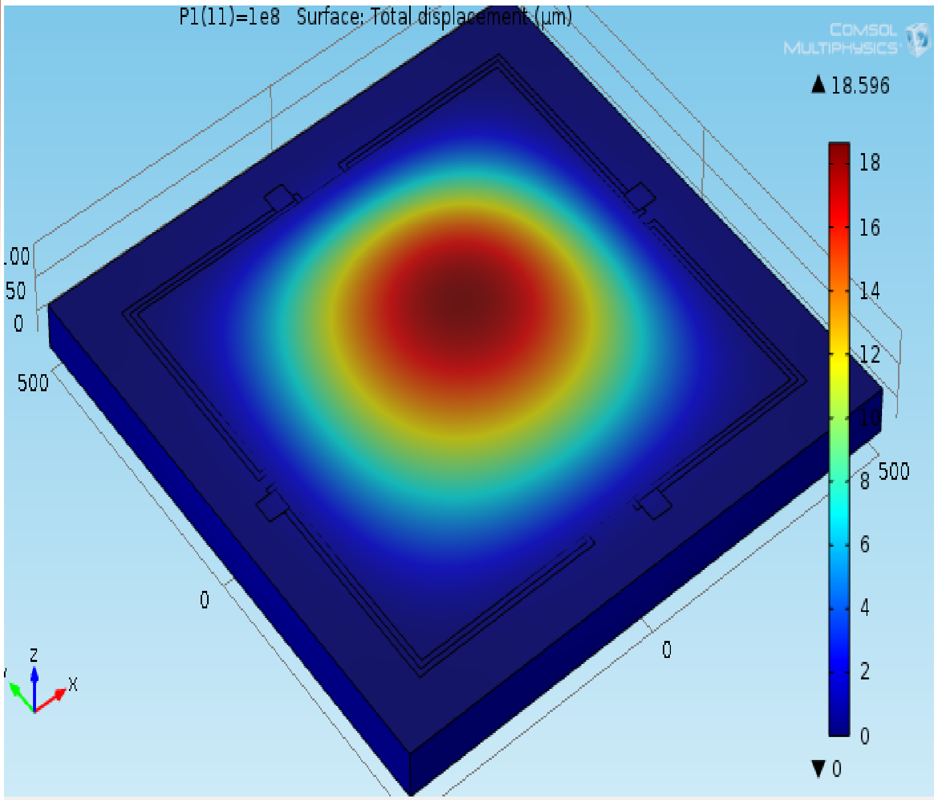
Displacement Profile and Potential Distribution of Model 2 [M Bao]

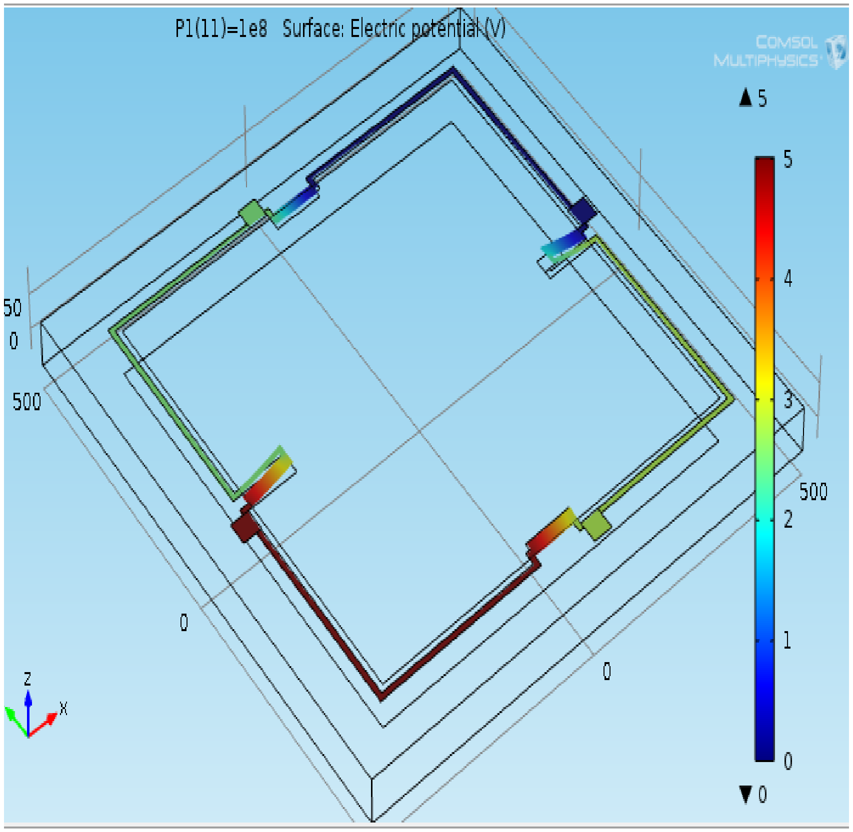




RESULTS AND DISCUSSION

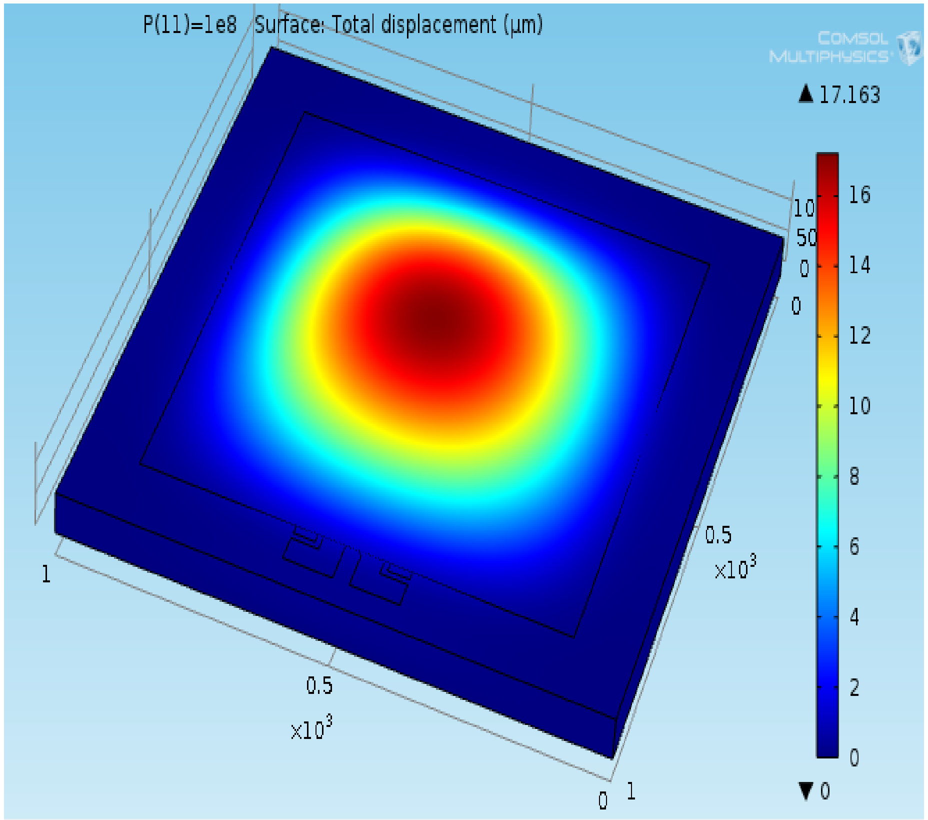
Displacement Profile and Potential Distribution of Model 3 [Tai-Ran Hsu]

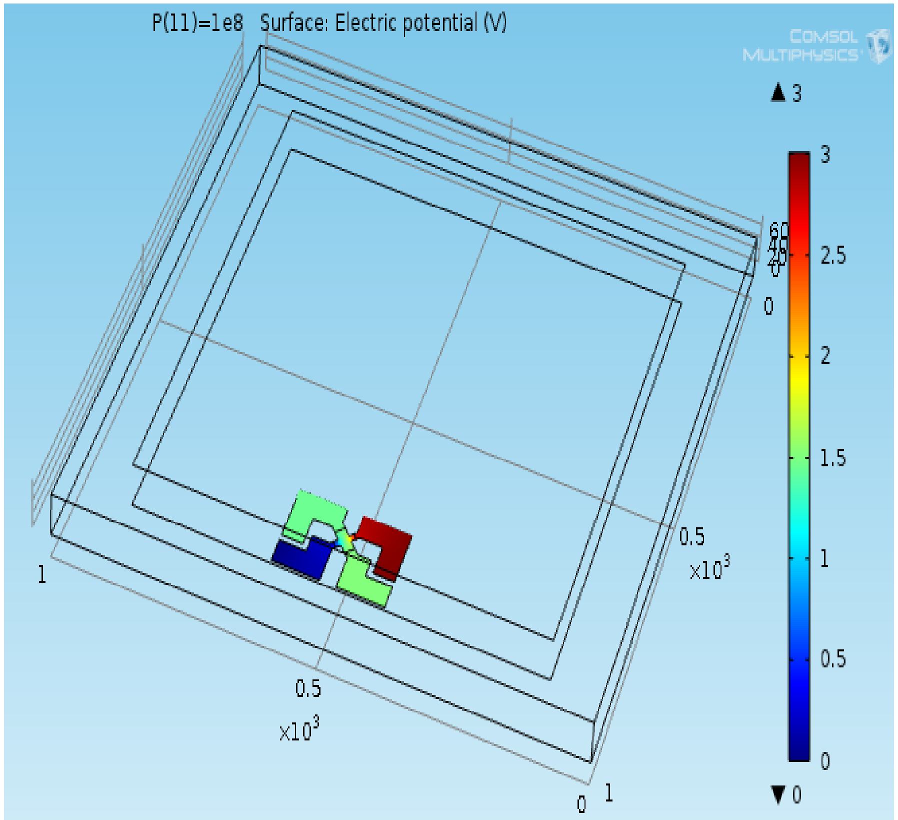




RESULTS AND DISCUSSION

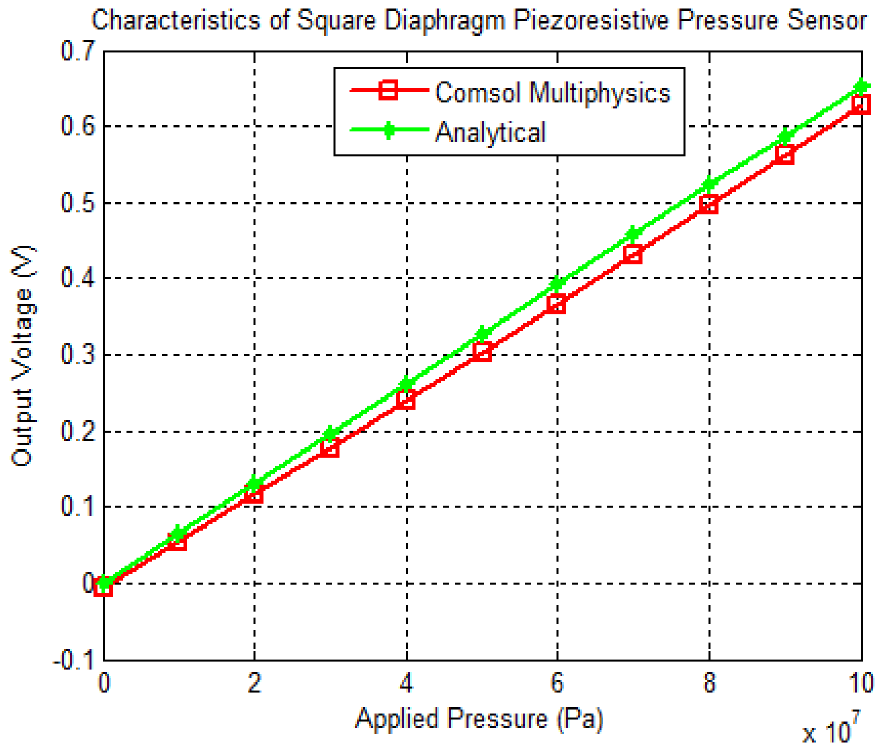
Displacement Profile and Potential Distribution of Model 4 [Stephen Senturia]

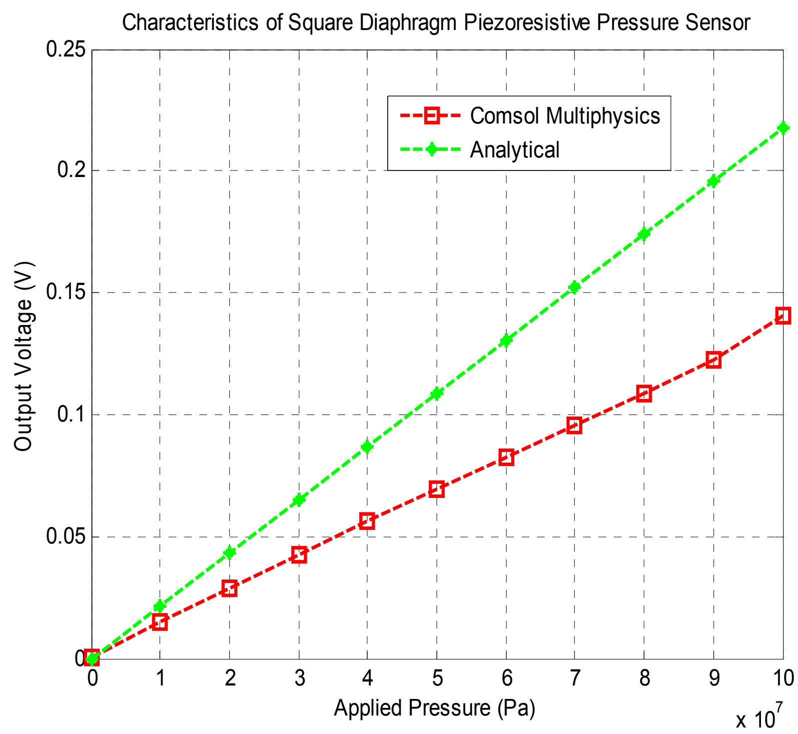




RESULTS AND DISCUSSION

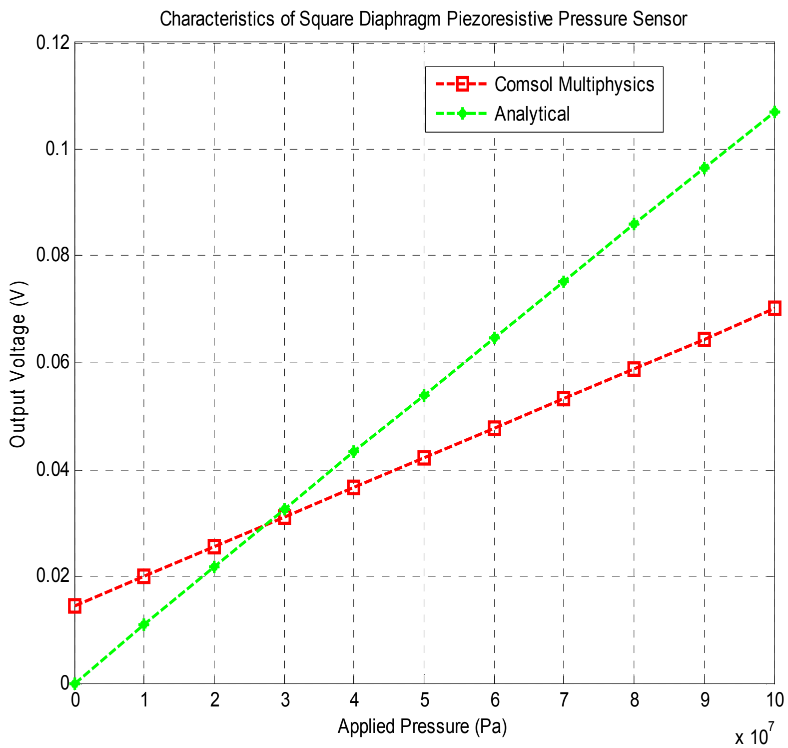
The analytical designs of all the sensors are simulated using Matlab using the expression given in 1.5 and the results are compared with the FEM models developed using Comsol Multiphysics, which are shown in figure.

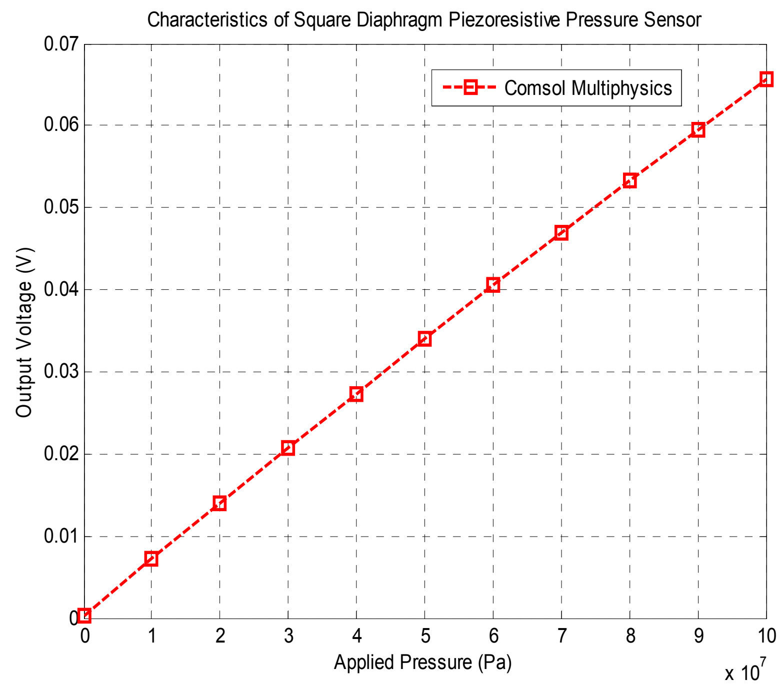




Characteristics comparison of Model 1 and Model 2

RESULTS AND DISCUSSION





Characteristics comparison of Model 3 and Model 4

Conclusion

It is observed that the output voltage values obtained from analytical equations are matching with the simulated results.

The analytical study of model 4 is not included in the scope of this work since the output voltage is taken across the resistor and requires further understanding. The sensitivity of each of the models are listed in table.

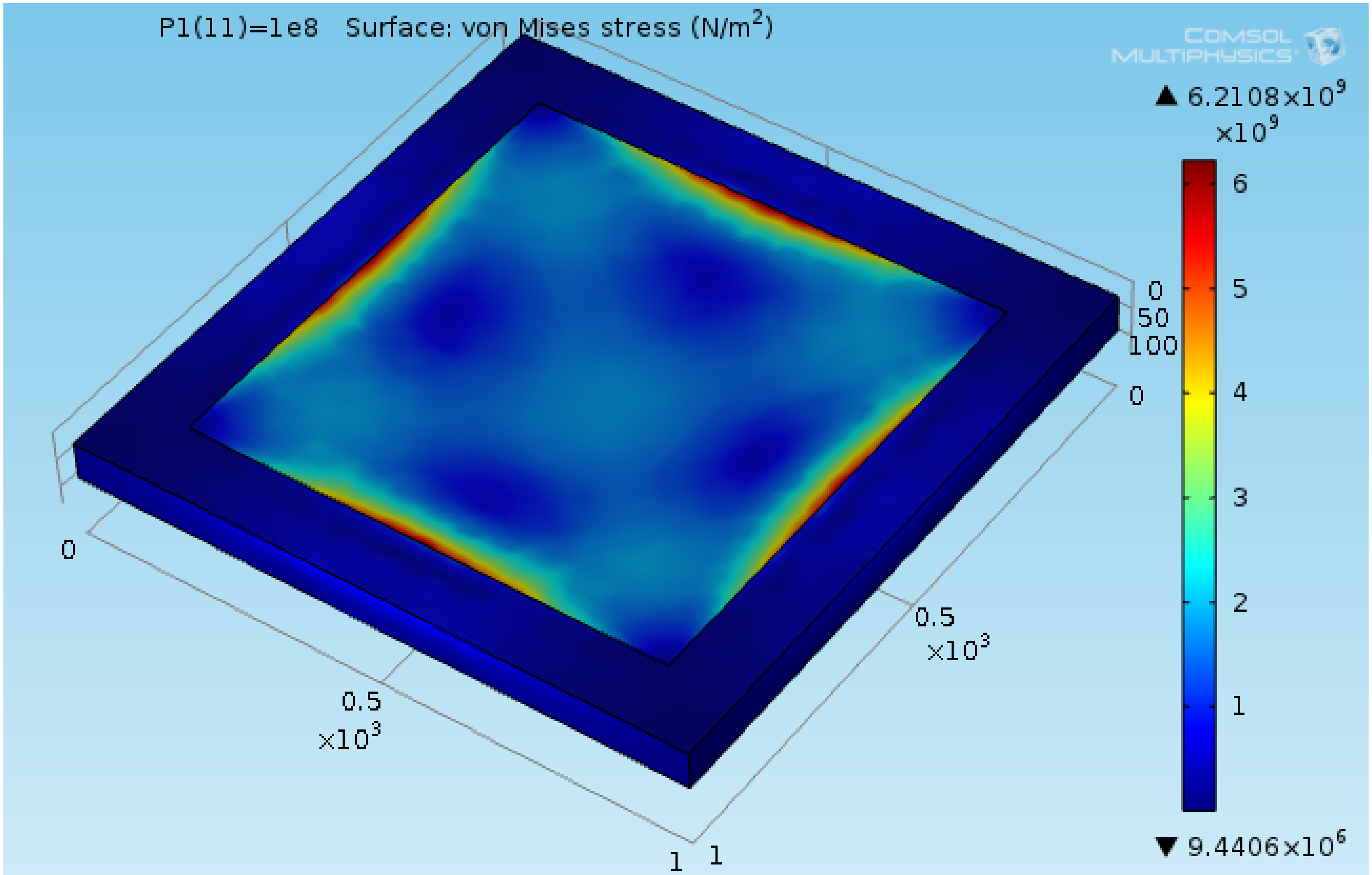
Models	Model 1 [Fuller]	Model 2 [M Bao]	Model 3 [Tai-Ran Hsu]	Model 4 [Stephen Senturia]
Sensitivity (mV/MPa)	6.657	1.854	0.562	0.617

From the table it can be concluded that the model proposed by Fuller gives a higher sensitivity of 6.657mV/MPa. Model 2 proposed by Bao also gives relatively higher sensitivity of 1.854mV/Mpa. The model 3 and 4 gives poor sensitivity for known reasons.

Conclusion

- The model 4 is not so recommended, as it suffers from temperature effects since it is not used in wheatstone bridge configuration.
- From the characteristics of model 3, it can be concluded that output voltage values obtained from analytical equations are deviating more for higher pressure with respect to simulated results.
- It can be justified that the stress variation over the edges vary drastically down towards its center, so that the stress is not constant over the piezoresistive area. It is mandatory for a design engineer to place the piezoresistor with in the maximum stress limits, which is normally a few microns from the edge. But in the analytical work stress is assumed to be constant throughout the piezoresistive structure and leads to higher output voltage.
- This can be avoided by reducing the length of piezoresistors which in turn reduce the sensitivity. Serpentine type of resistors are recommended to increase the sensitivity as used in model 1.

Conclusion



P1(11)=1e8 Surface: von Mises stress (N/m²)
COMSOL MULTIPHYSICS
▲ 6.2108×10⁹
×10⁹
6
5
4
3
2
1
▼ 9.4406×10⁶
0
50
100
0
0
0.5
×10³
0.5
×10³
1
1

References

- User Manual of Comsol Multiphysics 4.3A
- L. F. Fuller, S. Sudirgo, "Bulk micromachined pressure sensor", University / Government / Industry Microelectronics Symposium - UGIM, pp. 317-320, 2003.
- Minhang Bao, “Analysis and Design Principles of MEMS Devices”, 1st edition, Elsevier, pp.4-6, 2005.
- Tai-Ran Hsu, “MEMS and Microsystems Design and Manufacture”, 1st edition, Tata McGraw Hill Education Private Limited, pp.254, 2002.
- Stephen D. Senturia “Microsystem Design", Kluwer Academic Publishers, pp.481-485, 2002.
- S. Beebey, G. Ensell, M. Kraft, N. White (2004). “MEMS Mechanical Sensors, Artech House”, Boston.
- Warren C Young, Richard G. Budynas (2002). “Roark’s Formulas for Stress and Strain”, 7th edition, McGraw Hill, USA.

Thank you