Sensitivity Analysis of Different Models of Piezoresistive Micro Pressure Sensors

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Abstract:

Piezoresistive pressure sensors are receiving maximum attention over other type of sensors because of easiness of fabrication, low cost, simple measurement techniques, wide range of pressure sensing, etc. There is always a challenge in design with respect to appropriate positioning of piezoresistance, shape and temperature compensation. Different models of piezoresistive pressure sensors are proposed to enhance its sensitivity in terms of output voltage and linearity. This paper aims in sensitivity analysis of various models which are proposed in research papers.

Piezoresistive module of Comsol Multiphysics 4.3 is used to make a comparative study of all the models. All sensors used in this paper consist of a membrane, on which the pressure is applied and a surrounding fixed frame. The edge length of the square-membrane is 783 µm for each sensor. The edge length of the frame is 1000 µm and the thickness of both the membrane and the frame is 63 µm. The material of the whole diaphragm (membrane and frame) is single crystal, lightly doped n-silicon. The piezoresistance is of lightly doped p-silicon. A wheatstone bridge circuit is used for the measurement of change in resistance. The sensitivity and range of output voltage of each model is measured over an applied pressure range of 0 to 100MPa and compared. The merits and demerits are discussed as a result of the paper.

1. Introduction:

Piezoresistance is defined as a change in electrical resistance of solids when subjected to stress fields. Silicon piezoresistors that have such characteristics are widely used in microsensors and actuators. 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].

The schematic of a packaged pressure sensor is shown in figure 1.1. The top view of the silicon die shows four piezoresistors (R_1, R_2, R_3 and R_4) implanted beneath the surface of the silicon die. 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 as shown in figure.

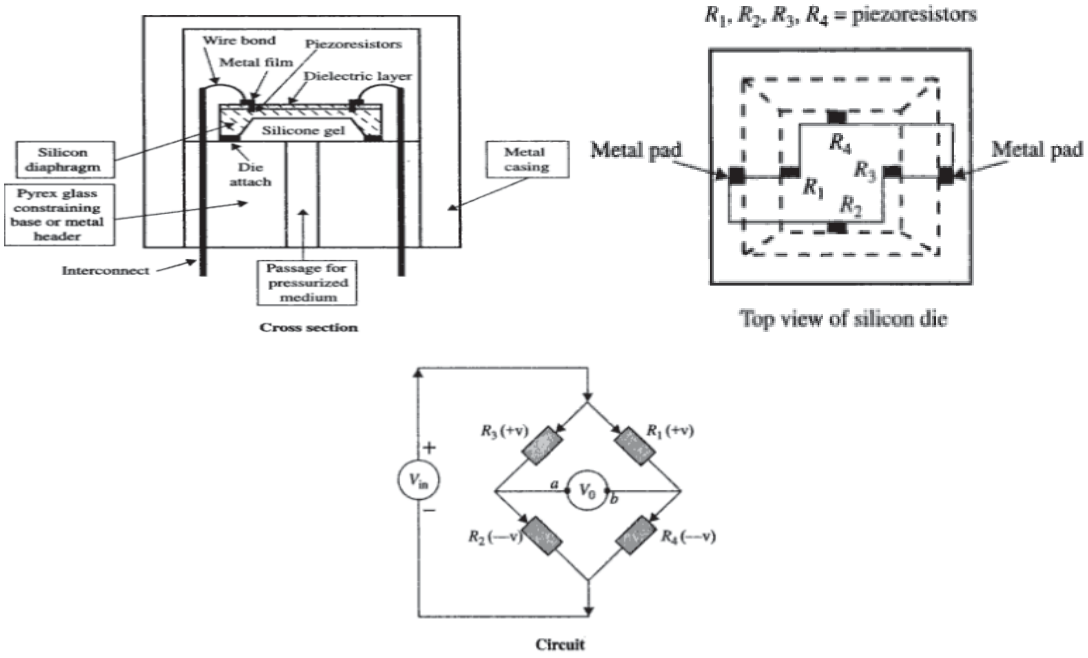

Fig. 1.1 Typical Piezoresistive Pressure Sensor Assembly

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

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

2. Sensor Models:

2.1 Model 1 - Piezoresistive Sensors by Lynn Fuller:

The structure proposed by [Lynn Fuller 2005] and its Comsol model are shown in figure 2.1. In this model, positions of the resistors are near the edges of the membrane (dashed line) because the piezoresistive effect depends on stress (respectively on strain) which is high near the fixed boarders. Considering the resulting distribution of stress, resistors R1 and R4 are arranged transversally and sensors R2 and R3 are arranged longitudinally. Because the strain decreases from the boarders to the center of the membrane, the longitudinal arranged resistors are divided into two shorter parts which are connected in series and positioned in a manner that a higher average strain is applied on the resistors in order to enforce the piezoresistive effect. An electric potential of 9V is applied between the metal pads A and C. The measured device output is the potential difference between the absolute values of the voltages at the metal pads B and D.

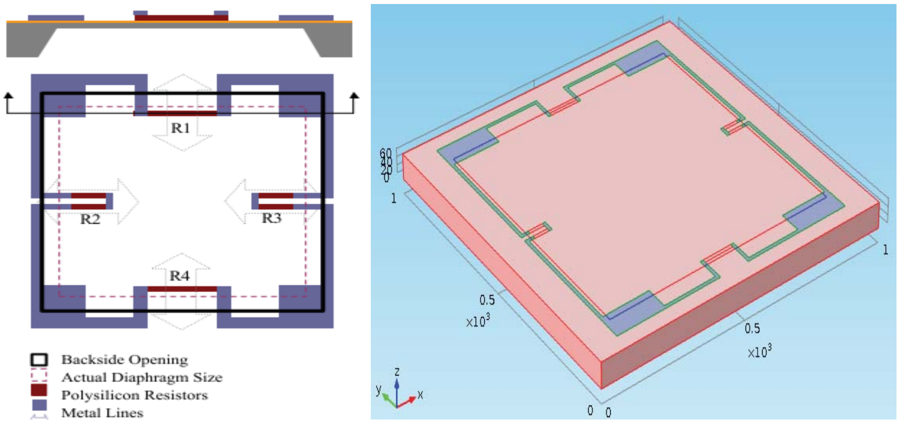

Fig 2.1 Piezoresistive Sensor by Lynn Fuller and its Comsol Model

2.2 Model 2 - Silicon pressure transducer by M Bao:

The structure proposed by [M.Bao 2005] and its Comsol model are shown in figure 2.2. In this model, all the four resistors are aligned along one edge in order to simplify the connections between them. The connection is realized using a wheatstone bridge again and is indicated by the grey areas in the figure. A potential difference of 3V is applied between the upper and the lower connection pad. The device output is the voltage between the middle connection pads. The analytical design of such a sensor is simulated using Matlab.

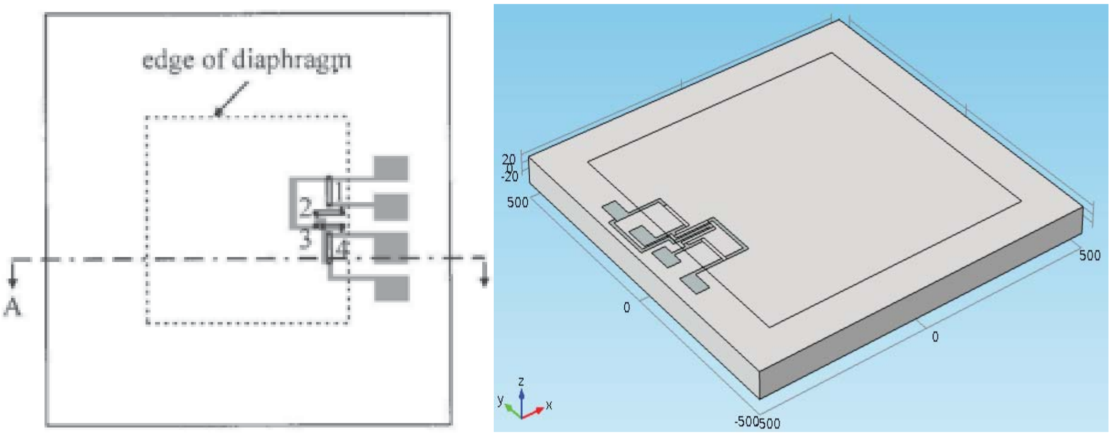

Fig 2.2 Piezoresistive Sensor by M Bao and its Comsol Model

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

The piezoresistive sensor proposed by Tai-Ran Hsu is shown in figure 2.3. The outer edges of them coincide with the edges of the membrane. Because the maximum stress appears in the middle of the edges of the membrane (next to the fixed frame) if a pressure is applied, the different alignment of the resistors concerning the directions of principal stress lead to different piezoresistive behavior. The piezoresistive layers are connected by conductive layers using a wheatstone bridge. This helps to reduce the effect of temperature changes of the piezoresistance. A potential difference of 5V is applied.

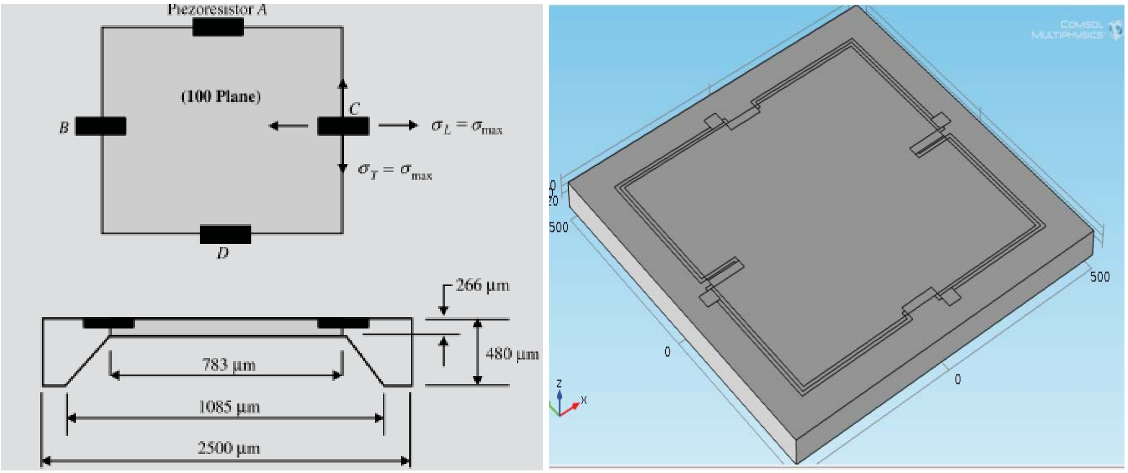

Fig 2.3 Pressure Sensor Die by Tai-Ran Hsu and its Comsol Model

2.4 Model 4 - Motorola Xducer piezoresistor:

The sensor has only one resistor which is oriented in a 45° degree angle to the side of the diaphragm edge and is situate near the membrane boarder as well as shown in figure 2.4. The resistor is connected to four contact pads which are highlighted by black colour in the figure. On two diagonally opposite connections a voltage of 3V is applied. The device output is measured between the two remaining contact pads.

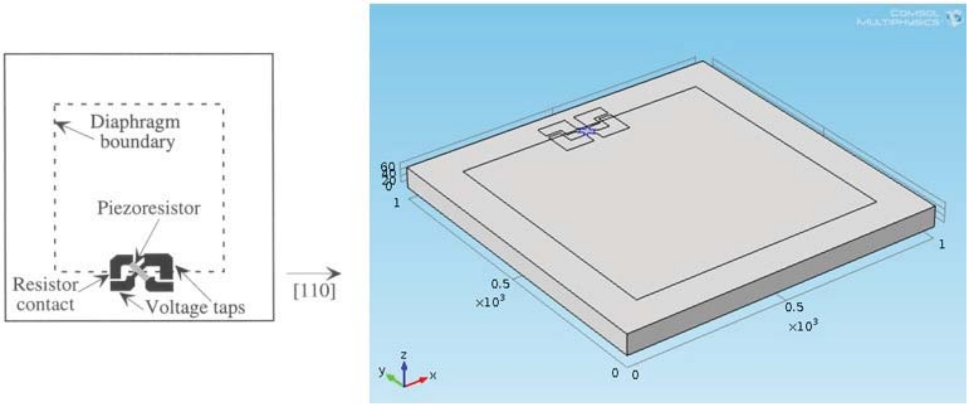

Fig 2.4 Motorola Xducer piezoresistor by Stephen Senturia and its Comsol Model

3. Modelling Using Comsol Multiphysics:

The sensors are, as mentioned above, modelled by using Comsol Multiphysics 4.3. For the purpose of this work, piezoresistive physics for boundary currents are chosen as the environment for the analysis. The additional term “boundary currents” is selected because the examined piezoresistive effects appear only in very thin layers which are applied on the diaphragm.

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, 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. The material properties like Young’s Modulus or Poisson Ratio are set according to the given literature.

After this, the structural, electrical and piezoresistive properties of the model were defined. The lower side of the frame is defined a fixed and a pressure is applied on the upper side of the membrane as boundary load. 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 a voltage, usually 3V, is applied between them. For easier analysis of the terminal current an average 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 mesh for the FEM analysis is built by the software on the base of the defined physics. The element size is defined as “finer”. Because of the simple geometry and the consideration of only a few physical effects, the computer generated mesh is sufficient and does not have to be optimized by user controlled settings in order to decrease the time which is needed for the numerical analysis.

4. Results of the study:

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 4.1 to 4.4.

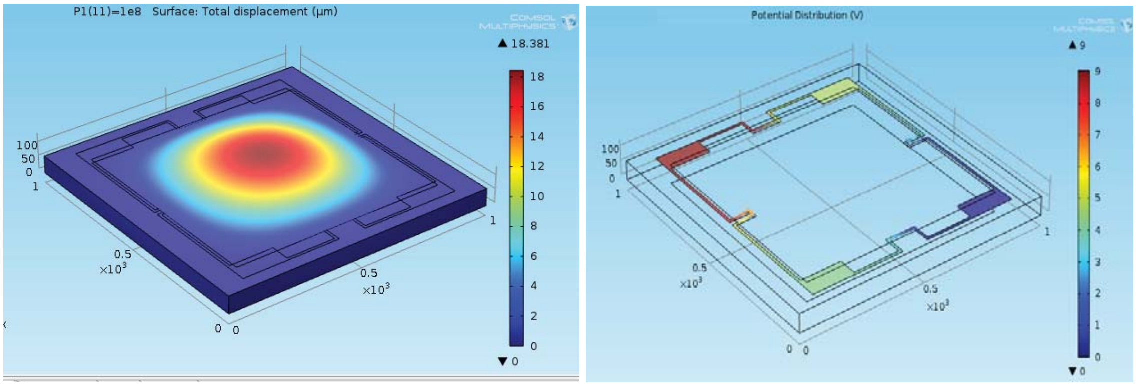

Fig 4.1 Displacement Profile and Potential Distribution of Model 1 [Lynn Fuller]

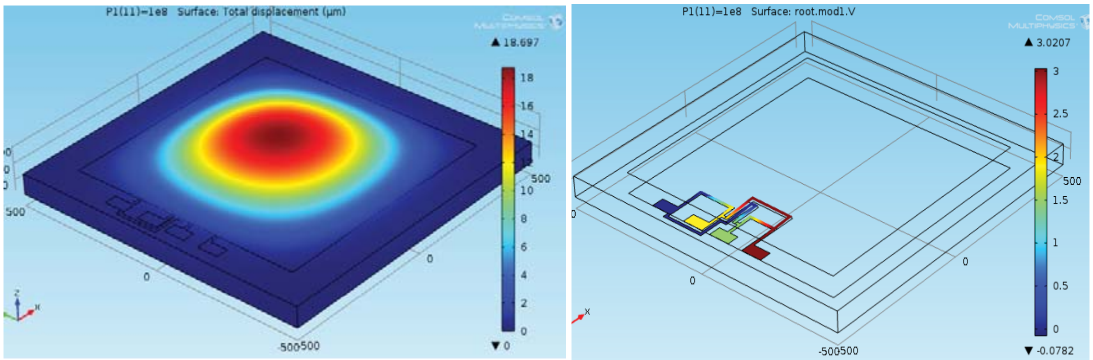

Fig 4.2 Displacement Profile and Potential Distribution of Model 2 [M Bao]

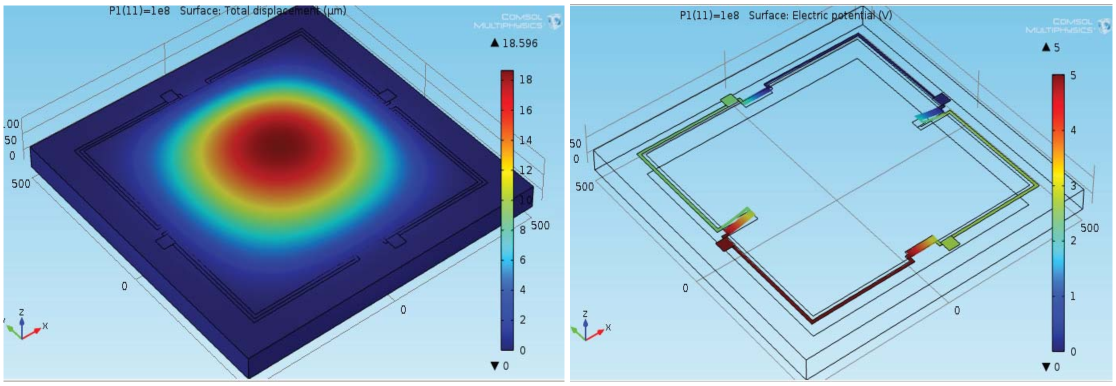

Fig 4.3 Displacement Profile and Potential Distribution of Model 3 [Tai-Ran Hsu]

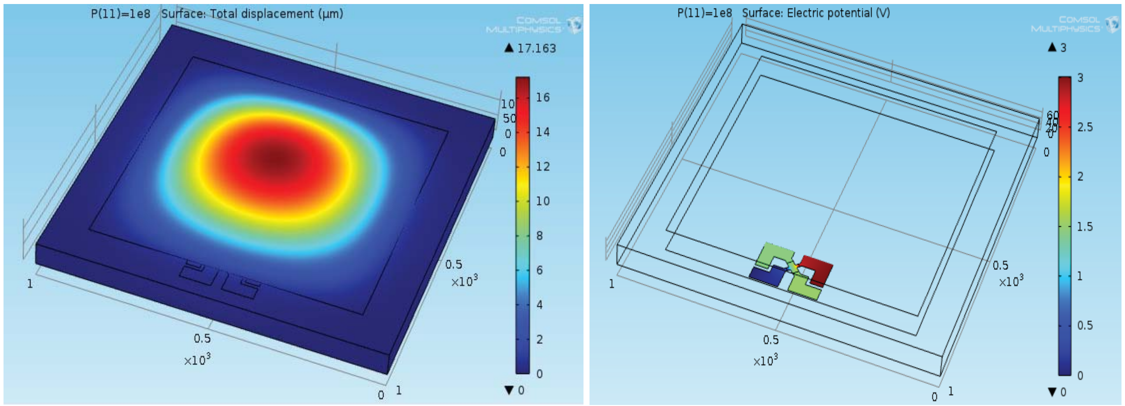

Fig 4.4 Displacement Profile and Potential Distribution of Model 4 [Stephen Senturia]

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 4.5 to 4.8.

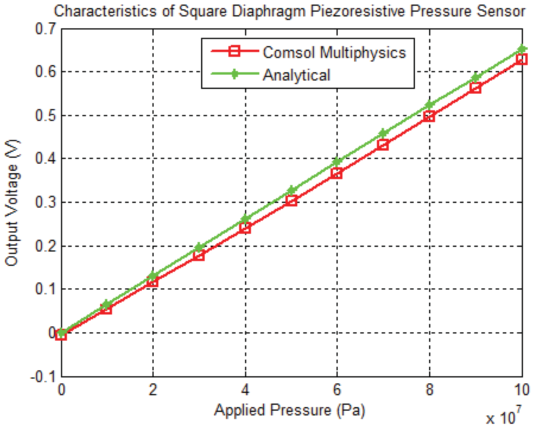

Fig 4.5 Characteristics of Piezoresistive Sensor of Model 1 [Lynn Fuller]

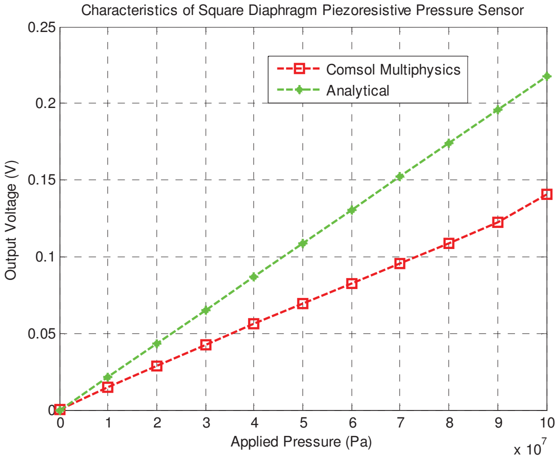

Fig 4.6 Characteristics of Piezoresistive Sensor of Model 2 [M Bao]

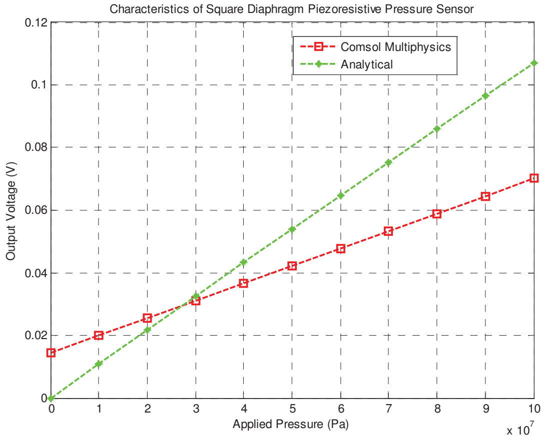

Fig 4.7 Characteristics of Piezoresistive Sensor of Model 3 [Tai-Ran Hsu]

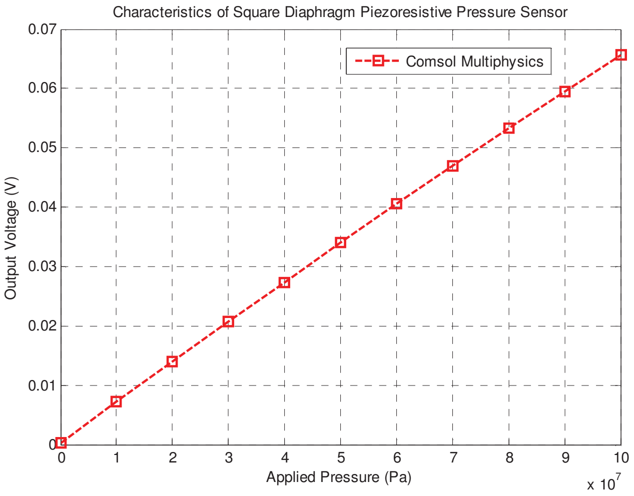

Fig 4.8 Characteristics of Piezoresistive Sensor of Model 4 [Stephen Senturia]

5. 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 5.1. It can also be observed that all the models are giving a highly linear ouput with respect to input applied pressure.

Table 5.1 Characteristics of Piezoresistive Sensor Models

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. From the analysis it can be understood that serpentine type of resistance can be more preferred for better sensitivity than any other configuration.

The model 4 is not so recommended, as it suffers from temperature effects since it is not used in wheatstone bridge configuration. From the figure 4.7, 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 noramally a few microns from the edge. But in the analytical work stress is assumed to be constant throughout the piezo resistive 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.

References:

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