MEMS Based Silicon Load Cell for Weighing Applications

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Abstract: Load cells are force sensors, which are used in weighing equipment. The objective of this work is to develop MEMS based load cell. In this work two different load cell designs are simulated. First design is based on compressing a meander like polysilicon strain gage for the measurement of high forces up to 10kN. Second design is based on MEMS pressure sensor consisting of membrane, on which force (up to 500N) is applied keeping the surrounding frame fixed. The simulation results depicts the sensitivity and range of output voltage for both load cells measured over range of applied forces.

Keywords: MEMS, Piezoresistance, Force sensor, Load cell, Simulation, Finite Element Modeling

1. Introduction

A load cell is a transducer which converts force into an electrical signals. Through mechanical deformation, an applied force can be measured electrically. Conventional load cells are made from steel or aluminium. When a load is applied, the metal part of the load cell deforms, which is measured by resistive strain gauges. To minimise hysteresis and creep, it is advantageous to make a load cell of silicon because in contrast to metals it does not suffer from hysteresis and creep.

MEMS piezoresistive strain sensors are preferred because of high sensitivity, low noise, better scaling characteristics, low cost, wide range of Force measurement etc. Furthermore, piezoresistive strain sensors need less complicated conditioning circuit.

2. Piezoresistance and its coefficients

Piezoresistivity is the material property defined as change in the bulk resistivity due to an applied stress or strain. Piezoresistance coefficients, π, relates the change in resistivity to stress and are expressed in Pa^{-1}. The π coefficients are derived by Ohm's Law to relate the electric field vector $\underset{E}{\rightarrow}$ to the current vector $\underset{J}{\rightarrow}$ by 3x3 resistivity tensor ρ:

$$\begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} = \begin{bmatrix} \rho_1 & \rho_6 & \rho_6 \\ \rho_6 & \rho_2 & \rho_4 \\ \rho_5 & \rho_4 & \rho_3 \end{bmatrix} \begin{bmatrix} J_1 \\ J_2 \\ J_3 \end{bmatrix} \tag{1}$$

For silicon and other crystals in the cubic family, the first three resistivity terms ρ_1, ρ_2, ρ_3, which represent resistivity along <100> axes, are identical:

$$\rho_1 = \rho_2 = \rho_3 = \rho \tag{2}$$

And the terms ρ_4, ρ_5, ρ_6, which relate the electric field in direction to perpendicular current, are zero:

$$\rho_4 = \rho_5 = \rho_6 = 0 \tag{3}$$

For a stressed crystal, the resistivity components are expressed by

$$\begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \\ \rho_5 \\ \rho_6 \end{bmatrix} = \begin{bmatrix} \rho \\ \rho \\ \rho \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} \Delta\rho_1 \\ \Delta\rho_2 \\ \Delta\rho_3 \\ \Delta\rho_4 \\ \Delta\rho_5 \\ \Delta\rho_6 \end{bmatrix} \tag{4}$$

Where $\Delta\rho_i$ is the change in resistivity due to stress, which is related to the piezoresistance coefficients and the stress by a 6x6 tensor, which for an isotropic material with cubic crystalline structure, reduces to three non-zero terms $\pi_{11}, \pi_{12}, \pi_{14}$. These coefficients relate the fractional change in resistivity in six crystal directions (figure 1) to the stress by

$$\frac{1}{\rho}\begin{bmatrix} \Delta\rho_1 \\ \Delta\rho_2 \\ \Delta\rho_3 \\ \Delta\rho_4 \\ \Delta\rho_5 \\ \Delta\rho_6 \end{bmatrix} = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} + \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_1 \\ \tau_2 \\ \tau_3 \end{bmatrix} \tag{5}$$

This relationship can be applied to Equation (1) to relate the electric field with applied stress by:

$$E_1 = \rho J_1 + \rho\pi_{11}\sigma_1 J_1 + \rho\pi_{12}(\sigma_2 + \sigma_3)J_1 + \rho\pi_{44}(J_2\tau_3 + J_3\tau_2) \quad (6)$$

$$E_2 = \rho J_2 + \rho\pi_{11}\sigma_2 J_2 + \rho\pi_{12}(\sigma_1 + \sigma_3)J_2 + \rho\pi_{44}(J_1\tau_3 + J_3\tau_1) \quad (7)$$

$$E_3 = \rho J_3 + \rho\pi_{11}\sigma_3 J_3 + \rho\pi_{12}(\sigma_1 + \sigma_2)J_3 + \rho\pi_{44}(J_1\tau_2 + J_2\tau_1) \quad (8)$$

To analyze piezoresistance in various crystal directions and orientations, longitudinal, π_l and transverse, π_t piezoresistance coefficients are calculated using statistical averaging techniques. These coefficients are related to principle piezoresistance terms by:

$$\pi_l = \pi_{11} + 2(\pi_{44} + \pi_{12} - \pi_{11})(l_1^2 m_1^2 + l_1^2 n_1^2 + m_1^2 n_1^2) \quad (9)$$

$$\pi_t = \pi_{12} + 2(\pi_{11} - \pi_{12} - \pi_{44})(l_1^2 l_2^2 + m_1^2 m_2^2 + n_1^2 n_2^2) \quad (10)$$

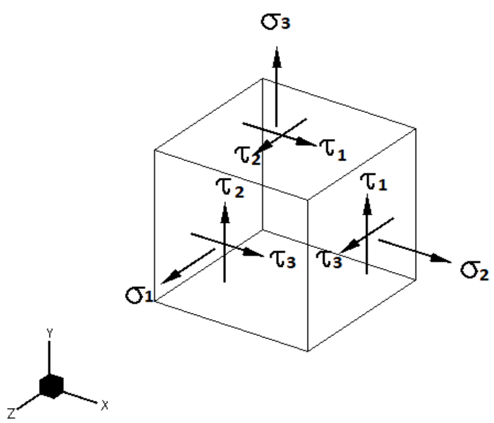


Figure 1. Stress element showing the principal stresses

Where l, m, n are direction cosines of the crystal lattice. The longitudinal and transverse π coefficients allow the calculation of the fractional change in resistivity along the direction of applied stress and transverse or perpendicular to applied stress, as expressed by:

$$\frac{\Delta\rho_l}{\rho_l} = \pi_l \sigma_l \quad (11)$$

$$\frac{\Delta\rho_t}{\rho_t} = \pi_t \sigma_t \quad (12)$$

Although π_t and π_l coefficients provide a more general application of principle piezoresistance coefficients, these should only be directly applied to single crystal silicon. In order to apply them to a polycrystalline material, a weighted average of the piezoresistance effect in various crystal directions must be employed. This is accomplished using the texture function, which express the probability of specific grain orientations. Average longitudinal and transverse piezoresistance coefficients are calculated as:

$$< \pi_l >= \pi_{11} - 0.400(\pi_{11} - \pi_{12} - \pi_{44}) \quad (13)$$

$$< \pi_t >= \pi_{11} + 0.133(\pi_{11} - \pi_{12} - \pi_{44}) \quad (14)$$

3. Concept and Sensor Design

3.1. Design 1: Meander Shaped Polysilicon Piezoresistive Silicon Load Cell

In sensor design 1, the load cell is placed between two pressing blocks. The force which is to be measured is applied on these blocks and the output is independent of the stress distribution and sensor is able to compensate for local temperature changes.

Figure 2 shows top and cross-sectional view of 0.5 by 0.5mm silicon chip. Two polysilicon piezoresistors (100µm thick) are deposited on it. Piezoresistor 1 is deposited on top of the chip and it is directly loaded/compressed with pressing blocks. Piezoresistor 2 is situated in grooves (10µm) in the substrate which is not directly loaded.

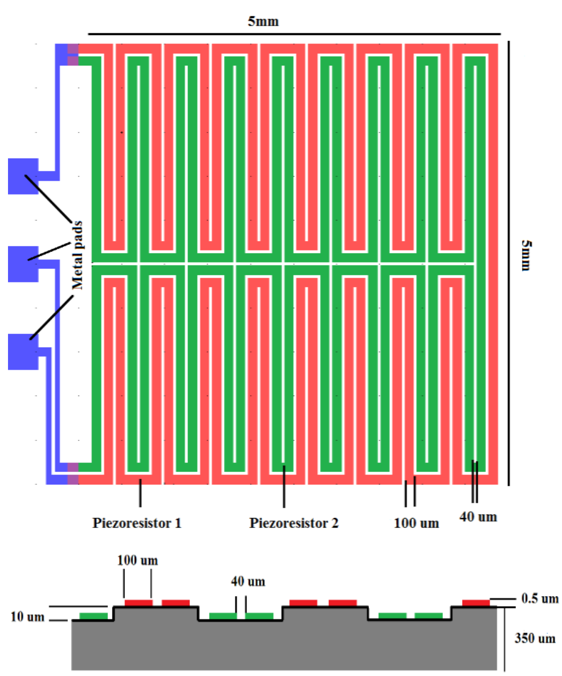


Figure 2. Top and cross-sectional view of load cell

The relative change of resistance $(\Delta R/R)$ in Piezoresistor 1 can be written as:

$$\frac{\Delta R_1}{R} = \pi_l(K_1\sigma_1) + \pi_t(K_2\sigma_1 + \sigma_1) + \alpha T \qquad (15)$$

Similarly, for Piezoresistor 2

$$\frac{\Delta R_2}{R} = \pi_l(K_3\sigma_1) + \pi_t(K_4\sigma_1) + \alpha T \qquad (16)$$

Where $K_1 = {\sigma_2^1}/{\sigma_1}$, $K_2 = {\sigma_3^1}/{\sigma_1}$, $K_3 = {\sigma_2^2}/{\sigma_1}$ and $K_4 = {\sigma_3^2}/{\sigma_1}$, depends on Poison's ratio and geometry.
On subtracting equations (15) and (16)

$$\frac{R_1 - R_2}{R} = \pi_l(K_1 - K_3) + \pi_t(1 + K_2 + K_4)\sigma_1 \quad (17)$$

The change in resistance under applied load and corresponding stress along the z-axis is $\sigma_1 = {F}/{WL}$, Where F is the applied force, W is the width of the Piezoresistor and L is the total length of Piezoresistor.

$$\frac{R_1 - R_2}{R} = K\frac{F}{WL} \qquad (18)$$

Where $K = \pi_l(K_1 - K_3) + \pi_t(1 + K_2 + K_4)$.

Potential divider arrangement shown in Figure 3 is used for the measurement of change in output voltage under applied load.

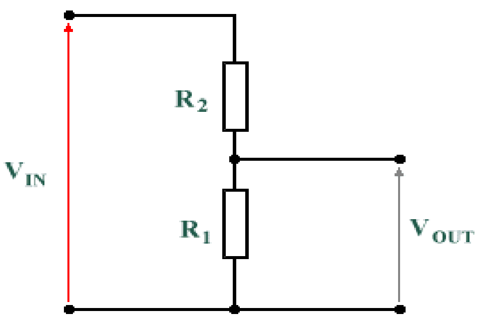


Figure 3. Potential divider for measurement of change in output voltage

3.2. Design 2: Pressure sensor based Piezoresistive Silicon Load Cell

This sensor design utilizes pressure applied on diaphragm to determine the applied force. Pressure (P) is related to the force (F) and area of contact (A) by $P = {F}/{A}$. Figure 4 shows four piezoresistors R_1, R_2, R_3 and R_4 (each 30 µm thick) deposited on the top surface of silicon membrane. R_1 and R_4 are arranged transversally and piezoresistor R_2 and R_3 are arranged longitudinally. These piezoresistors convert the stresses induced in the silicon membrane by applied load into change in electrical resistance, which is then converted into voltage output by a Wheatstone bridge circuit as shown in figure 5.

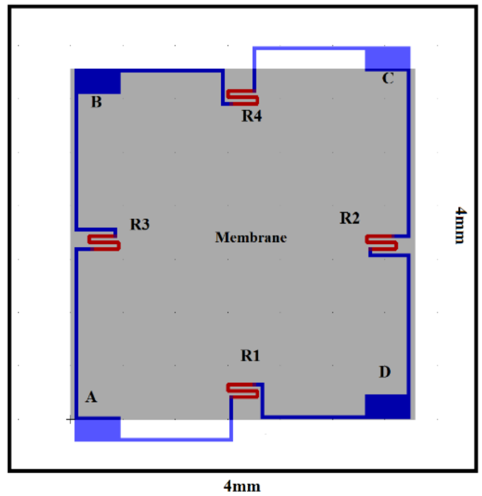


Figure 4. Top view of Pressure Sensor based Silicon Load cell

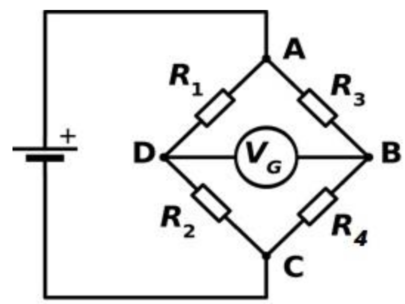


Figure 5. Wheatstone bridge circuit used for measurement of change in electrical resistance

The governing equation for membrane displacement under a uniform pressure loading p is

$$\frac{\partial^4 w}{\partial x^4} + 2\frac{\partial^4 w}{\partial x^2\,\partial y^2} + \frac{\partial^4 w}{\partial y^4} = \frac{P}{D} \qquad (19)$$

The maximum displacement at the center (w_{center}) of rectangular diaphragm (with dimension of a x b) under a uniform pressure p is

$$w_{center} = \frac{\alpha p b^4}{E t^3} \qquad (20)$$

The value of proportionality constant α determined by the ratio of a to b.

An electric potential of 5V is applied between metal pads A and C. The output is the potential difference between the values of voltages at metal pads B and D. The output of Wheatstone bridge is given by:

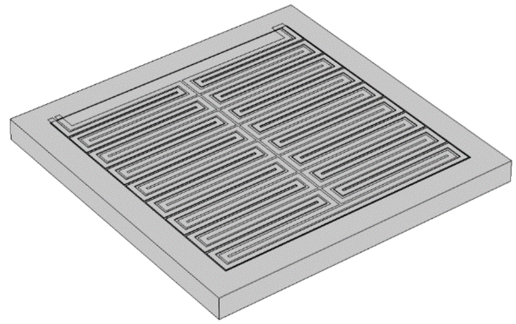
$$V_G = V_S\left(\frac{R_2}{R_1+R_2} - \frac{R_4}{R_4+R_3}\right) \tag{21}$$

4. Modelling using Comsol Multiphysics

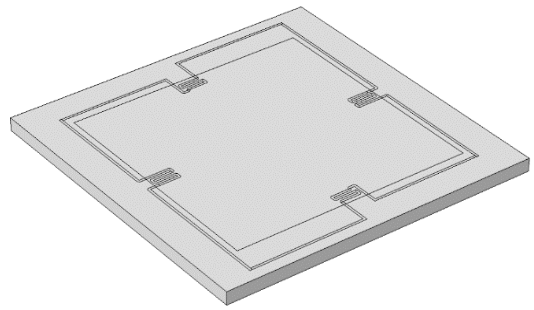
Both the sensor design are modeled by using Comsol Multiphysics 4.3a. Piezoresistivity, boundary current (pzrb) physics under Structural mechanics module is used to design and simulate various model of Load cell. The sensors used for simulations consists of lightly doped p-type polysilicon deposited on top of device (Design 1) or on a membrane (Design 2) on which the force is applied. The material used for the frame/membrane is single crystal lightly doped n-type silicon.

The geometry is created using block of the required values of width, depth and height. A 2-D work plane is defined on the top of block on which geometry of piezoresistors and connections are defined. Aluminium is used as metal interconnect between piezoresistors. Default values of material properties given in Comsol Multiphysics are used for the purpose of simulation. Next step is to define structural, electrical and piezoresistive properties of our sensor models. For the sensor design 1 fixed constraint is applied on the bottom of block i.e. the lower side of the block is kept fixed and load is applied on the top of the block as boundary load. Piezoresistor 2 is situated under the 10µm deep grooves hence only piezoresistor 1 is loaded. In case of sensor design 2 the all the surface of block except top and bottom are kept fixed and load is applied on the top of membrane. The areas within the boundary of connections are defined as thin conductive layer of thickness 500nm and the area within the boundaries of piezoresistors are defined as thin piezoresistive layer of thickness 500 nm. Electrical properties are set by defining ground and terminal at the connection pads. Terminal is set to 5V. The mesh for FEM analysis is built using defined physics. The element size is set to fine. The Comsol Model of sensor design 1 and 2 is shown in figure 6.

Simulation of design 1 is carried out using parametric sweep from 0N to 10kN, in steps of 500N is applied and for design 2 parametric sweep from 0N to 500N using step size of 10N is applied. In order to determine voltage at output terminals of voltage divider (design 1) or Wheatstone bridge (design 2) an average is defined over the boundaries/edges enclosing the output pads.



(a)

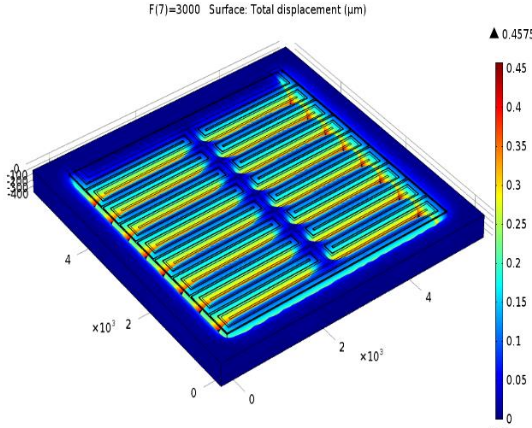


(b)

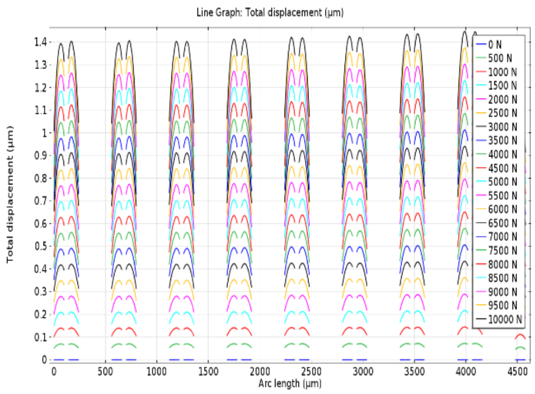
Figure 6. Comsol Models of Load cell (a) Sensor design 1: (b) Sensor design 2

5. Results

The displacement profile, potential distribution of the sensor design 1 are shown in figure 7 and figure 8 represents its output characteristics.



(a)



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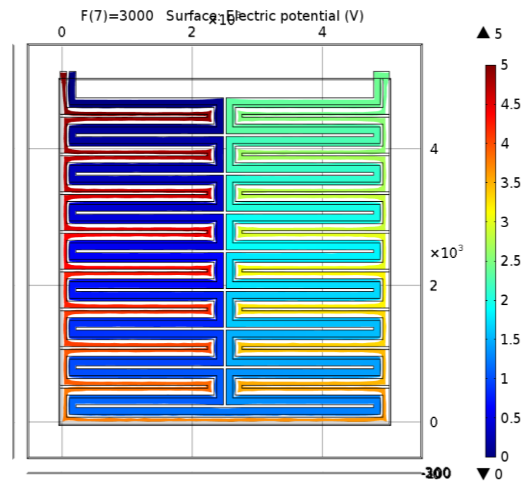


(c)

Figure 7. (a) Displacement profile, (b) Total displacement along the length of sensor under applied loads and (c) Potential distribution for sensor design 1.

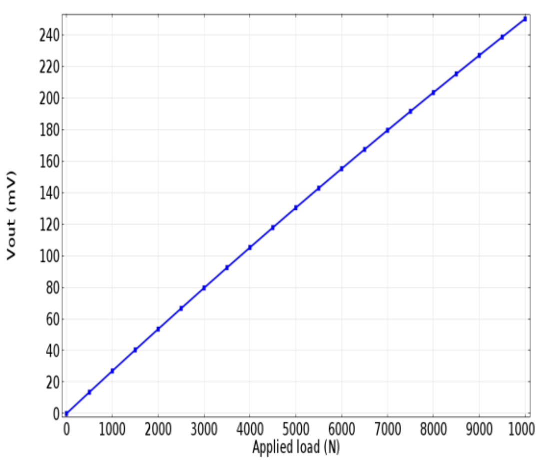
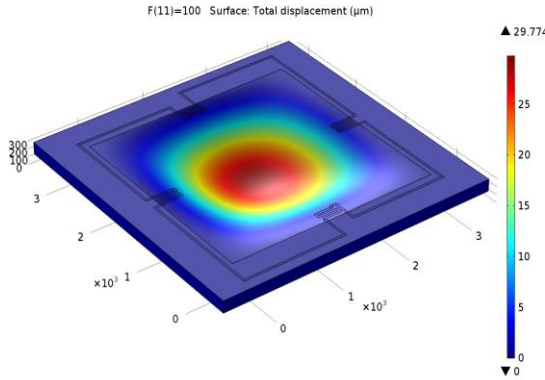
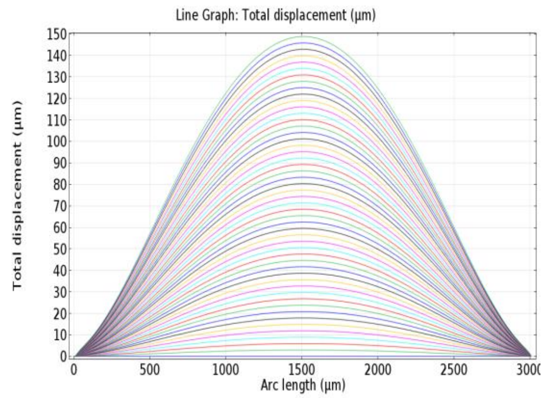


Figure 8. Output characteristics of sensor design 1 (Vout vs Applied load)

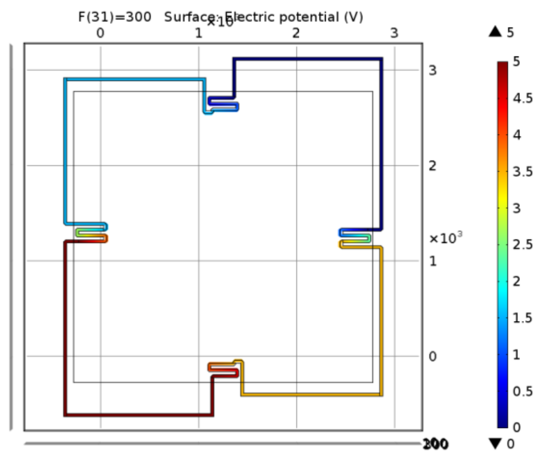
Similarly the displacement profile, potential distribution and output characteristics for sensor design 2 are shown in figures 9 and 10.



(a)



(b)



(c)

Figure 9. (a) Displacement profile, (b) Total displacement of membrane along its length under applied loads and (c) Electric potential distribution for sensor design 2.

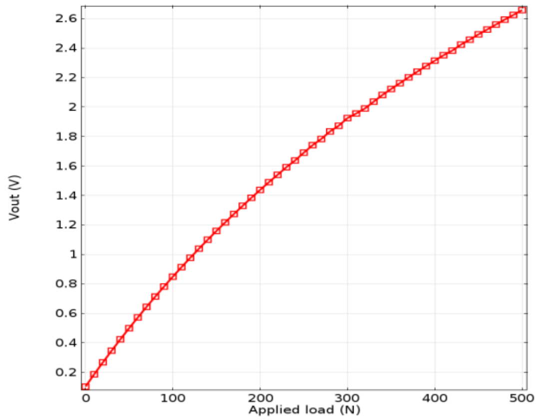


Figure 10. Output characteristics of sensor design 2 (Vout vs Applied load)

6. Conclusion

Sensor design 1 is simulated for loads up to 10kN and maximum change in output voltage obtained using Potential divider arrangement is 250.03 mV at 10kN. Maximum output voltage obtained with sensor design 2 under maximum load of 500 N is 2.65 V.
The sensitivity of each of the model is listed in table 1 below.

Models	**Meander Shaped Polysilicon Piezoresistive Silicon load cell**	**Pressure sensor based Piezoresistive silicon load cell**
Sensitivity	49.06µV/V/Kg	10.29mV/V/Kg

Table 1. Sensitivity of Sensor designs

From the table above, it can be concluded that Model 2 has higher sensitivity. It is evident from figure 10 that the output of model 2 tends to become nonlinear for higher load values and hence drop in the sensitivity occurs. For better results and accuracy it is recommended to used model 2 for the measurement of loads up to 250-300N. On the other hand Model 1 has a very low sensitivity as compared to model 2, which makes this model applicable only for measuring of high forces up to 10kN. Furthermore the sensitivity of model 1 can be increased by using a total of four piezoresistors out of which two are active and remaining two are dummy gauges, arranged in Wheatstone bridge configuration.

7. References

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