Finite Element Analysis of MEMS based Piezoresistive Diamond Thin Film Cantilever Pressure Sensor

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Abstract - *MEMS (Micro-Electro-Mechanical Systems) technology is an emerging technology, now-a-days, which consists of both electrical and mechanical components integrated on the same chip. The main objective of this paper is to design and simulate the cantilever based pressure sensor using MEMS technology. Performance parameters such as stress, deflection and sensitivity has been studied and compared for the cantilever using different materials i.e. diamond and poly-silicon. Ultrananocrystalline diamond (UNCD) technology may be used for producing diamond thin film (DTF). Four piezoresistors of p-type silicon are incorporated on the sensor in wheat stone bridge configuration. The stress is being induced in the structure, on the application of external pressure, which changes the electrical resistance of the piezoresistor. The output voltage is then calculated from the change in resistance. The simulated results depicts that cantilever designed with DTF gives sensitivity of 6.92 × 10*$^{-10}$*mΩ/kPa which is higher as compared to the cantilever designed with poly-silicon. The simulation is done using software COMSOL Multiphysics 4.4.*

Key Words: **MEMS pressure sensor, cantilever, stress, deflection, sensitivity, UNCD, DTF.**

1.INTRODUCTION

Micro Electro Mechanical System (MEMS) pressure sensors play a vital role in both industrial as well as commercial sector. A pressure sensor is a device which is used to measure pressure, acts as a transducer generating a signal as a function of the pressure [1]. The study of micro-cantilevers is one of the most important application of the MEMS technology. Nallathambi [2] discussed design which uses finite element analysis to simulate the geometrical specifications for poly silicon placed piezoresistive micro cantilevers sensor. The displacements and the variation of the change in the resistance to the original resistance of the cantilevers were also examined. Abdul-Aziz Yousif Ahmed et al. [3] analyzed the existing commercial sensing technology which shows that micro cantilever sensors must satisfy the variable properties such as better sensitivity, cheaper cost, smaller in size and reliability.

The main objective of this paper is to design a cantilever based pressure sensor with higher sensitivity. The sensitivity of the sensor depends upon the various parameters such as shape and size of the cantilever, material of cantilever, placement of the piezoresistors etc. The parameter taken in the respective simulation is the selection of the material.

In the first simulation, cantilever is designed using poly-silicon as a material. The stress, resistance and the sensitivity is calculated. In the second simulation, cantilever is designed using diamond thin film (DTF) as a material on the silicon base. Similarly stress, resistance and sensitivity is determined. The results of both the studies are then compared. The simulation is done using COMSOL Multiphysics 4.4. The final results show that the cantilever designed with DTF gives higher sensitivity as compared to cantilever designed with poly-silicon.

2. MEMS PIEZORESISTIVE SENSORS

2.1 Piezo Resistive Effect

The piezo-resistive effect can be defined as the variation of the change in electrical resistance to the original resistance on the application of force to the resistor. It is expressed by the given equation 1,

$$G = \frac{\Delta R}{R\sigma} \tag{1}$$

where G = Gauge Factor
ΔR = Change in Resistance
R = Original Resistance
σ = Stress Induced

The resistance R of a resistor of length L, width W, thickness t and the resistivity ρ, is expressed by the relation,

$$R = \frac{\rho L}{Wt} \tag{2}$$

where ρ = Resistivity of the Material
L = Length
W = Width and t = Thickness

2.2 Design of Sensor

The performance of the piezoresistive pressure sensor depends on the dimensions, material of the cantilever and the position of the piezoresistors on the cantilever. In order to obtain high deflection, the thickness of the cantilever should be small [4]. The dimensions for the cantilever and piezoresistors used in simulation are stated in Table 1.

Table -1: Dimensions for Cantilever and Piezoresistor

	Length	Width	Thickness
Cantilever	1000μm	200 μm	10 μm
Piezoresistor	110 μm	70μm	400nm

MEMS pressure sensor uses a piezoresistor as a electrical component and cantilever as a mechanical component. The cantilever is designed using DTF as a material placed on the silicon base. Diamond has a Young modulus (1100GPa) which is much higher than poly-silicon (160GPa) which relates to stress, indicating the stiffness of material, thereby making it a unique material for the MEMS technology. The four piezoresistors are generally arranged in the form of a Wheatstone bridge over the structure to derive the electrical output as shown in Fig -1 [5].

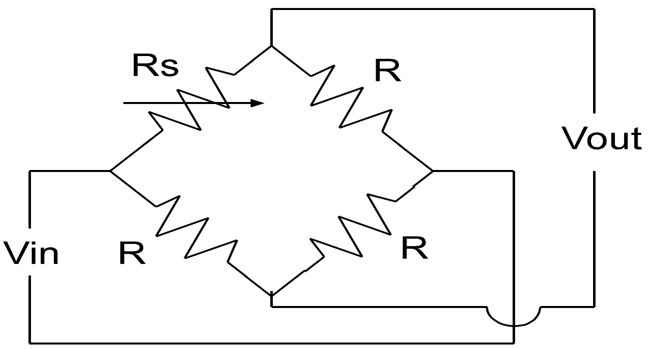


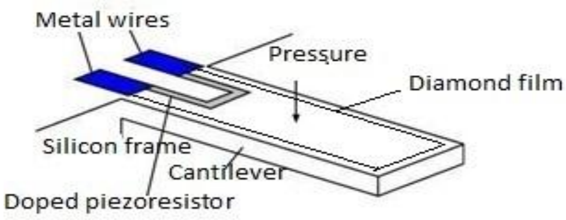
Fig -1: Schematic Representation of Wheatstone Bridge Circuit.

When there is no applied pressure, the bridge will be in balanced condition and there will no output. When pressure is applied, the cantilever will deform and there will be a change in resistance in one of the four resistors which is placed on the cantilever.

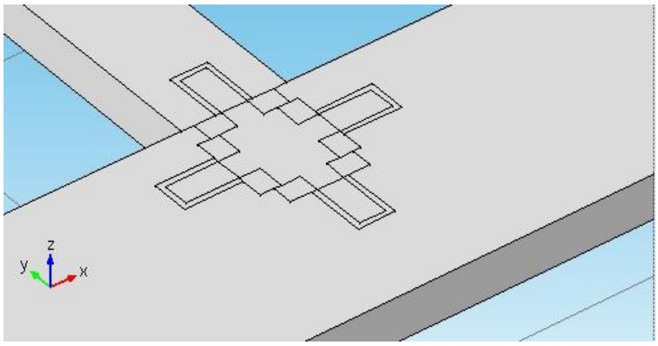
If all the change in resistance is equal then the output voltage will be [5]

$$V_{out} = -\frac{\Delta R/2}{2R+\Delta R} \cdot V_{in} \quad (3)$$

The Fig -2(a) shows one of the four similar piezoresistors placed on the cantilever while Fig -2 (b) shows the overall placement of all four piezoresistors in wheat stone bridge configuration on the sensor.



(a)



(b)

Fig -2: Structure of Cantilever: (a) Cantilever with Piezoresistor Incorporated on it. (b) Placement of Four Piezoresistors on the Sensor

The material used for piezoresistor is p type silicon with a dopant density of 1.32×10^{19}(1/cm3). The external pressure is applied to the mechanical structure due to which stress is induced in the structure which further leads to the deformation of the structure. This stress is converted into the change in resistance by the piezoresistors [2]. The applied stress is related to the change in resistance by the piezo resistive coefficients. For a piezoresistor which is subjected to longitudinal and transverse stress, the change in resistance is defined by equation 4,

$$\Delta R/R = \pi_l \sigma_l + \pi_t \sigma_t \quad (4)$$

Where
π_l and π_t is Longitudinal and Tangential Piezoresistive Coefficient,
σ_l and σ_t is Longitudinal and Tangential Stress in Cantilever
R = Original Resistance.

The deflection in cantilever can also be calculated using modified Stoney's formula [4],

$$\delta = \frac{3\sigma l^2(1-\vartheta)}{t^2 E} \quad (5)$$

Where υ = Poisson's Ratio
σ = Stress Induced in the Material
E = Young's Modulus
l = Beam Length
t = Cantilever Thickness

3. SELECTION OF MATERIAL

Diamond is coming out as an emerging material for the MEMS devices. It has more hardness, roughness, high young's modulus (1100 GPa), high mechanical strength, low coefficient of friction as compared to the poly-silicon. The key issues to wide adoption of diamond-based MEMS sensor are cost and performance [6]. Both of these issues have now been resolved by the use of UNCD technology.

Using UNCD technology films as thin as 100 nm and as thick as 20 microns can be deposited on wafers. UNCD films are now commercially available in the market [6]. There are a number of congenital properties of diamond that makes it a suitable material for the development of the sensors such as high distinct speed, low abjection, low frequency reversal reactions etc. Due to such excellent properties, diamond is emerging out as epitome material for the MEMS technology.

4. RESULT AND DISCUSSION

The micro-cantilever is designed using poly-silicon and DTF. The maximum displacement and the stress induced is determined for both the materials and compared. The sensitivity of the pressure sensor highly depends on the selection of material.

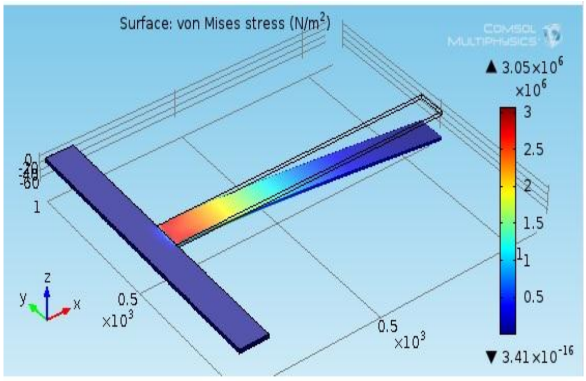
4.1 Calculation of Resistance

A cantilever of length 1000µm, width 200 µm and thickness 10µm has been constructed. Poly-silicon and DTF are used as material for designing the cantilever. The mechanical properties for both the materials are stated in Table-II.

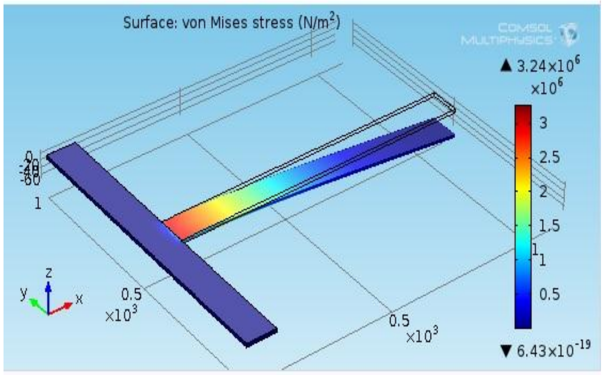
TABLE-2: Comparison between Mechanical Properties of Poly-silicon and Diamond.

	Poly-silicon	Diamond
Young Modulus	160 GPa	1100 GPa
Poisson Ratio	0.20	0.22
Density	$2.328 g/cm^3$	$3.51 g/cm^3$

The calculated stress and the graphical representation are shown in the following Fig -3 and Fig -4 for applied pressure range from 10kPa to 50kPa.

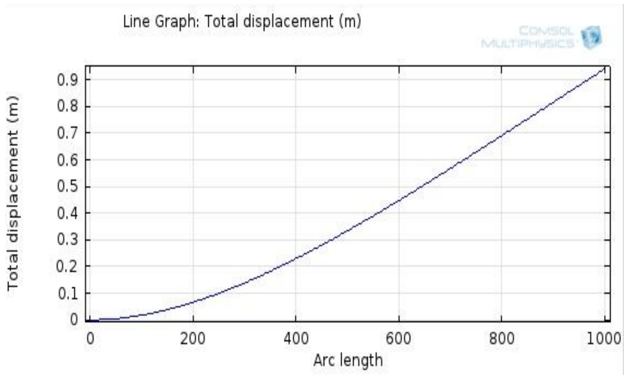


(a)

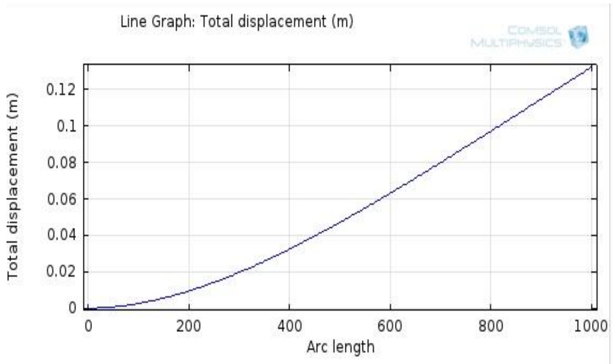


(b)

Fig -3: Stress Induced on Cantilever with (a) Poly-silicon and (b) Diamond. The Maximum Stress is observed at the Fixed End of the Cantilever.



(a)



(b)

Fig -4: Graphical Representation between the Displacement and Arc Length for (a) Poly-silicon and (b) Diamond. The Graph Shows that the Displacement Increases as the Pressure Increases.

Fig -5 shows the stress induced in all four piezoresistors.

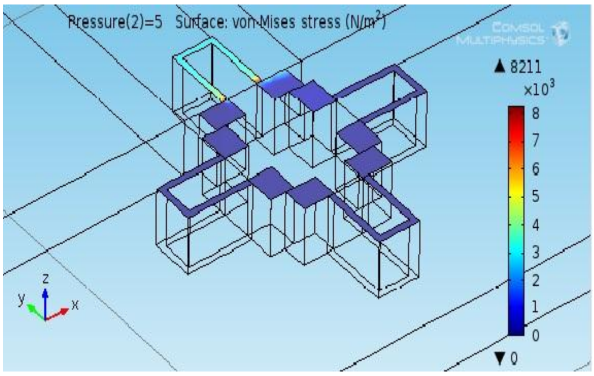


Fig -5: Stress Induced in the Structure

The results shows that the structure designed with DTF results in higher stress as compared to poly-silicon. Table III shows the comparison between the stress induced in the structure for both the materials.

TABLE -3: Comparision between the Induced Stress for Poly-silicon and DTF

Pressure(kPa)	Stress(N/M²)	
	Poly-silicon	DTF
10	3.05×10^5	3.24×10^5
15	4.58×10^5	4.87×10^5
20	6.11×10^5	6.49×10^5
25	7.63×10^5	8.11×10^5
30	9.16×10^5	9.75×10^5
35	1.07×10^6	1.14×10^6
40	1.22×10^6	1.30×10^6
45	1.37×10^6	1.46×10^6
50	1.53×10^6	1.62×10^6

With the increase in stress induced in the piezoresistor, the change in resistance of the piezoresistor also increases. This change in resistance corresponds to the device output voltage. Fig -6 shows the graphical representation of the stress and pressure. This graph shows the variation of the stress with the external pressure before the placement of the piezoresistors on the cantilever. The values of the stress changes when the piezoresistors are placed on the cantilever.

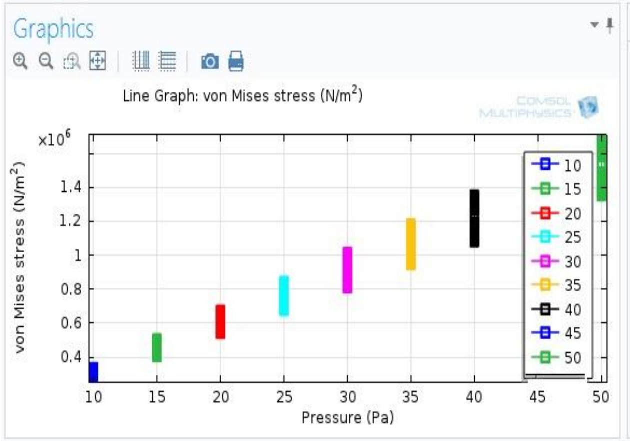


Fig -6: Generalized Graphical Representation of Stress versus Pressure before the Placement of Piezoresistors.

As the pressure applied to the structure increases, the stress induced in the structure also increases. This increase in resistance leads to the increase in the change in the resistance varied with the pressure. Table IV shows the variation of the change in resistance with the applied pressure.

TABLE-4: Variation of the Change in Resistance with the Pressure

Pressure (kPa)	Change in Resistance(mΩ)
10	0.0428×10^{-12}
15	0.0855×10^{-12}
20	0.0129×10^{-11}
25	0.0130×10^{-11}
30	0.0171×10^{-11}
35	0.0214×10^{-11}
40	0.0214×10^{-11}
45	0.0257×10^{-11}
50	0.0300×10^{-11}

The increase in the change in resistance enhances the performance of the sensor.

4.2 Analysis of Sensitivity

After designing the cantilever, external pressure is applied to the complete structure. The pressure range varies from 10kPa to 50kPa. As the pressure increases, the stress induced in the structure also increases. This increase in the stress increases the change in resistance. The increase in resistance then leads to increase in the sensitivity of the sensor. Sensitivity defines the performance of the sensor and is given as in equation (6).

$$\text{Sensitivity} = \frac{\Delta R}{P} \tag{6}$$

where ΔR = Change in Resistance
P = Pressure Applied

The calculated maximum sensitivity comes out as 6.92×10^{-10} mΩ/kPa at a maximum pressure of 50kPa.

3. CONCLUSIONS

The micro-cantilever with DTF has been simulated and its sensitivity is analyzed using different input pressure. The experimental results show that the micro-cantilever pressure sensor with DFT exhibits a better performance with the increase in the pressure. The range of pressure varies between 10kPa to 50 kPa. As the pressure increases the sensitivity of the sensor also increases. The maximum sensitivity of the pressure sensor comes out as 6.92×10^{-10} mΩ/kPa at a maximum pressure of 50kPa. Hence, we conclude that the cantilever based pressure sensor has been designed with DTF deposited on the silicon base resulting in the better performance.

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