DESIGN AND SIMULATION OF UNDER WATER ACOUSTIC MEMS SENSOR

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Abstract: Silicon based MEMS have wide applications in under water sensors. This work has aims at one such applications, hydrophone, in order to study and improve its performance and dynamic range. The structure consists of two parts: high precision four-beam micro-structure and rigid plastic cylinder which has the same density of water and is fixed at the center of the microstructure. When the plastic cylinder is stimulated by sound, the strain gets generated and the piezoresistor transforms the resultant strain into a electrical output signal.

In this paper ,the intension is to simulate a MEMS based high precision 4 beam microstructure which can be used for under water applications for detection of the flow direction and flow rate of the medium surrounding the structure using COMSOL multyphysics tool based on the piezoresestive physics.

Keywords—MEMS vector hydrophone, piezoresistor, 4 beam microstructure

1. Introduction:

SONAR operation is based on the propagation of waves between target and a receiver. There are two types of sonar systems: passive and active. In passive sonar systems energy originates at a target and propagates to a receiver whereas in active sonar systems acoustic wave propagates from a transmitter to a target and back to a receiver. Acoustic wave refers to sound wave in any medium. Water being an elastic medium any disturbance in water propagates away from its origin as a wave. When water or air molecules are pushed or pulled apart, they exert a restoring force that resists the motion. The force will be felt locally as pressure or force per unit area. The fundamental parameter of an acoustic wave is pressure and frequency. As the level of radiated noise of submarines become lower and lower each year, the application of vector hydrophone suffice the requirement of submarine sound detection well [1]. Hydrophone detects the pressure variations of acoustic signal and noise in the water and produces an output voltage proportional to the pressure [3]. The free field voltage of hydrophone is defined as the ratio of the open circuit voltage amplitude to the free field pressure amplitude of an incident sound wave which in turn defines also the sensitivity[2].The hydrophone realizes vector detection of underwater acoustic signal .In this paper attempt is made to design and simulate MEMS based underwater acoustic sensor whose working is based on piezoresistive physics .Piezoresistive transducers translate a force in to a change in the value of resistor . They are widely used as sensing elements in pressure sensors [4].

2. Theory of piezoresistive sensing elements:

Piezoresistivity is a property of certain materials which change their electrical resistance when being subject to tensile or compressive stresses. Its effect is dominant in semiconductors such as silicon. It is a function of doping, temperature etc. Piezoresistive readout is commonly used to measure the deflection of membranes such as cantilevers. It is possible to deduce the magnitude of force on a cantilever using piezoresistive region at the base where the maximum stress occurs, by measuring resistance changes.

If the electrodes are positioned at the two ends of a layer of rectangular material of crystalline silicon of length L, width b and thickness h(i.e, L>>b>>h), the structure is simply a resistor. If the material of the resistor is stress free, the resistivity of the silicon material is a scalar, ρ_0, and the resistance between the two electrodes is
$R_0=(L\,\rho_0)/(bh)$.-------------------------(1)
The I-V relationship of the resistor is ohms law for isotropic material, $V=IR_0$.----------(2)
When the material of the resistor is stressed , the resistivity of the material, ρ' is a tensor of the second rank relating the electric field tensor and the current density tensor.
As the electric field and the electric current in the normal direction of the layer are negligible and there is no such current flow across the side walls of the resistors and the length being much larger than width b one can write
$E_X' = \rho_1' J_X'$ -----------(3)
$E_y' = \rho_6' J_x'$. -------------(4)Since $E_x' = Vs/L$,----------(5)

where Vs is the voltage difference between the two electrodes, the current passing through the resistor is :
$I_x' = J_x' bh = (bh\,Vs)/(L\,\rho_1')$.-------------(6)
If this relation is compared with the Ohms law for the isotropic material , we find that the resistance:
$R=(L/bh)\,\rho_1'$. -------------(7)
The resistance is stress dependent from the term ρ_1'. When this relation is compared with the original resistance
$R_0= L\,\rho_0/bh$, -----------(1)

the relative change of the resistance is

$\Delta R/R_0=(\rho_1'-\rho_0)/\rho_0=\Delta'$

where $\Delta'=\pi'_{11}T_1'+\pi'_{12}T_2'+\pi'_{13}T_3'+\pi'_{14}T_4'+\pi'_{15}T_5'+\pi'_{16}T_6'$. -------------------------(8)

For most applications in pressure transducers and accelerometers , the resistor is placed on the thin diaphragm or beam. Therefore the material is stressed in to two dimensions at the surface plane. In this case $T_3'=T_4'=T_5'=0$.

Now $\Delta R/R=\pi'_{11}T_1'+\pi'_{12}T_2'+\pi'_{16}T_6'$--------------------(9).

So two terminal silicon resistor is sensitive to the stress or strain in the material. Therefore it can be used as sensing element for stress or strain. We can also write

$\Delta R/R=\pi_l T_l+\pi_t T_t+\pi_s T_s$-------------------------------(10)

where subscripts l designates longitudinal, t designates transversal and s designates shearing. Thus

$\pi_l=\pi_{11}'$is often referred to as the longitudinal piezoresistive coefficient, $\pi_t=\pi_{12}'$ is the transversal piezoresistive coefficient and $\pi_s=\pi_{16}'$ is the shearing piezoresistive coefficient. If the resistors are parallel to the beam direction i.e., along x, y is in surface plane and perpendicular to the beam direction and z is normal to the surface plane then

$\pi_{11}'=1/2\pi_{44}$ and $T_t=T_s=0$. $\Delta R/R=(\pi_{44}/2)T_l$ ……….(11)

Therefore, if the Wheatstone bridge has a supply voltage of V_s the output is

$V_{out}=V_s\,\Delta R/R$---------------------(12)

3.Sensor Design:

The structure of hydrophone consists of two parts: high precision four-beam micro-structure and rigidity plastic cylinder which has the same density of water and is fixed at the center of the microstructure. Figure 1 shows the actual design of the structure. In this paper we have simulated four beam microstructure consisting of 4 vertical cantilever beams which are attached to the center block on one side and other end are fixed at the support. Both the center block and the beams have same thickness and the whole structure has complete axial symmetry and shown in figure 2.

P type silicon piezoresistors are integrated on cantilever beams . The center block material is silicon with the dimensions being 500 µm long,500 µm thick and 10 µm thick.The cantilever is 1000µm long,120µm wide and 10µm thick.

The mass will have a horizontal displacement and an angular rotation, when it is subjected to axial or radial stress. And then the structure will be subject to deformation, an amplified and concentrated strain is generated on the slim sensing beams. The piezoresistors converts the stresses induced in the silicon beam 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 the figure3. A Wheatstone bridge is widely used to pickup variation in the electrical resistances of the strain gauges. When a bridge is balanced, there is no output voltage (when there is no resistance change from its balance value) but the bridge indicates a voltage output if the resistance is varied from it nominal value. The resistance variation depends on the strain generated in the resistor and mainly by the change in resistivity which is dominant in semiconductors. In this structure two Wheatstone bridges are formed by diffusing eight equal strain Resistor R1,R2,R3,R4,R5,R6,R7,R8 as shown in figure 3 . Resistances R1,R2,R3 and R4 connection into the first wheatstone bridge to give the electrical output voltage corresponding to the stress in the axial direction ;R5,R6,R7 and R8 connection into the second wheatstone bridge to give the electrical output voltage corresponding to the stress in the radial direction .

This change of resistance is induced by the applied measurand pressure is measured from the Wheatstone bridge.

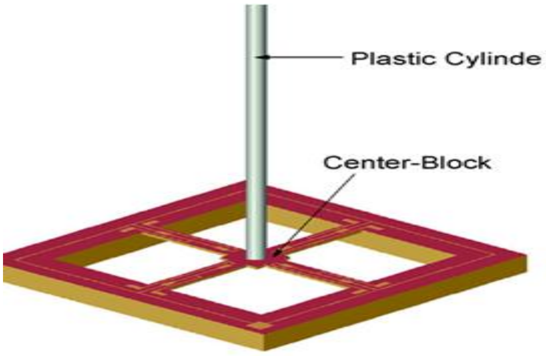

Fig1: Structure of hydrophone

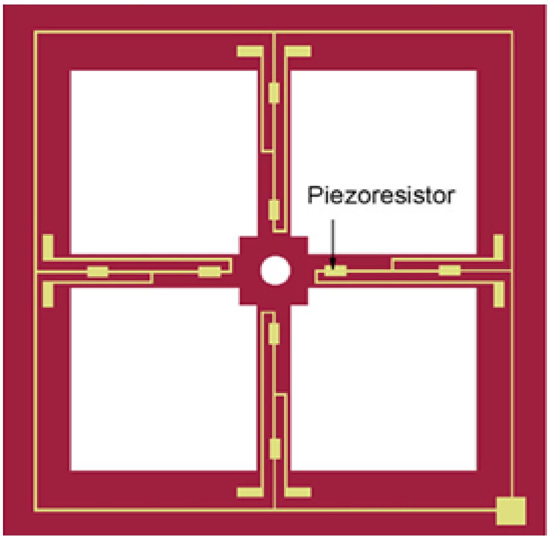

Fig2: 4 Beam Microstructure

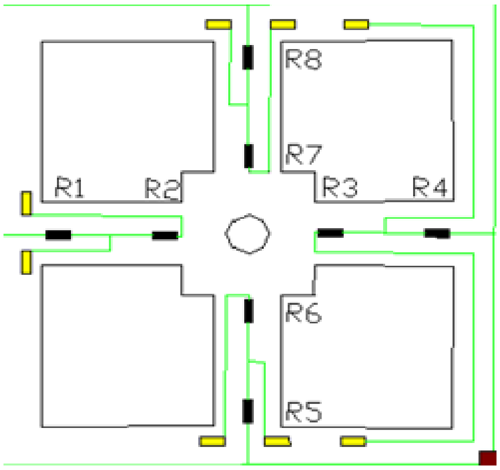

Figure 3. Distribution of Strain Varactor Connection Diagram

4.Modelling Using Comsol Multiphysics:

The sensor geometry as mentioned above is modelled using Comsol Multiphysics 5.0, piezoresistive physics for domain currents module. The geometry is created using a block (the beam) with the given values for width, depth and height and which is attached to the center block. The starting material of a beam is a 7µm p type silicon layer with a 3µm thick n type epitaxial layer. The material used for central block is silicon with L=500µm,W=500 µm and thickness=10 µm dimensions. Two work planes are defined. The dimensions of the resistors and the connections are defined by a 2D drawing on the upper work plane. The material properties like Young's Modulus and Poisson Ratio are set according to the given literature. After this, the structural, electrical and piezoresistive properties of the model were defined. The areas within the boundaries of the beams are determined as thin conductive layers and the area bordered by the geometry of the resistors are defined as thin piezoresistive layers.

One of the ends of all four cantilever beams are attached to the center block and the other end are made fixed i,e they are attached to the support or frame. The pressure and force in axial and radial directions are applied as boundary load corresponding to the acoustic particle motion to the center block.

5. Results and Discussion:

During simulation, pressure corresponding to the under water acoustic particle motion is applied to the central block ; The center block will have displacement . Therefore the structure will be subjected to deformation , an amplified and concentrated strain is generated. The resultant displacement and stress are recorded. Deformation of beams andStress distribution over the entire volume is shown in Figure 5&6respectively.. It could be could observed that the maximal stress is located at the beam-block interface and near the support frame. The piezoresistors of the structure are located at these places of the beam where the stress profile is optimal. Because of this compressive stress there will be change in piezoresistvity of all piezoresistors because of the variation in semiconductor band gap and shown in Figure 8. The structure is applied with various pressures and corresponding change in resistance is tabulated in table 1.

It is found that the change in resistivity hence resistance of the resistors used for these types of piezoresistive microsensors is proportional to the external pressure and it changes linearly as shown in fig 7.

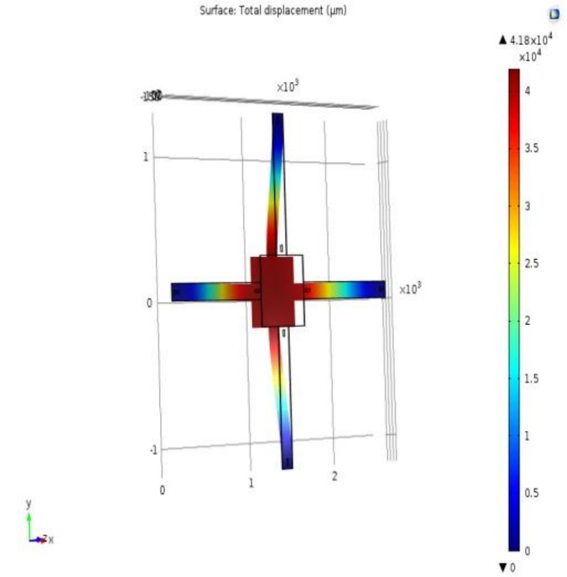

Fig5:

Fig5: Displacement when subjected to 10MPa load.

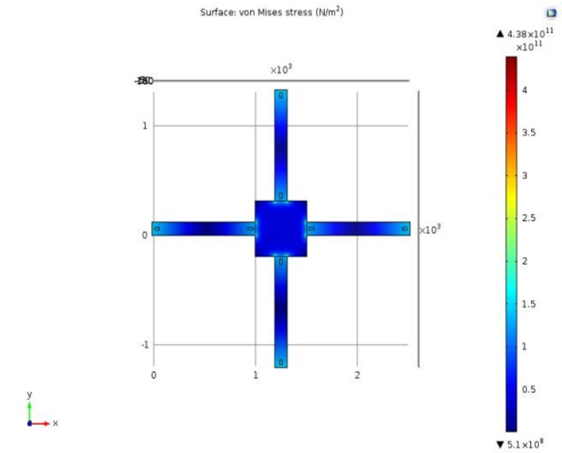

Fig6:Stress plot for a pressure of 10MPa

Pressure (MPa)	Change in resistivity (Ω-m)of resistances R2,R3,R6,R7
10	1.4054
20	2.8107
30	4.1978
40	5.5848
50	7.031
60	8.5497

Table 1: Data pertaining to pressure and resistivity

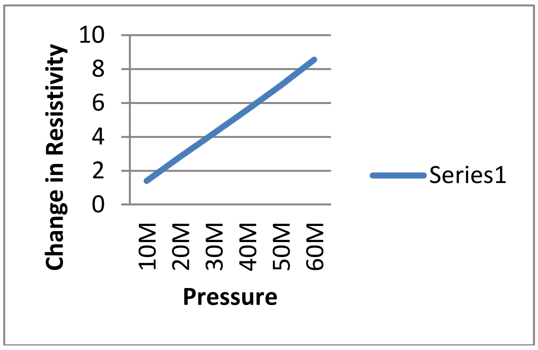

Fig7: Linear relationship between change in resistivity and pressure

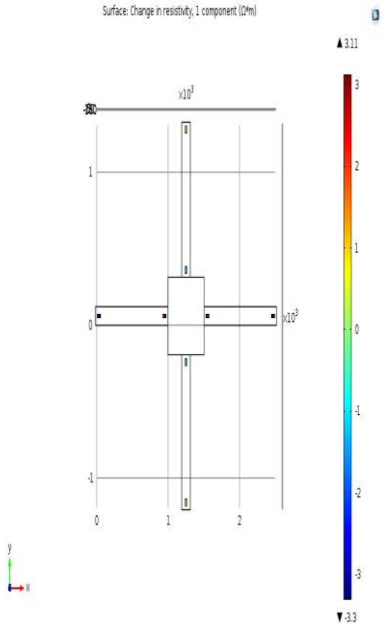

Fig8: Change in piezoresistivity plot for a pressure of 10 MPa.

When a lateral force is applied to the central block in x direction the deflection of the central block occurs only in the lateral direction , which means that the vertical deflection and the transverse shear stresses are zero. When the center block is subjected to axial force due to an acceleration , in the x-direction, axial deformation of the beams take place i.e. beam consisting of R3 and R4 is subjected to compression and beam consisting of R1and R2 is subjected to tension as a result resistivity change occurs as shown in Fig 9&Fig 10 and the bridge formed by R1,R2,R3 and R4 provides the output voltage and indicates the direction of force as axial direction i,e as +x direction. The opposite will happen for –ve axial direction.

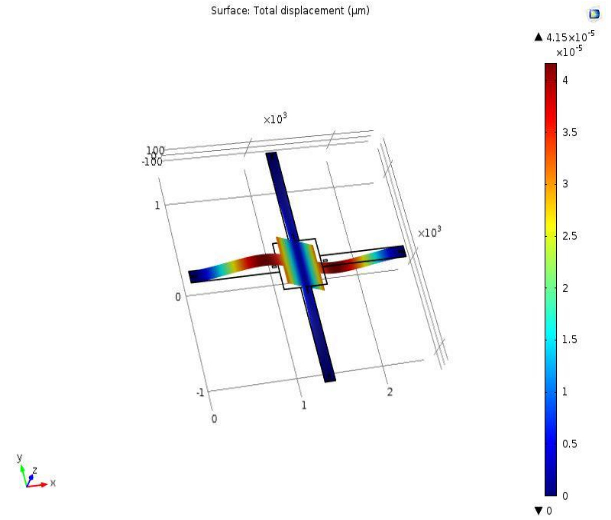

Fig9:Axial deformation of the beams when subjected to 25 N force in +x direction

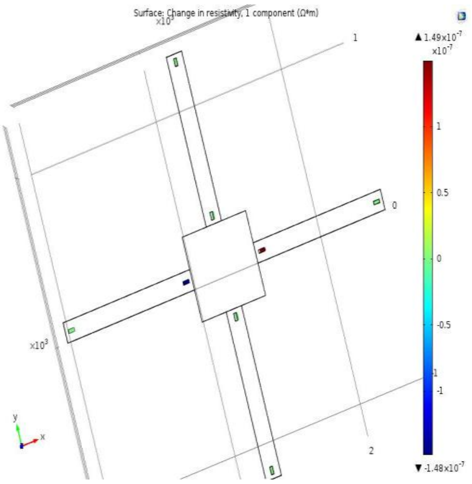

Fig 10: Change in resistivity plot of the beams when subjected to 25 N force in +x direction

When the center block is subjected to vertical motion of the mass due to acceleration in the y direction it induces the bending of the beams and beam consisting of R7 and R8 is subjected to compression and $R_6$and R_5 is subjected to tension as a result of resistivity change that occurs as shown in Fig 11 & Fig 12 and wheatstone bridge with R5,R6,R7,R8 gives the output corresponding to direction of force in y direction.

The opposite will happen for –ve radial direction.

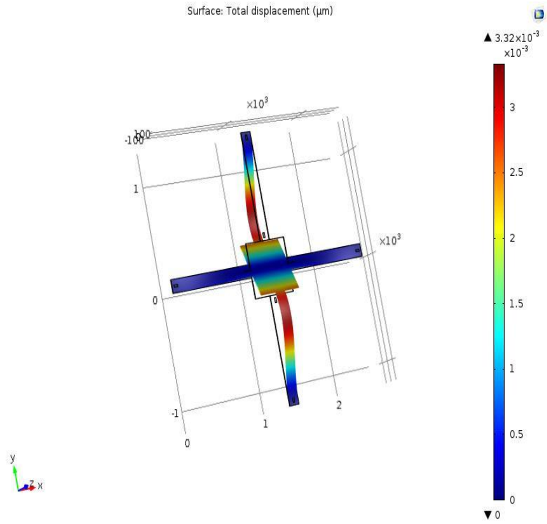

Fig 11:Radial deformation of the beams when subjected to 25 N force in +Y direction

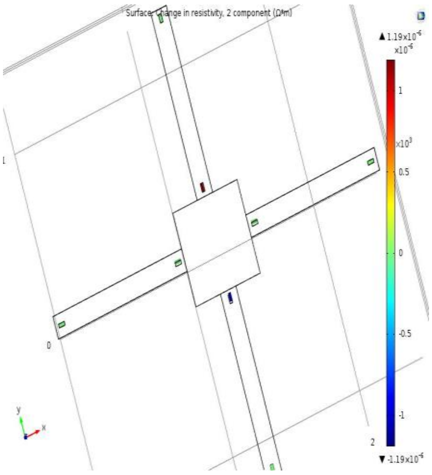

Fig 12:Change in resistivity plot of the beams when subjected to 25 N force in +Y direction

6. Conclusion:

COMSOL Multiphysics was used to investigate piezoresistive effect in p-type silicon for a range of pressure variations and simulation results demonstrate a linear relationship between the resistance change and stress for various pressures loading. The resistance of the piezoresistor implanted in the sensitive structure is changed, when the signal is transmitted to it.

The radial and tangential resistance changes due to the radial and tangential strains corresponding to the acoustic particle motion along axial and radial direction. When there is an incentive direct current, the bridge output will be detected as per flow direction and hence the structure is used to detect the vector underwater acoustic signal.

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