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Design and Simulation of T-Shaped Hydrophone Utilizing COMSOL Multiphysics

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Abstract:
Silicon based MEMS devices have wide applications in under water sensors. This paper reports the design and simulation of T – Shaped hydrophone. This MEMS based hydrophone is inspired by the lateral line of the fish. The structure consists of a T - shaped cantilever beam and supporting block with piezoresistors placed on them. The design and simulation of the microstructure is carried out using COMSOL Multiphysics. The location where piezoresistors must be placed is confirmed through simulation. The stress, displacement and change in resistivity for different pressures are noted. The change in resistivity with respect to different pressures and forces applied is linear. The first order resonant frequency and range of frequencies that can be detected by the T – shaped hydrophone is found.

Keywords: MEMS Sensors, Hydrophone, Stress, Displacement, Piezoresistors.

I. INTRODUCTION

MEMS (Microelectro mechanical system) is a process technology used to create integrated devices or systems having characteristic length less than 1mm but more than 100nm and combines electrical and mechanical components. MEMS devices are smaller, produced in batches, reliable and economical. By imitating fish's lateral line MEMS bionic sensor is designed and simulated. The T – Shaped hydrophone is based on piezoresistivity. Acoustic waves are sound waves; sound is a vibration that propagates as a audible mechanical wave of pressure, displacement through medium such as water. 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 [2]. The fundamental parameters of an acoustic wave are pressure and frequency. The hydrophone can realize vector detection of underwater acoustic signals which are sensitive to low frequencies [1]. Piezoresistors are used for low frequency detection. Piezoresistance is the change in electrical resistance of solids when they are subjected to stress. Piezoresistors have high gain, they exhibit good linear relationship between applied pressure and the resistance change output, the fabrication of piesoresistors are easy and low cost. They are broadly used as sensing elements in pressure sensors.

II. 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 $_{\text{the}}$ output is

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

III. SENSOR DESIGN

Principle of Operation

The performance of the biological sensory system has inspired engineers to design their artificial counter parts. Bionics is the application of biological methods found in nature to study and design engineering system in technology. The lateral line organ is a type of highly specialized skin sense organ of the fish and aquatic amphibians. A fish's lateral line organ consists of set of individual neuromasts on the fish surface; each neuromast contains hundreds hair cells. The nerve endings of hair cells link to the vagus nerve emitted by the medulla oblongata. Water pressure will change under external forces such as sound waves, vibration waves and changes in the water flow velocity. This pressure travels into the lateral line canal through the lateral line pore, where the force is transferred to the mucus, causing the flowing of mucus which makes the displacement of hair cell. By taking the analogy of a fish, the sensory hair imitated by the long cantilever beam, sensory cells by the piezoresistors and efferent nerve by metal lead. The principle of operation of T – Shaped hydrophone is as follows: The external forces or vibrations will cause the change in water pressure; this will lead to the displacement of the cantilever beam. The displacement of the cantilever beam will cause the change in resistivity of piezoresistors which are connected in the form of Wheatstone bridge. A Wheatstone bridge is widely used to pick up variation in the electrical resistances of the strain gauges. When a bridge is balanced, there is no output voltage, the bridge indicates a voltage output if the resistance is varied from it nominal value.

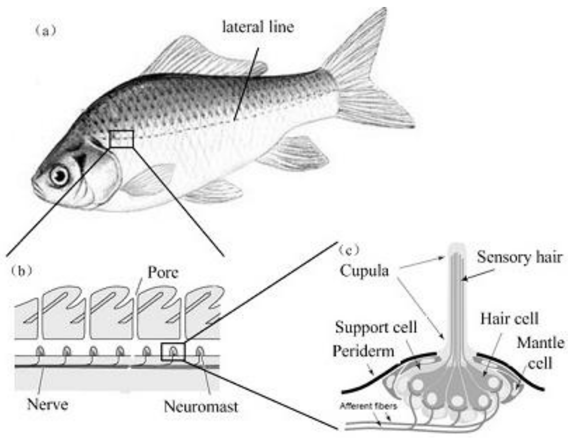

Figure.1. Schematic drawing of fish lateral line

The resistance variation depends on the strain generated in the resistor and mainly by the change in resistivity which is dominant in semiconductors. R1, R2 are piezoreisitors and R3,R4 are the reference resistors. The change in resistance is induced by the applied pressure is measured from the Wheatstone bridge

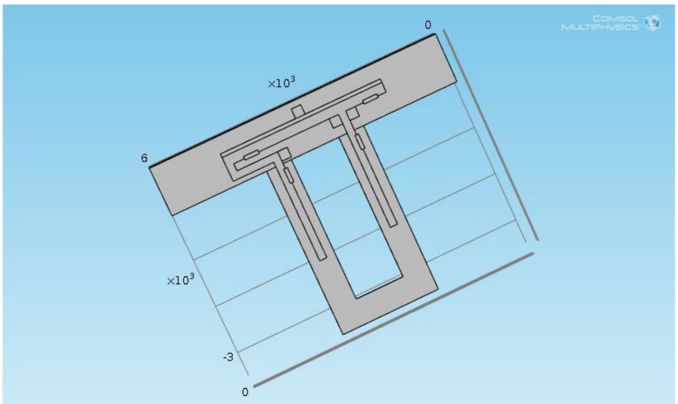

Figure.2. Structure of t –shaped hydrophone

IV. SIMULATION OF THE STRUCTURE

The hydrophone is simulated using COMSOL Multiphysics. The size of the structure and the location of piezoresistors is be confirmed by simulation. The piezoresistors are not arranged in non – linear region and they are placed in the region of stress. The piesoresistors are located 100µm away from the root of the beam. The size of the cantilever beam is 20x3020x3480 (thickness x width x length), piezoresistors is 10x75x300 (thickness x width x length), supporting structure is 200x1000x6000 (thickness x width x length). The supporting beam is fixed and pressure is applies on the cantilever beam. The material of the supporting structure is silicon. It is used because it is abundantly available and are economical. In single crystal silicon there is no hysteresis and almost no energy dissipation. Silicon is reliable since it suffers from very little fatigue and it has long life time. The material of the pieroresistors is p – type silicon and n – type silicon is used for the cantilever beam. Gold is used as electrode and pads because of its high electrical conductivity, high thermal conductivity, stability and optical reflectivity.

V. RESULTS AND DISCUSSION

During the simulation, pressure corresponding to the underwater acoustic particle motion is applied to the cantilever beam. Therefore the structure will be subjected to deformation, an amplified and concentrated strain is generated. The resultant displacement and stress are recorded. When 1 MPa load are given along Z – direction to the cantilever beam, maximum stress is located at the root of the beam and the cantilever beam is displaced upward. The change in resistivity is mainly due to material properties of silicon and the piezoresistors are subjected to tensile stress.

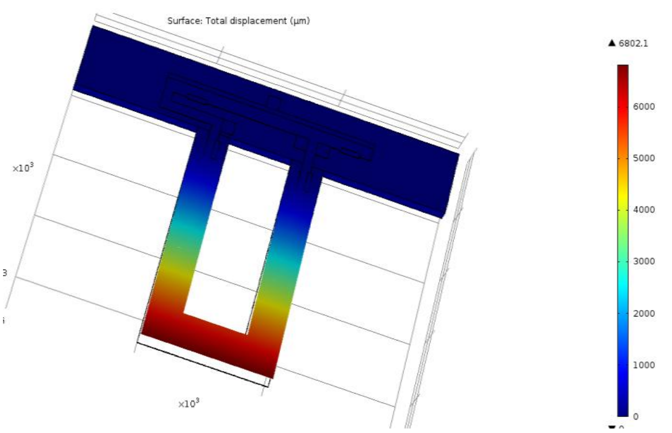

Figure.3. Displacement of the cantilever beam when 1 mpa pressure is applied on the whole beam.

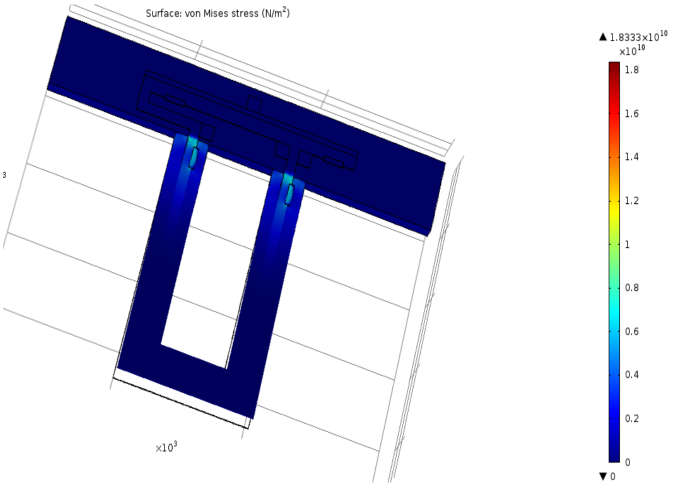

Figure.4. Stress on the cantilever beam when 1 mpa pressure is applied on the whole beam.

When 1MPa load are given along Z – direction to the top portion cantilever beam, maximum stress is located at the root of the beam and the cantilever beam is displaced downward. The change in resistivity is due to bandgap of the silicon and the piezoresistors are compressive stress.

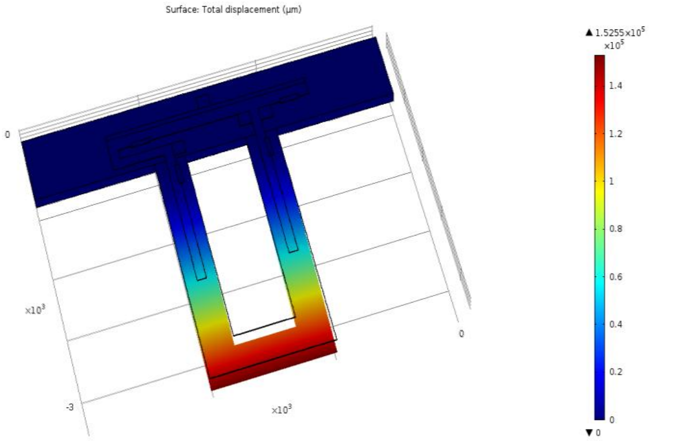

Figure.5. displacement of the cantilever beam when 1 mpa pressure is applied on the top beam.

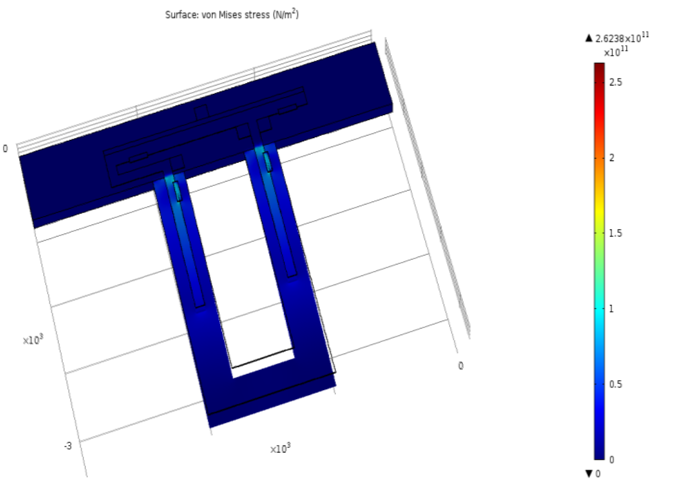

Figure.6. Stress on the cantilever beam when 1 mpa pressure applied on the top beam.

When 1MPa load are given along Z – direction to the bottom portion cantilever beam, maximum stress is located at the root of the beam and the cantilever beam is displaced downward. The change in resistivity is due to bandgap of the silicon and the piezoresistors are subjected to tensile stress.

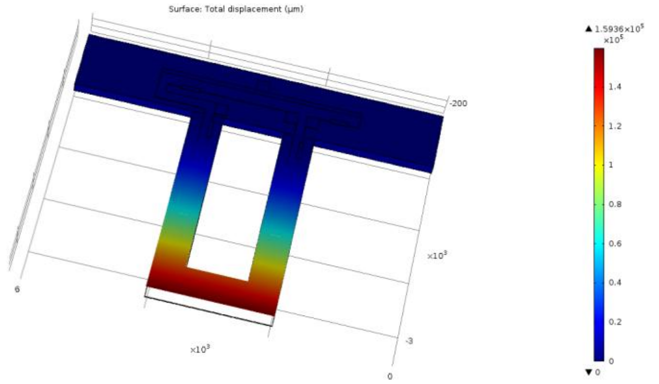

Figure.7. Displacement of the cantilever beam when 1 mpa pressure is applied on the bottom beam.

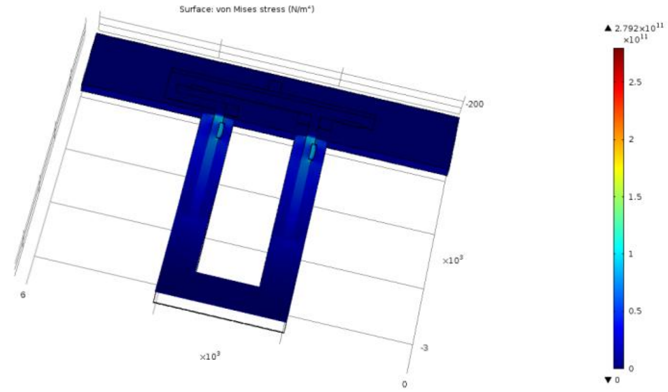

Figure.8. Stress on the cantilever beam when 1 mpa pressure is applied on the bottom beam.

When 1N force is applied on the whole beam(x – direction), maximum stress is located at the root of the beam and the cantilever beam is displaced upward in x - direction. The change in resistivity is due to bandgap of the silicon and the piezoresistors are subjected to compressive stress.

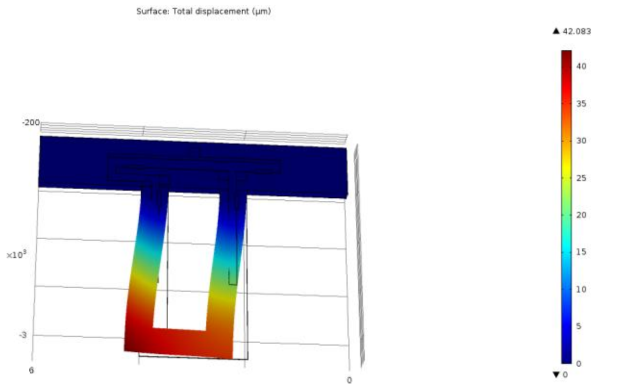

Figure.9. Displacement when 1n is applied on the whole beam(x – direction)

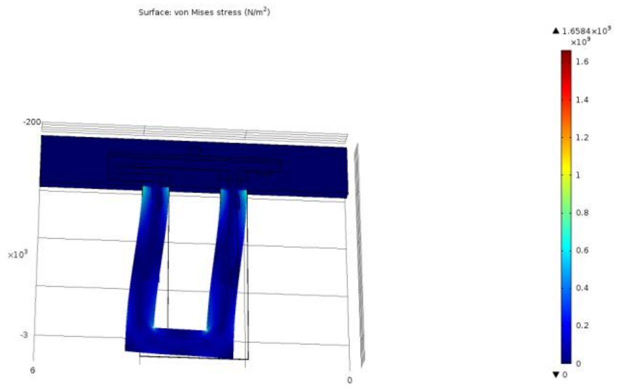

Figure.10. Stress when 1n is applied on the whole beam(x – direction)

When 1N force is applied on the whole beam(y – direction), maximum stress is located at the root of the beam and the cantilever beam is displaced downward. The change in resistivity is due to bandgap of the silicon and the piezoresistors are subjected to tensile stress.

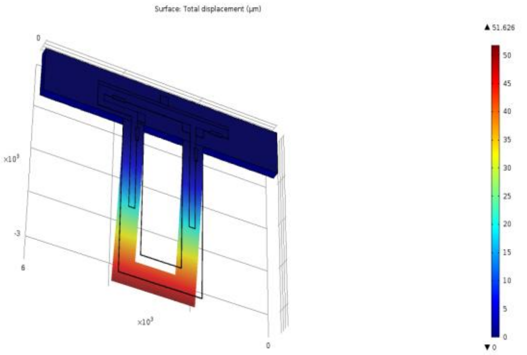

Figure.11. Displacement when 1n is applied on the whole beam(y – direction)

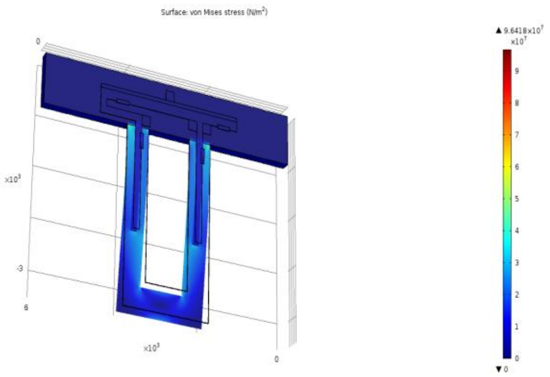

Figure.12.Stress When 1n Is Applied On the Whole Beam(Y – Direction)

Different pressures and forces are applied on the cantilever beam. The change in resistivity with respect to applied pressure is linear.

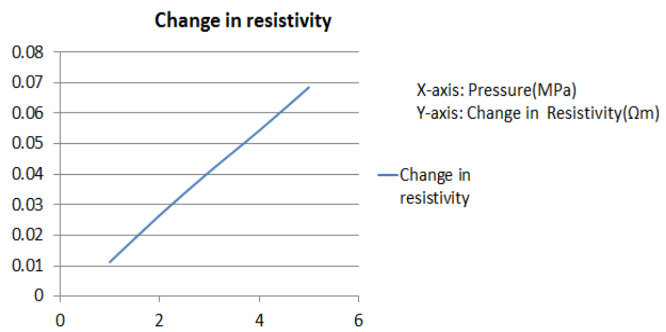

Figure.13. Plot of change in resistivity for varying pressures for piezoresistor

The Eigen frequency analysis gives all the natural frequencies of the system. The natural frequencies of a structure are the frequencies at which the structure naturally tends to vibrate if it is subjected to a disturbance. Once the Eigen frequency analysis is performed, to find all potential modes frequency domain analysis is performed by giving a range of frequencies between the Eigen frequencies. The Eigen frequency of the hydrophone is 2130 Hz. The range of frequencies from frequency domain analysis is from 1600 Hz to 6100Hz. The T – Shaped hydrophone can effectively detect the frequencies ranging from 1600 Hz to 6100 Hz.

VI. CONCLUSION

The T – Shaped hydrophone is subjected to different pressures. Due to these pressures and forces which are applied, the cantilever beam will be displaced, this displacement will cause change in resistivity. We observe that the change in resistivity of piezoresistors will vary linearly with applied pressure or force. The T – Shaped hydrophone can detect low frequencies upto 2.13KHz. This hydrophone can effectively detect the frequencies ranging from 1.6KHz to 6.1KHz.

VII. REFRENCES

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