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SIMULATION AND ANALYSIS OF DIFFERENT PIEZOELECTRIC MATERIALS IN MEMS CANTILEVER FOR ENERGY HARVESTING

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ABSTRACT MEMS Energy Harvesting(EH) devices are excepted to grow in the upcoming years, due to the increasing aspects of MEMS EH devices in vast applications. In Recent advancements in energy harvesting (EH) technologies wireless sensor devices play a vital role to extend their lifetime readily available in natural resources. In this paper the design of MEMS Cantilever at low frequency (100Hz) with different piezoelectric materials Gallium Arsenide (GaAs), Lead Zirconate Titanate (PZT-8), Tellurium Dioxide (TeO2), Zinc oxide (ZnO) is simulated and performance with different materials are compared. The results are analyzed with various parameters such as electric potential voltage, von mises stress, displacement. The paper discusses the suitability of the piezoelectric material for MEMS fully cochlear implantable sensor application.

Keywords
MEMS Energy Harvesting, Piezoelectric Materials, Cochlear Implantable sensor.

1. INTRODUCTION

Micro-electro-mechanical systems(MEMS) is a rapidly emerging technology that plays a major role due to its magnificent features which interface the physical world and the electronic world in our day-to-day life. It allows mechanical devices to be miniaturized in the range of micro-level which is equivalent to our human hair. Micromachining is the most important technique used for fabrication in microelectromechanical devices for integrated circuits. MEMS instantly uses common mechanical parts such as channels, diaphragms, cantilevers, membranes, grooves, springs, gears, suspensions, and other complex structures. The MEMS cantilever beam was constrained at one end and kept free at another end. When a force is applied, the cantilever deflects which results in displacement and stress within the beam. The common material used for fabricating process is silicon as a substrate. The main advantage is reduced volume and weight, increased performance, reliability and decreased cost, easy to integrate, low power consumption, improved thermal expansion, highly resistant to vibration and radiation [1]. Many MEMS devices are fabricated and shipped in commercial volume such as pressure sensor, accelerometer, micro-valve, projection display chips, biosensors, inkjet nozzle arrays, electrical arrays, optical fiber switching, fluid control etc [2]. Energy harvesting can be known as power harvesting or energy scavenging which is used for low-powered electronic devices, and to replace batteries due to high cost, reliability, frequent power, and to increase its life span. Energy harvesting is the process of converting small amounts of readily available energy into usable electrical energy; this can be stored or conditioned for direct usage [3]. The efficiency of the energy harvester is based on the type of material to be coated on the substrate. Piezoelectric Energy Harvesting (PEH) is broadly used as the area of research due to its simple structure and self-power sources for sensors. The geometry of piezoelectric cantilever determines the vibrational energy harvesting ability. In recent developments, most of the PEH is primarily used with MEMS technology and it has applications in various areas like wireless sensors, monitoring systems and medical implantable sensors etc [4].

In this paper an unimorph MEMS piezoelectric rectangular cantilever beam is designed and simulated using COMSOL Multiphysics to convert mechanical energy into electrical energy. The Eigen frequency analysis of the cantilever beam is obtained at low frequency of 100 Hz [5]. The results obtained in COMSOL Multiphysics the parameters such as von mises stress, displacement, and electric potential voltage with different piezoelectric material are compared and a detailed study has been done to find the suitability of the material to be implemented in the cochlear implantable device [7].

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2. DESIGN PARAMETERS

2.1 Structure of MEMS Piezoelectric Energy harvester

The unimorph piezoelectric energy harvester is designed with Poly-Silicon substrate as bottom layer and different piezoelectric materials like Gallium Arsenide(GaAs), Lead Zirconate Titanate(PZT-8), Tellurium Dioxide(TeO2), Zinc oxide(ZnO) as top layer [7]. The two materials are bonded perfectly in X, Y and Z directions. One end of the cantilever beam with X-axis along its length is fixed at x=0; another end along the thickness is kept free to deflect on the Z-axis. The length(X) varies, the width(Y) and thickness(Z) of the beam are kept constant (900μm,5μm) for different piezoelectric cantilever beams [8].

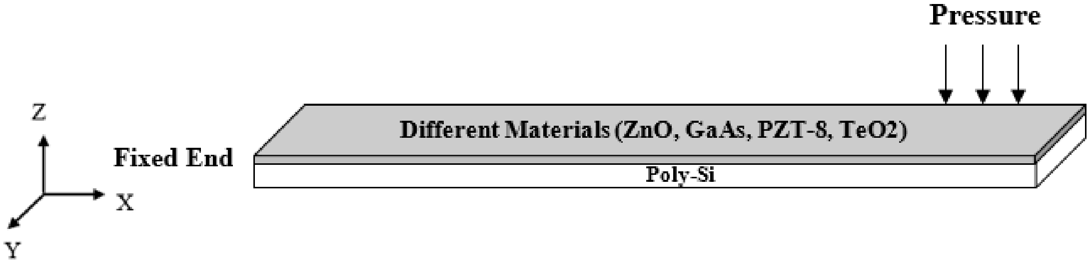

Figure 1. (a) Schematic view of Piezoelectric Cantilever beam.

2.2 Stress charge form for piezoelectric material

Piezoelectric material produces electrical charge when it is mechanically deformed. The piezoelectric energy harvester is governed by the following equations written in the stress-charge format [9].

$$T = C_E S + eE \quad (1)$$

$$D = e^T S + \varepsilon_s E \quad (2)$$

Where **S** is the strain vector; **T** is the stress vector; **D** is the electric flux density vector; **E** is the electric field vector; $\mathbf{C_E}$ is the elasticity matrix; **e** is the piezoelectric stress matrix; $\boldsymbol{\varepsilon_s}$ is the dielectric matrix.

2.3 Material Properties

PEH is a mechanism used to harvest vibration from ambience to direct usable electrical energy. The piezoelectric material converts mechanical strain to electrical power that can be used for small and large power densities.

Table 1: Physical properties of PZT materials

PZT Materials	Young's Modulus [x10^9]	Density [kg/m^3]	Poison's ratio
Gallium Arsenide	82.68	5307	0.31
Lead Zirconate Titanate (PZT-8)	63	7600	0.31
Tellurium Dioxide	76.092	5990	0.651
Zinc oxide	195	5680	0.358

The piezoelectric cantilever beam under study is tested with the four different PZT materials: Zinc oxide, Lead Zirconate Titanate (PZT-8), Tellurium Dioxide deposited on the top layer. The physical and material properties are reported in Table 1 and Table 2.

Table 2.Piezoelectric Material Properties1. Elasticity Matrix (cE) x10^{10} Pa

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$$\left[\begin{matrix} 20.9714 & 12.114 & 10.5359 & 0 & 0 & \\ 20.9714 & 10.5359 & 0 & 0 & 0 & \\ 21.1194 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 0 & 4.23729 & 0 & \\ 0 & 0 & 0 & 0 & 4.23729 & \\ 0 & 0 & 0 & 0 & 0 & 4.4 \end{matrix}\right. \qquad \left[\begin{matrix} 11.9263 & 5.99859 & 11.9263 & 0 & 0 & \\ 5.99859 & 5.99859 & 0 & 0 & 0 & \\ 11.9263 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 0 & 5.37634 & 0 & \\ 0 & 0 & 0 & 0 & 5.37634 & \\ 0 & 0 & 0 & 0 & 0 & 5.3 \end{matrix}\right.$$

ZnO **GaAs**

$$\left[\begin{matrix} 14.6876 & 8.1087 & 14.6876 & 0 & 0 & 0 \\ 8.10537 & 8.10537 & 0 & 0 & 0 & 0 \\ 13.1712 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.1348 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3.1348 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.289 \end{matrix}\right. \qquad \left[\begin{matrix} 5.70042 & 5.24587 & 5.70042 & 0 & 0 & \\ 2.2424 & 2.2424 & 0 & 0 & 0 & \\ 10.6275 & 0 & 0 & 0 & 0 & \\ 0 & 0 & 0 & 2.65252 & 0 & \\ 0 & 0 & 0 & 0 & 2.65252 & \\ 0 & 0 & 0 & 0 & 0 & 6.5 \end{matrix}\right.$$

PZT-8 **TeO_2**

2. Coupling Matrix (eES) C/m^2

$$\left[\begin{matrix} 0 & 0 & -0.567005 & 0 & 0 & -0.5670 \\ 0 & 0 & 1.32044 & 0 & -0.480508 & 0 \\ -0.480508 & 0 & 0 & 0 & 0 & 0 \end{matrix}\right. \qquad \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.139785 & 0 & 0 & 0 \\ 0.139785 & 0 & 0 & 0 & 0 & 0.139785 \end{bmatrix}$$

ZnO **GaAs**

$$\begin{bmatrix} 0 & 0 & -3.87538 & 0 & 0 & -3.87538 \\ 0 & 0 & 13.9108 & 0 & 10.34480 & 0 \\ 10.3448 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \qquad \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.21565 & 0 & 0 \\ 0 & -0.21565 & 0 & 0 & 0 & 0 \end{bmatrix}$$

PZT-8 **TeO_2**

3. Relative permittivity(ε_{rs})

$$\begin{bmatrix} 8.5446 & 0 & 0 \\ 0 & 8.5446 & 0 \\ 0 & 0 & 10.204 \end{bmatrix} \qquad \begin{bmatrix} 12.459 & 0 & 0 \\ 0 & 12.459 & 0 \\ 0 & 0 & 12.459 \end{bmatrix}$$

ZnO **GaAs**

$$\begin{bmatrix} 904.4 & 0 & 0 \\ 0 & 904.4 & 0 \\ 0 & 0 & 561.6 \end{bmatrix} \qquad \begin{bmatrix} 22.702 & 0 & 0 \\ 0 & 22.702 & 0 \\ 0 & 0 & 24.7 \end{bmatrix}$$

PZT-8 **TeO_2**

3. MODELING

3.1 Displacement Modeling

Pressure is applied in the Z-axis direction, the displacement on Z-axis component of the beam induces sensitivity thereby stress or strain is produced due to one Pascal on boundary load [10]. The inverse of the radius of curvature(r) can be expressed in below equation 3.

$$\frac{1}{r}=\frac{d^2h(x)}{dx^2}=\frac{M(x)}{WD_1}=-\frac{F}{2WD_1}[L-x]^2 \qquad (3)$$

The x varies from $0< x<L$, where $h(x)$=Axial Displacement, $M(x)$=Bending moment of the cantilever, D_1 is the Bending Modulus per unit width and can be expressed as equation 4.

$$D_1=\frac{E_s^2t_s^4+E_p^2t_p^4+2E_sE_pt_st_p(2t_s^2+2t_p^2+3t_st_p)}{12(E_st_s+E_pt_p)} \qquad (4)$$

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Where, E_s and E_p are the Young's Modulus of polysilicon substrate and Piezoelectric layer. The parameters t_s, t_p are the thickness of the polysilicon substrate and piezoelectric layer.

$$h_{tip} = -\frac{F}{WD_1}\left[\frac{L^3}{8}\right] \qquad (5)$$

In equation 5, W & L are width and length of the Poly-silicon and one Pascal (Pa) force (F) is applied in terms of pressure (P). Stiffness constant(K) of the beam is defined as the force required for unit tip displacement can be derived from equation (6).

$$K = \frac{F_a}{h_{tip}} = \frac{8WD_1}{L^3} \qquad (6)$$

3.2 Frequency Response

The resonant frequency of cantilever beam simulated at 100Hz is calculated manually by equation 8,9 and compared using Comsol Multiphysics.

$$S_{d_1} = \frac{2}{3}\frac{Wt_{seq}e_{31}}{\omega_n^2} \qquad (7)$$

$$k = \frac{8WD_1}{L^3} \ and \ \omega_n = \sqrt{\frac{k}{m}} \qquad (8)$$

$$F = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \qquad (9)$$

4. RESULTS AND DISCUSSION

The different PZT Materials on MEMS cantilever beam are simulated, the parameters such as displacement, von mises stress and potential voltage for 100 Hz are compared using COMSOL Multiphysics software [11]. When compared to four materials, the zinc oxide material gave highest potential voltage, displacement and von mises stress when compared to others materials due to its high value of piezoelectric coefficients and coefficient of the electromechanical transformation. Hence, Zinc oxide is an excellent material to be used in MEMS Cochlear implants piezoelectric sensor applications

(a)

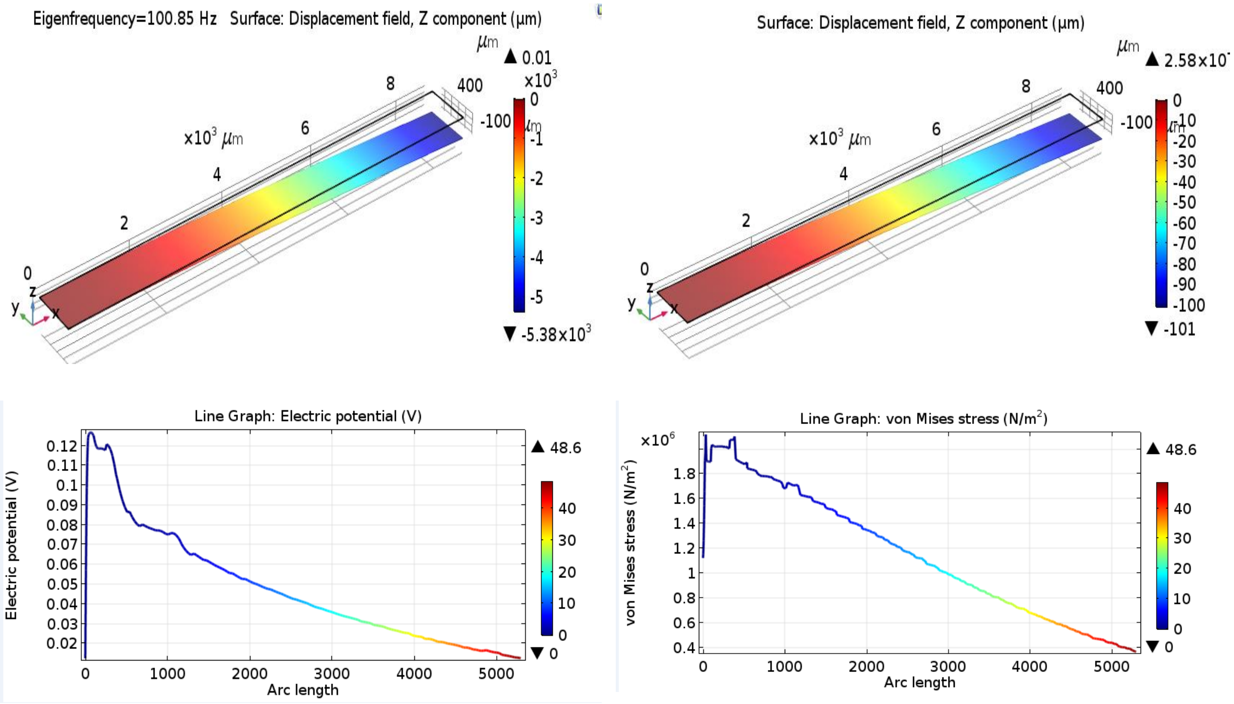

Figure 2. (a) Eigen Frequency, Displacement, Electric Potential and Von Mises stress for Gallium Arsenide (GaAs).

(b)

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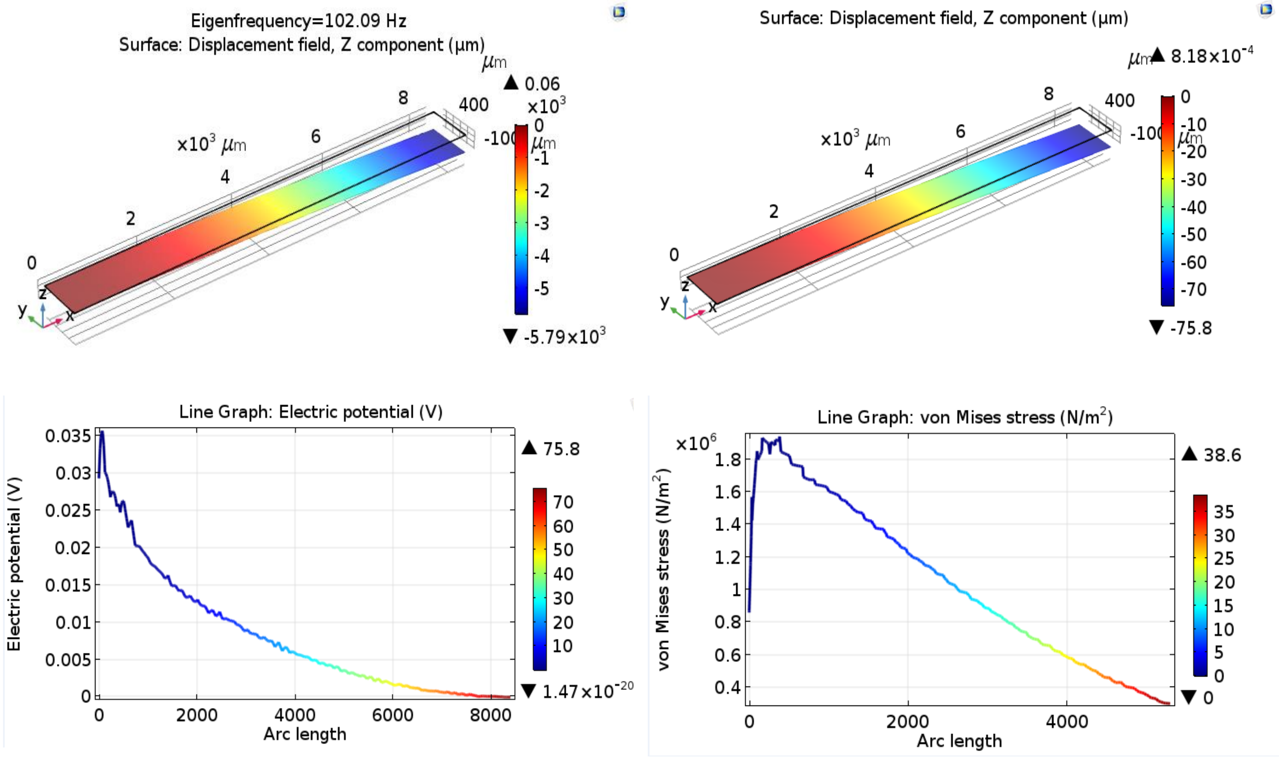

Figure 2. (b) Eigen Frequency, Displacement, Electric Potential and Von Mises stress for Lead Zirconate Titanate(PZT-8)

(c)

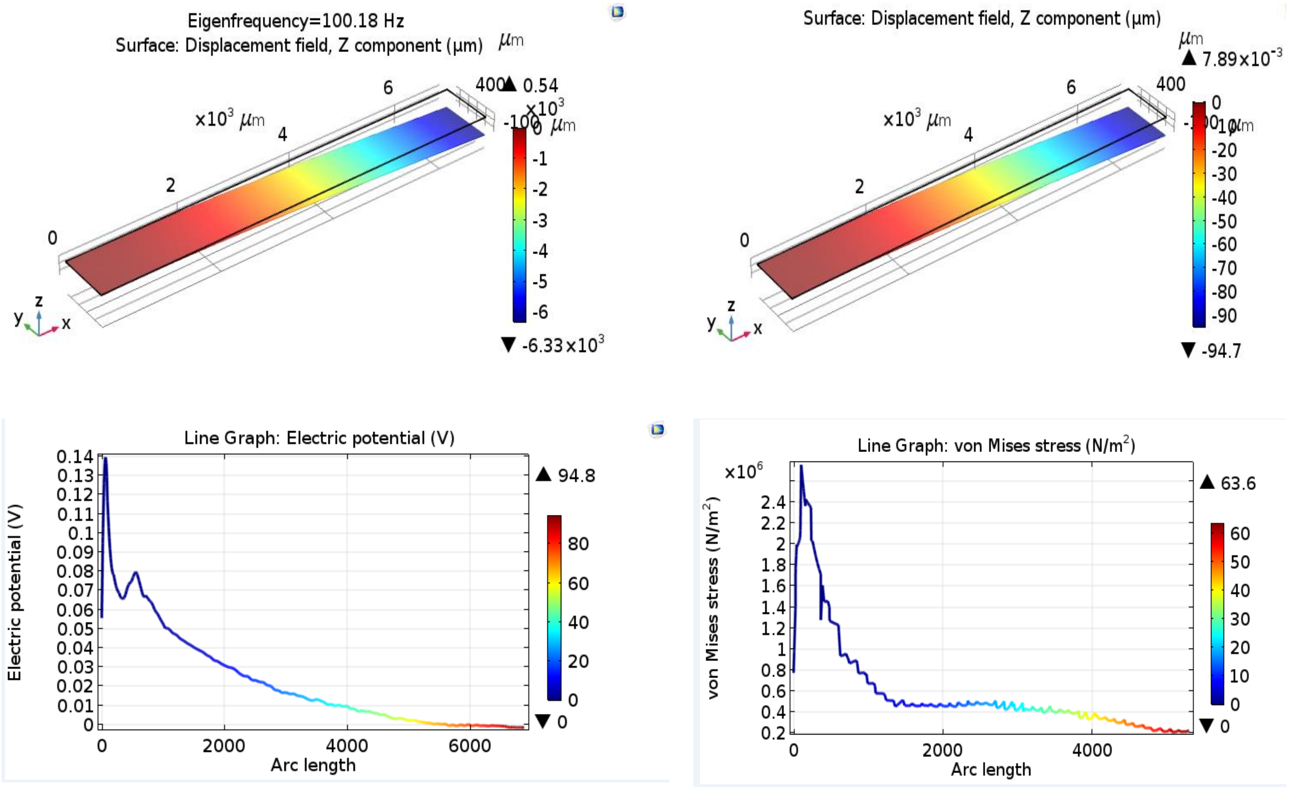

Figure 2. (c) Eigen Frequency, Displacement, Electric Potential and Von Mises stress for Tellurium Dioxide(TeO2)

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(d)

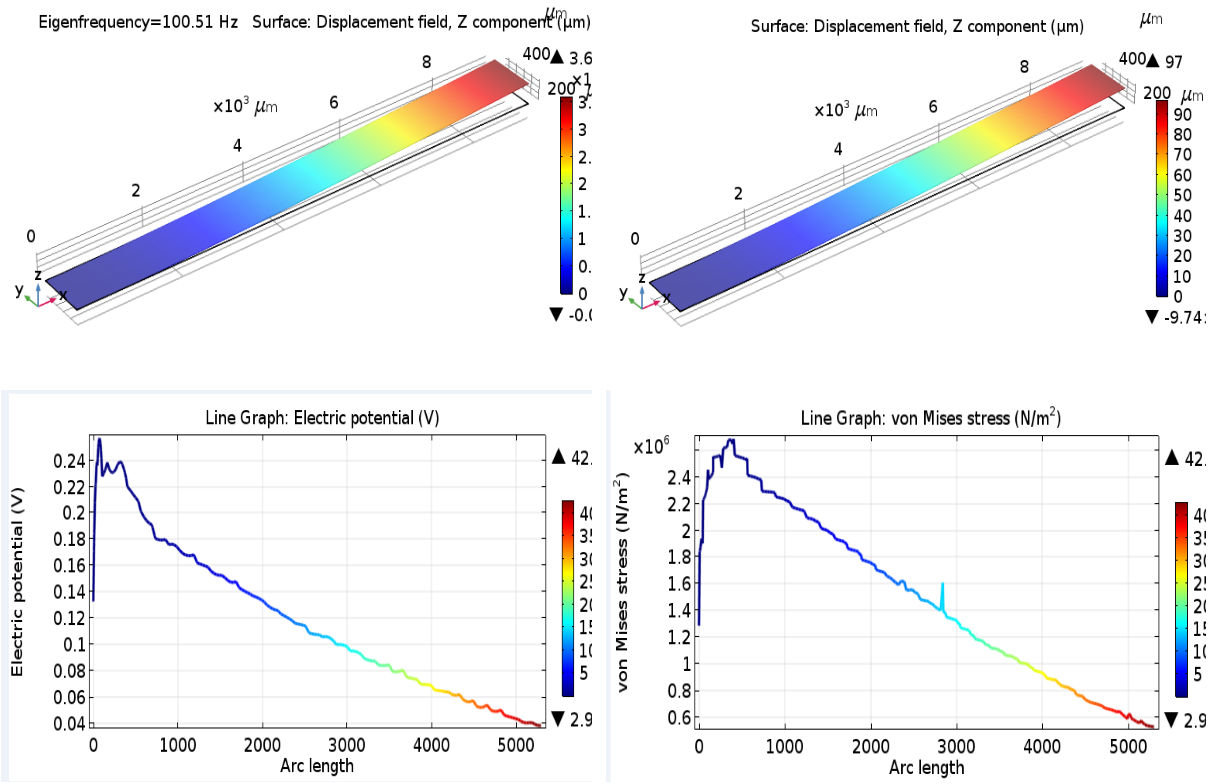

Figure 2. (d) Eigen Frequency, Displacement, Electric Potential and Von Mises stress for Zinc Oxide(ZnO)

PZT Materials	Displacement	Von mises stress $\mathrm{N/m^2}$	Potential Voltage (mV)	Frequency (Hz)
Gallium Arsenide	$2.58\text{x}10^{-4}$	$0.18\text{x}10^{6}$	120	100
Lead Zirconate Titanate (PZT-8)	$8.18\text{x}10^{-4}$	$1.8\text{x}10^{6}$	35.0	100
Tellurium Dioxide	$7.89\text{x}10^{-4}$	$2.4\text{x}10^{6}$	140	100
Zinc oxide	$\mathbf{97\text{x}10^{-6}}$	$\mathbf{2.4\text{x}10^{6}}$	**240**	**100**

Table 3. Simulated different piezoelectric materials parameters for Eigen frequency at 100 H

Fig 2. (a) shows the Eigen frequency at 100 Hz, with a displacement of 258 μm, maximum electric potential voltage of 120mV and Von mises stress of $0.18\text{x}10^{6}\ \mathrm{N/m^2}$ for Gallium arsenide. Fig 2. (b) shows the Eigen frequency at 100 Hz, with a displacement of 818 μm, maximum electric potential voltage of 35 mV and Von mises stress of $1.8\text{x}10^{6}\ \mathrm{N/m^2}$ for Lead Zirconate Titanate (PZT-8).Fig 2. (c) shows the Eigen frequency at 100 Hz, with a displacement of 789 μm, maximum electric potential voltage of 140 mV and Von mises stress of $2.4\text{x}10^{6}\ \mathrm{N/m^2}$ for Tellurium Dioxide. Fig 2. (d) shows the Eigen frequency at 100 Hz, with a displacement of 97 μm, maximum electric potential voltage of 240 mV and Von mises stress of $2.4\text{x}10^{6}\ \mathrm{N/m^2}$ for Zinc oxide. The results are simulated and analyzed which is tabulated above in Table 2.

CONCLUSION

This paper deals with designing MEMS cantilever beam with different piezoelectric materials and the simulation results (resonant frequency, displacement, von mises stress) are analyzed and compared using COMSOL Multiphysics software. The proposed geometry can operate at 100 Hz frequency and the zinc oxide gives the highest electric

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potential of 240mv. Hence Zinc oxide is the excellent and suitable material for the fully cochlear implantable sensor design for further research. This method of MEMS energy harvesting on sensors must be implemented to supply energy to the sensor over its lifetime. MEMS piezoelectric energy harvesting would be a great promise to the future generation in developing and designing sensors in micro scales in all aspects.

6. FUTURE WORK

MEMS Implantable sensors are designed to reduce size, low cost and power consumption. They are widely used in biotechnology, medicine, energy harvesting, fluidics, optical and wireless communications, inertial sensing, and consumer product applications. Cochlear Implantable sensors are designed using piezoresistive, piezoelectric, and capacitive accelerometer sensors. In future MEMS cantilever beam using piezoelectric materials is to be designed for fully cochlear implantable sensor.

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