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Modelling and Simulation of Piezoelectric Cantilevers in RF MEMS Devices for Energy Harvesting Applications

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***Abstract*—In this paper we report the results of the simulations of three piezoelectric materials, namely, Zinc Oxide, Lead Zirconate Titanate (PZT-2) and Quartz, for the purpose of producing RF functionality and thereby converting the lost mechanical energy into electrical energy. The scope of this paper extends to fatigue analysis of cantilevers made out of these materials separately. Multiphysics simulation software was used for simulation and analysis of the beams and piezoelectric materials. Performance of these materials towards varied frequencies was studied. The results of our study give a prospect to estimate viability of using piezoelectric materials in RF MEMS devices to reduce power consumption and also, they shed light on prospective applications they may fit.**

Keywords-Piezoelectric Materials; RF Funtionality; Energy Harvestation; COMSOL Multiphysics

I. INTRODUCTION

Use of wireless technology is an indispensable aspect of modern lifestyle. The past decade has seen a dramatic surge in the usage of microelectronic devices, and this dependence on wireless transmission for most applications in the field of communication has caused an upsurge in power consumption accruing to the RF circuitry in the device. Micro-Electro-Mechanical Systems (MEMS) technology is widely used and readily implemented for providing Radio-Frequency (RF) functionality. RF MEMS play a crucial role in determining the power consumption of wireless devices. RF MEMS are surface-micro-machined devices which make use of mechanical movement to produce millimeter-length waves to provide RF functionality. In mobile devices a major source of power dissipation is wireless transmission, this work aids in finding a novel method of harvesting the dissipated mechanical energy of resonators providing RF functionality. [1-3]

The work helps establish the potential of developing an energy harvesting system that can convert the vibrations from resonators by converting the mechanical energy back to electrical energy in RF MEMS, thus reducing the power consumption and making the system self-powered. [4] Energy scavenging is an emerging area of research where bounteous avenues await through this work we wish to establish a new source for renewable generation. As piezoelectric materials readily convert the mechanical stain inflicted on them into electrical energy, they play a pivotal role in designing and modeling of self-powered RF MEMS resonators employing cantilever beams. Resonators make use of cantilever beams to produce RF functionality, these dissipate a lot of electrical energy in the form of mechanical and heat energy. [5-8]

In this paper, we have analyzed cantilever beams designed using three piezoelectric materials, namely, Zinc Oxide, Lead Zirconate Titanate (PZT-2) and Quartz separately, for their mode shapes and Eigen frequencies for converting the mechanical vibrations into electrical voltages. Also, the fatigue analysis of the beams is in the scope of this paper. The results in this paper are very encouraging and may directly be used for implementing energy harvesting micro-machines.

II. ENERGY HARVESTING FOR SUSTAINABLE DEVELOPMENT

Power dissipation in mobile devices is mainly accrued to various modules present inside them and one of which is resonators. Dissipation in the form of mechanical energy due to vibrating beams and heat loss are major reasons for increased power consumption. Thus it makes good sense in working towards minimizing this dissipation by capturing the lost energy, and reinvesting it in the device through novel methods.

Recently a lot of emphasis is paved on harvesting / scavenging of energy from various sources like ambient vibrations, solar power, heat gradients, fluid flow etc. but harvesting energy through parasitic mechanical vibrations by the use of piezo electrics has a potential for aiding in the goal of sustainable development and green energy generation. Also, it will help curtail the energy consumption and power dissipation.

Energy scavenging is thus a pivotal area of research for promoting sustainable development. The energy lost in the environment if retained and reused can help devices reduce their energy needs and if possible, even become self-powered. Harvesting the lost energy requires the transducers, which can capture the lost energy in the form of heat or mechanical vibrations.

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III. THEORY

A. RF MEMS

Radio-Frequency Microelectromechanical Systems are widely used to produce RF functionality in most wireless devices, the study of RF MEMS leads to four distinctive areas, namely, (1) RF MEMS switches, varactors, and inductors; (2) Micro machined transmission lines, high-Q resonators, filters, and antennas; (3) FBAR (thin film bulk acoustic resonators) and filters; (4) RF micromechanical resonators and filters. [1] The category of RF resonators is of relevance and interest to this work, resonators use mechanical vibrations of micro scale beams to achieve a high-Q resonance. These vibrations are achieved by the employment of micro scale fixed-fixed or cantilever beams. [9] The strain so produced in these beams can be converted to electrical energy through the usage of suitable transducers.

B. Piezoelectric Materials

Piezoelectric materials can readily convert a mechanical strain inflicted on the surface volume into electrical charge, piezoelectric effect is used to convert the mechanical energy into electrical energy. The materials used in this work to harness mechanical energy through piezoelectric effect are Zinc Oxide, Lead Zirconate Titanate (PZT-2) and Quartz. We have two piezoelectric modes namely, d_{31} and d_{33}, these are usually used in piezoelectric transducers. The d_{31} mode has distinct electrodes one on the top and other on the bottom, whereas the d_{33} mode has only an interdigitated electrode on the top, and does not have a bottom electrode. The d_{33} mode gives a fairly high open-circuit voltage when compared to d_{31} mode transducer given the same dimensions and parameters, this fact is of particular interest as a high open-circuit voltage is essential to overcome the forward bias in rectifying diodes. [6] We have used the d_{33} mode for the voltage generation in the piezoelectric materials in this paper.

C. Cantilever Beams

Cantilever Beams are essentially omnipresent in microelectromechanical systems (MEMS). These are beams that are hinged at one end and free to oscillate or freedom of movement is not restricted on the other end. Cantilever beams are most commonly fabricated using anisotropic wet or dry etching technique, materials used for fabrication is usually silicon (Si) or silicon nitride (Si_3N_4). Cantilever used in MEMS are usually unimorphs or bimorphs. RF MEMS extensively employ cantilever beams for producing radio frequencies with the high-Q resonators.

IV. COMPONENTS OF MODELLING

The simulations for this work were done using COMSOL multiphysics.

A. Multiphysics

Simulating a practically relevant model involves more than one physical phenomenon, thus it is crucial to apply multiple physical phenomenon simultaneously. Various phenomenon like current, heat gradient, fluid flow, voltage drop, pressure gradient etc. are understood using computer simulations. Simulations for this paper were done using COMSOL Multiphysics which is a very robust software, it provides an interactive platform for modelling and simulating various problems and stimulus. COMSOL Multiphysics makes the use of finite element analysis method for simulation designs.

B. Finite Element Analysis

Finite Element Analysis allows us to model and simulate any material or design that is subjected to mechanical strain. There are traditional types of analysis in use today, namely, 2-D modelling and 3-D modelling. 2-D modelling yields less accurate results while 3-D modelling allows relatively better results in terms of accuracy. Although, a fastest processing system is required for higher precision in 3D modelling. This method uses a complex system of points called nodes which make a grid called mesh. In this paper we have used tetrahedral finite element. [9]

C. Eigen Frequency Analysis

In dynamic analysis, the natural frequencies and mode shapes of the structure are determined. These values indicate the response of the structure to dynamic loading and characterize the structure's basic dynamic behavior.

Eigen frequency analysis helps compute the dynamic interaction between a component and its supporting structure. Cantilever beams have a set of natural frequency and associated mode shapes determined by beam properties and dimensions. The frequency at which the structure naturally vibrates if subjected to a disturbance is the natural or normal frequency of the structure.

D. Fatigue Analysis

Fatigue analysis plays a decisive role in modelling, it allows us to have an insight at the response to the stimulus given to a structure considering its yield strength. Through this we will be able to decide not only the efficiency but also the efficacy of the beams that are to be designed. This will also enable us to determine the suitability and usability of the material for certain applications.

The damage caused during the fatigue process is generally irreversible and cumulative in nature. Failures of such type usually occur without warning making them impossible to detect beforehand. Moreover, periods of rest do not lead to any significant recovery.

Not only bending a metal back and forth would lead to breakage but also, repeated stresses of marginal amplitudes within the elastic range of the material produce irrevocable fractures.

V. SIMULATIONS

The simulation of the micro-scale cantilever beams was done using COMSOL Multiphysics. The dimensions of the beam were taken to be 40.8μm × 8μm × 1μm. Mathematical modelling already proposed [10-11] have been used for calculating various parameters.

A. Mode shapes

The figures 1-3 depicted below illustrate certain selected mode shapes of each material corresponding to their Eigen frequencies.

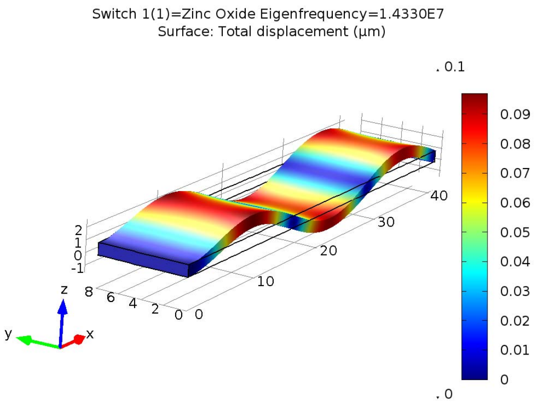

Figure 1 Mode shape of Zinc Oxide Cantilever

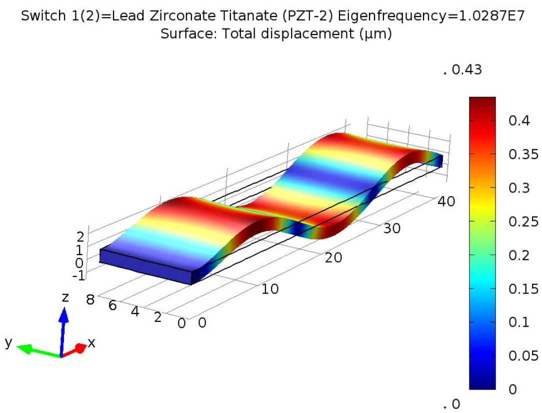

Figure 2 Mode shape of PZT-2

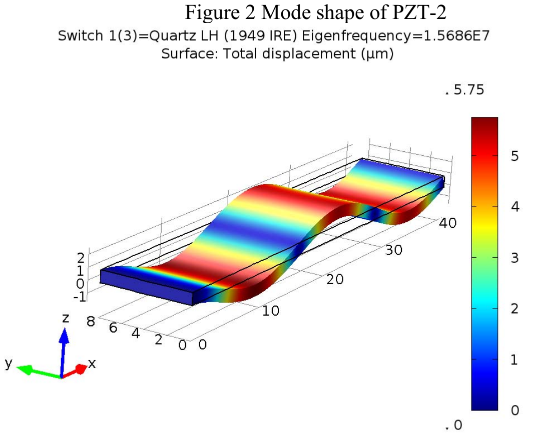

Figure 3 Mode shape of Quartz cantilever

B. Electric Potentials

The figures 4-6 depicted below illustrate certain selected voltage gradient plots of each material corresponding to their Eigen frequencies.

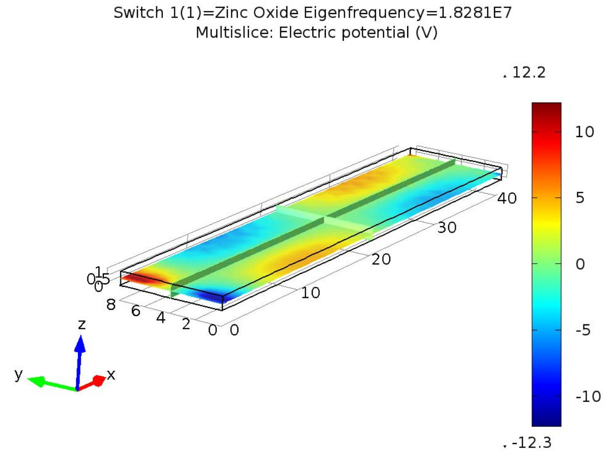

Figure 4 Voltage gradient across Zinc Oxide cantilever

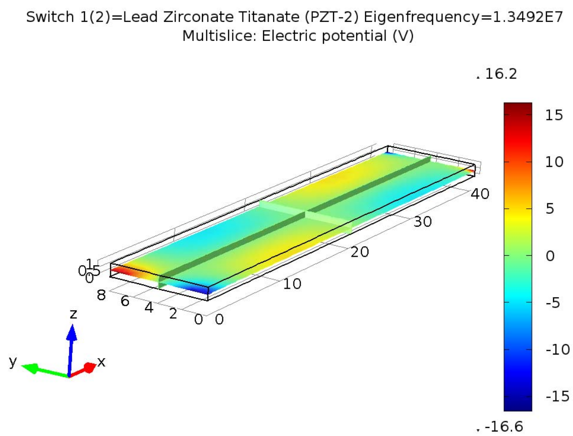

Figure 5 Voltage gradient across PZT-2 cantilever

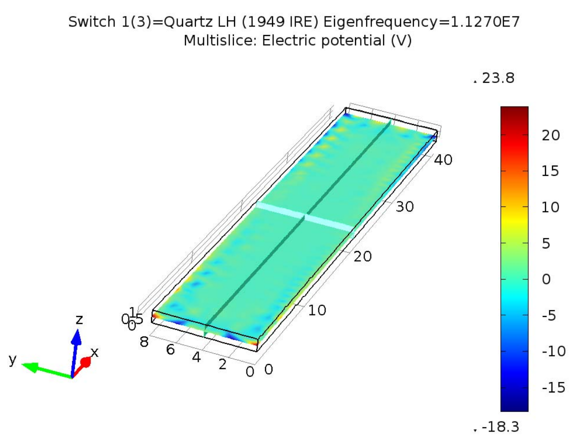

Figure 6 Voltage gradient across Quartz cantilever

C. Fatigue Mode Shapes

The figures 7-9 depicted below illustrate the fatigue mode shapes of each material. The maximum possible displacement for cantilever for each material is shown. The displacement recorded are in micrometers.

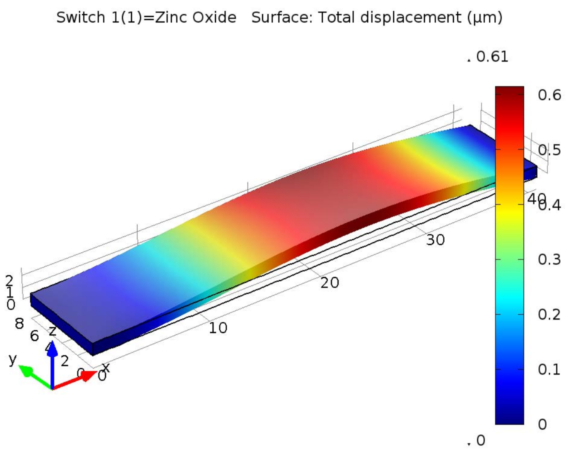

Figure 7 Fatigue Mode shape of ZnO cantilever

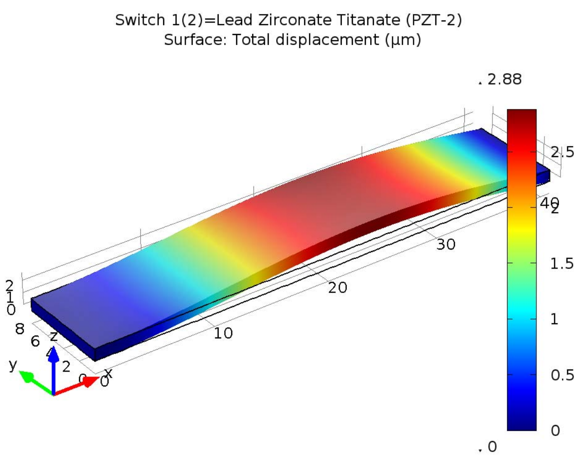

Figure 8 Fatigue Mode shape of PZT-2 cantilever

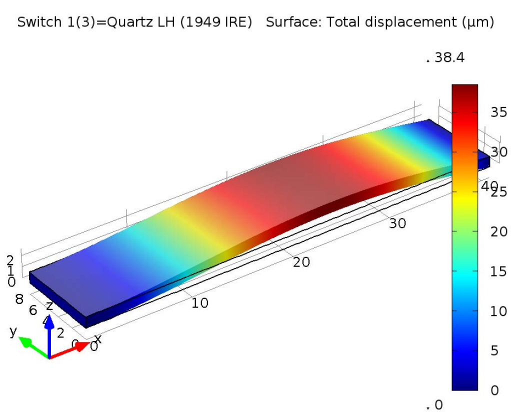

Figure 9 Fatigue Mode shape of Quartz cantilever

D. Voltages

The figures 10-12 depicted below illustrate the voltage gradient plots corresponding to the fatigue mode shapes of each material.

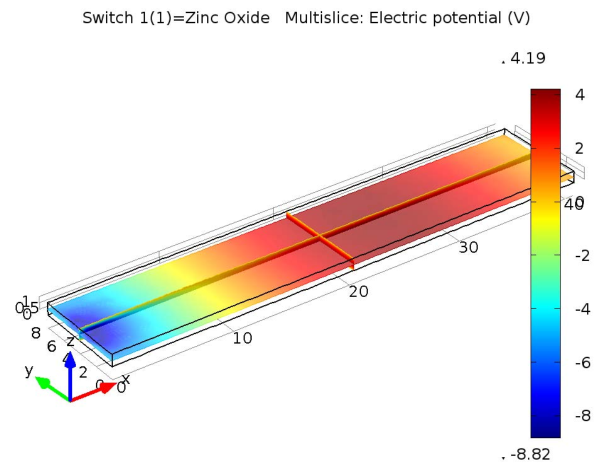

Figure 10 Voltage Gradient plot of Fatigue mode shape of Zno

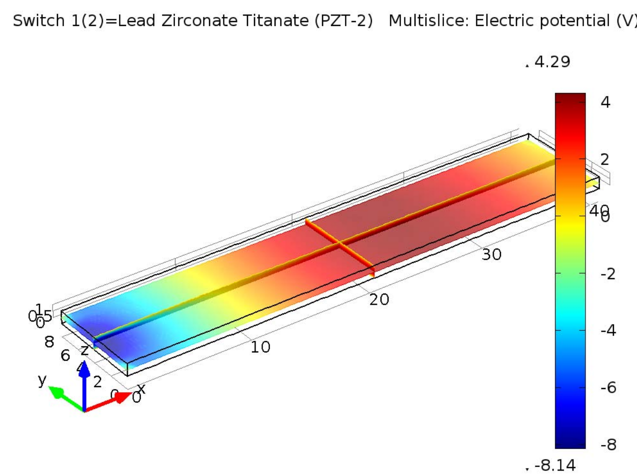

Figure 11 Voltage Gradient plot of Fatigue mode shape of PZT-2

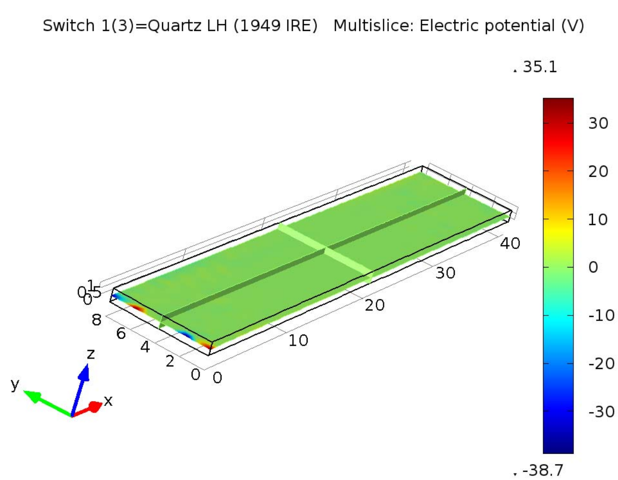

Figure 12 Voltage Gradient plot of Fatigue mode shape of Quartz

VI. RESULTS

The analysis of the Eigen frequencies and the corresponding displacements and voltages produced for the materials are represented by the figures and values are tabulated in the tables.

A. Zinc Oxide

Eigen Frequency	Total Displacement(µm)	Voltage (V)
2.1113E6	0.61	8.82
3.5865E6	32.7	35.5
6.8491E6	0.2	8.3
8.7902E6	0.74	15.8
1.4330E7	0.1	4.93
1.8281E7	0.27	12.2

TABLE I. CHARACTERISTICS FOR ZINC OXIDE

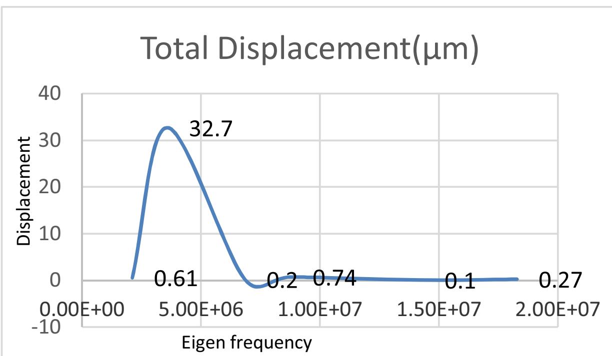

Figure 13 Plot depicting absolute displacement for corresponding Eigen Frequencies for ZnO

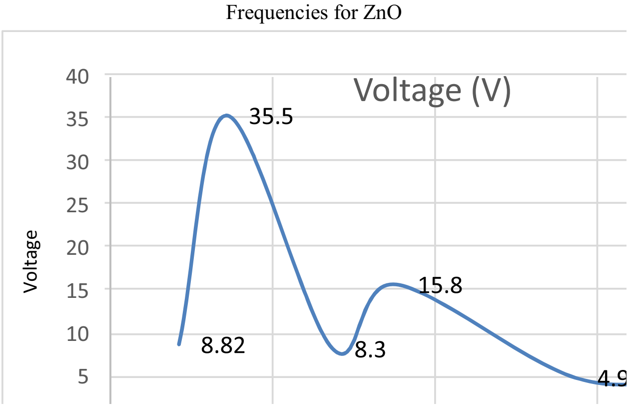

Figure 14 Plot depicting voltages for corresponding Eigen frequencies for ZnO

B. LEAD ZIRCONATE TITANATE (PZT-2)

TABLE II. CHARACTERISTICS FOR LEAD ZIRCONATE TITANATE

Eigen Frequency	Total Displacement(µm)	Voltage (V)
1.5217E6	2.88	8.14
2.5542E6	105	45.9
4.9290E6	0.91	7.58
6.5094E6	2.56	19.8
1.0287E7	0.43	4.85
1.3492E7	1	16.2

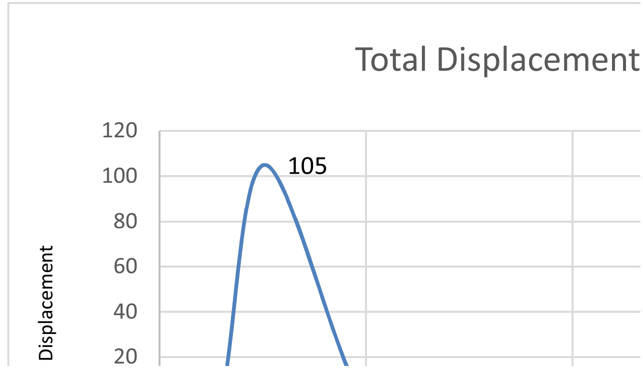

Figure 15 Plot depicting absolute displacement for corresponding Eigen Frequencies for PZT-2

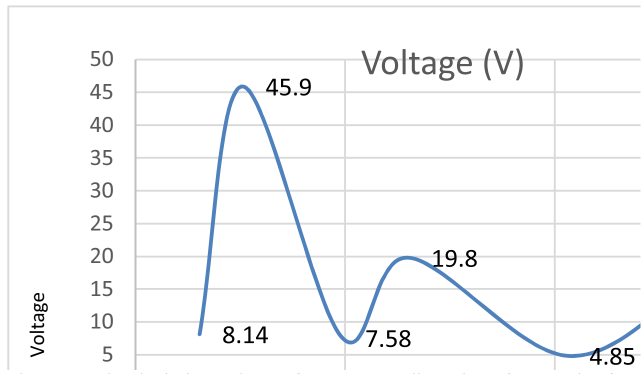

Figure 16 Plot depicting voltages for corresponding Eigen frequencies for PZT-2

C. QUARTZ LH (1949 IRE)

TABLE III. CHARACTERISTICS FOR QUARTZ LH (1949 IRE)

Eigen Frequency	Total Displacement(µm)	Voltage (V)
2.1113E6	0.61	8.82
3.5865E6	32.7	35.5
6.8491E6	0.2	8.3
8.7902E6	0.74	15.8
1.4330E7	0.1	4.93
1.8281E7	0.27	12.2

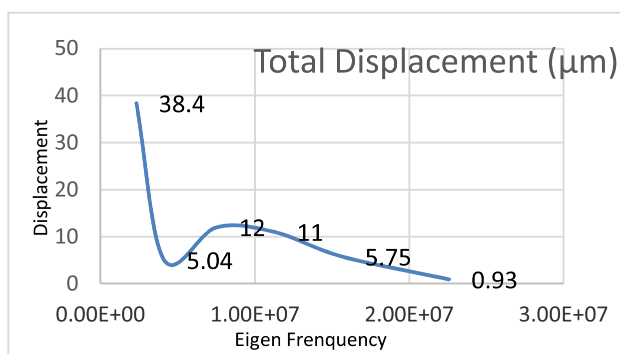

Figure 17 Plot depicting absolute displacement for corresponding Eigen Frequencies for Quartz

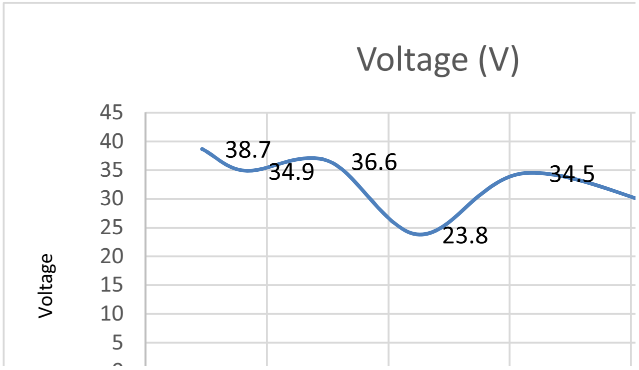

Figure 18 Plot depicting voltages for corresponding Eigen frequencies for Quartz

The fatigue analysis of the materials is shown in Table IV.

TABLE IV. FATIGUE ANALYSIS CHARACTERISTICS

Material	Total Displacement	Peak Potential Values
Zinc Oxide	0.61	4.19, -8.82
Lead Zirconate Titanate	2.88	4.29, -8.14
Quartz LH (1949 IRE)	38.4	35.1,-38.7

The maximum displacement of the cantilever typically corresponds to the maximum voltage output for the cantilevers of piezoelectric materials. It is evident that the voltages produced corresponding to the displacements are viable and the maximum fatigue displacements can be used to determine the limit and extent of displacement that can be harnessed. Also, the fatigue displacements are indicative of the yield strength and maximum voltage output that can be harnessed.

VII. CONCLUSION AND FUTURE SCOPE

In this paper the materials used to simulate beams for resonators in RF MEMS show a positive result for harvesting energy from mechanical vibrations. The voltages produced by the beams under stimulus to produce radio-frequencies are amicable, these values point to sustainability of power consumption and also indicate that the beam can possibly be self-powered, although it would be premature to state that Zinc Oxide, Quartz and Lead Zirconate Titanate can be used as a direct alternative to fabrication material in RF MEMS.

The materials show a good yield strength at frequencies typical of radio waves and can be employed in energy harvesting systems. The voltage outputs produced can be readily rectified and be used to fulfill the objective of making the RF MEMS self-powered or at least reduce the power consumption to an optimum level.

The future work will comprise of developing an energy harvesting micro-machine that can harvest the mechanical energy. Also, we will work on the viability, design and possible new structures for generating RF functionality through MEMS that are energy efficient and if possible self-powered.

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