Modeling and Simulation of MEMS Device Based on Epitaxial Piezoelectric Thin Film

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ABSTRACT: In this paper unimorphs has been designed in COMSOL Multiphysics 3.5 in 3D view Thin film piezoelectric materials offer a number of advantages in microelectro mechanical systems (MEMS), due to the large motions that can be generated, often with low hysteresis, the high available energy densities, as well as high sensitivity sensors with wide dynamic ranges, and low power requirements. a Multiphysics 3.5 in 3D view to decrease operating frequency and improve output power. Unimorphs are designed with two different nonpiezoelectric materials as Aluminum and Gold. Eigen frequency analysis has been performed to obtain resonant frequency and generated voltage from the unimorphs with different piezoelectric epitaxial thin film. Unimorphs of dimension 100mm×30mm×4mm has been modeled with 2mm thin film epitaxial layer of piezoelectric material. From the simulation results Gold is preferred over Aluminium as about 100Hz less frequency response is observed. A Unimorph with gold and PZT-5A material is considered the best model with resonance frequency of about 160Hz with generated electric voltage of 107 volts is applied at the tip of unimorph. spiral cantilever is designed to achieve compactness, low resonant frequency and minimum damping coefficient, simultaneously.

Key words: MEMS. Aluminium nitride,Tellurium Dioxide,Gallium Arsenide,Lithium NiobatePZT-5APZT-5H

IINTRODUCTION

Piezoelectric materials produce electrical charge or voltage across them when a mechanical stress or strain is applied, or vice versa [8]. When subjected to mechanical strain, piezoelectric materials become electrically polarized and the degree of polarization is proportional to the applied strain. Conversely, these materials deform when exposed to an electrical field. This functionality enables the use of piezoelectric materials to convert mechanical energy into electrical energy. As previously reviewed, several methods exist for obtaining electrical energy from vibration sources including the use of electromagnetic induction, electrostatic conversion, and piezoelectric materials. Of these three vibration-based devices, PVEH devices have received the most attention because piezoelectric devices convert applied strain energy from vibration into usable electrical energy directly. There is no requirement for having complex

Geometries and numerous additional components and thus, PVEHs are the simplest type of generator to fabricate. Another major advantage is that piezoelectric generators are well suited for application not only to macroscopic but also micro-scale devices since several processes exist for depositing piezoelectric films (thin and thick) [9]. Piezoelectric based harvesters are also capable of delivering relatively high output voltage (but only at low electrical current), providing the needed voltage level (0.3-4 Volts) to charge a secondary battery or run a sensor directly. This is in contrast with electromagnetic generators that may require transformers to meet applications with required voltage higher than ~2 V [1, 7, 21]

II RELATED WORK

MEMS devices based on an epitaxial piezoelectric thin film grown directly on silicon. the goal of this MaNEP sub-project was to develop the controlled growth of epitaxial piezoelectric thin films on full silicon wafers through oxide layers, and develop appropriate fabrication process to pattern them to realize micro machined structures for specific applications. the epitaxial growth of PZT thin films and related oxides on wafer-scale silicon substrates (2″ silicon wafers). Research activities at EPFL-SAMLAB involved the development of micro fabrication processes for the epitaxial thin films on silicon, and the realization of epitaxial PZT MEMS devices, which are the main goals of this thesis. Study the properties of epitaxial oxide films and the techniques for their integration on silicon wafers for the realization of piezoelectric MEMS. The knowledge gained supported the development of compatible micro fabrication techniques and the design of the piezoelectric MEMS devices Investigate the degradation in ferroelectric and piezoelectric properties of epitaxial PZT thin films due to micro fabrication Processes and material used as a top electrode. The goal here is to acquire all the knowledge that is necessary to produce high quality and reproducible epitaxial piezoelectric MEMS devices with special attention on maintaining the superior properties of epitaxial PZT thin films in operating devices for better performance

III PROPOSED SYSTEM

Energy harvesting devices are attractive as an energy source for powering micro-devices, such as small wireless sensor networks, biomedical implants, environmental condition monitoring systems and structural health monitoring systems .The development of devices able to convert kinetic energy from vibrations, forces or displacements into electric output has advanced rapidly during the past few years because such energy can be found in numerous applications, including industrial machines, transportations, household goods, civil engineering structures, and portable and wearable electronics .Several transduction methods can be used for energy harvesters including electromagnetic induction, electrostatic generation and piezoelectric materials. The choice of the transduction methods depends mainly on the applications since there is no clear evidence with respect to the preferred transduction methods .Nevertheless, among these methods, piezoelectric materials have received the most attention due to directly convert vibration energy into electrical energy with a high power density and ease of integration into a system and thus they are well suited to miniaturization. Moreover, harvesters based on piezoelectric materials have a wider operating range at low frequency than the other transduction methods, which can be efficiently utilized to harvest energy from common environmental vibrations. The fabrication throughput, reproducibility and device miniaturization seem to be limited. While the growth of epitaxial piezoelectric thin films on silicon is promising for MEMS based energy harvesters, several challenges still remain for the development of high performance devices based on the epitaxial PZT thin films. The realization and characterization of vibration energy harvesting MEMS devices based on an epitaxial $Pb(Zr_{0.2}Ti_{0.8})O_3$ thin film having a high piezoelectric coefficient and a low dielectric constant. The analytical power model and finite element model used to design and optimize the devices, and the choice of the actual PZT stoichiometry for energy harvesting applications. The results on the fabrication and characterization of the epitaxial PZT cantilevers with and without a Si proof mass are presented. Different characteristics of the fabricated epitaxial PZT harvester's .their dynamic behavior, electromechanical coupling coefficient and energetic performances. The electrical characteristics of the harvesters, i.e. power, voltage, current were experimentally investigated and the results obtained are in good agreement with the analytical model. The performances of the epitaxial PZT harvesters are also compared with other demonstrated energy harvesters The vast majority of piezoelectric energy harvesting devices uses a cantilever beam structure. A cantilever beam, by definition, is a beam with a support only one end, and is often referred to as a "fixed-free" beam. When the generator is subjected to vibrations in the vertical direction, the support structure will move up and down in sync with the external acceleration. The vibration of the beam is induced by its own inertia, since the beam is not perfectly rigid, it tends to deflect when the base support is moving up and down Typically, a proof mass is added to the free end of the beam to increase that deflection amount. This lowers the resonant frequency of the beam and increases the deflection of the beam as it vibrates. The larger deflection leads to more stress, strain, and consequently a higher output voltage and power .Electrodes covering a portion of the cantilever beam are used to conduct the electric charges produced to an electrical circuit, where they can be utilized to charge a capacitor or drive a load.

CANTILEVER: Cantilevered beams are the most ubiquitous structures in the field of microelectro mechanical systems (MEMS). MEMS cantilevers are also finding application as radio frequency filters and resonators. Two equations are key to understanding the behavior of MEMS cantilevers. The first is Stoney's formula, which relates cantilever end deflection δ to applied

stress σ: $\boldsymbol{\delta = 3\sigma\ 1 - v\ E\ (\ \ t\ )/2}$

Where ν is Poisson's ratio, E is Young's modulus, L is the beam length and t is the cantilever thickness. Very sensitive optical and capacitive methods have been developed to measure changes in the static deflection of cantilever beams used in decoupled sensors. The second is the formula relating the cantilever spring constant k to the cantilever dimensions and material constants:

$$\boldsymbol{k = F\ \delta = E\omega t\ 4L/3}$$

Where F is force and w is the cantilever width. The spring constant is related to the cantilever resonance frequency ω0 by the usual harmonic oscillator formula $\boldsymbol{\omega 0} = k\ \ m$ A change in the force applied to a cantilever can shift the resonance frequency. Different electrode lengths or shapes are frequently used to affect the output voltage, since strain is not uniform across the beam [5].

PIEZOELECTRIC EFFECT: The piezoelectric effect, in essence, is the separation of charge within a material as a result of an applied strain. This charge separation effectively creates an electric field within the material and is known as the direct piezoelectric effect.

MODES OF VIBRATION AND RESONANCE: A cantilever beam can have many different modes of vibration, each with a different resonant frequency. The first mode of vibration has the lowest resonant frequency, and typically provides the most deflection and therefore electrical energy. A lower resonant frequency is desirable, since it is closer infrequency to physical vibration sources and generally more power is produced at lower frequencies [6]. Therefore, energy harvesters are generally designed to operate in the first resonant mode. Each mode of vibration has a characteristic mode shape.

PIEZOELECTRIC EFFECT: The piezoelectric effect, in essence, is the separation of charge within a material as a result of an applied strain. This charge separation effectively creates an electric field within the material and is known as the direct piezoelectric effect. Piezoelectric MEMS based on epitaxial PZT thin films: Epitaxial PZT thin films grown on silicon substrates are receiving a lot of interest for many applications especially their excellent properties are promising for the realization of high performance MEMS devices. The integration of high-quality epitaxial PZT thin films on silicon substrates can be achieved through a buffer layer based on epitaxial oxide thin films. From below six analysis the Beam material is kept same as Aluminum with different piezoelectric layers on it. Fig.13 shows the variation of resonant frequencies obtained from Eigen frequency analysis of unimorph for different piezoelectric materials.

- Aluminium nitride
- Tellurium Dioxide
- Gallium Arsenide
- Lithium Niobate
- PZT-5A
- PZT-5H

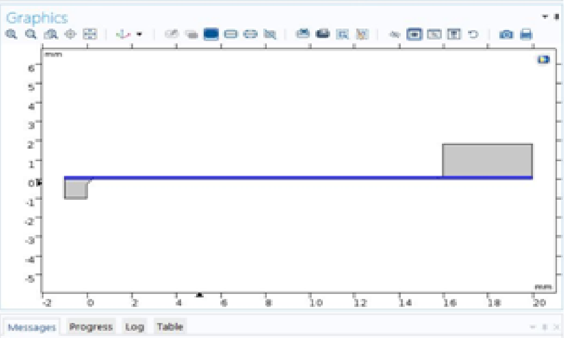

Fig.1 Aluminium nitride material

Epitaxial grown thin film crystalline aluminum nitride is used for surface acoustic wave sensors (SAWs) deposited on silicon wafers because of AlN's piezoelectric properties. One application is an RF filter which is widely used in mobile phones, which is called a thin film bulk acoustic resonator (FBAR) Aluminum nitride has a hexagonal crystal structure and is a covalent bonded material. The use of sintering aids and hot pressing is required to produce a dense technical grade material. The material is stable to very high temperatures in inert atmospheres. In air, surface oxidation begins above 700°C. A layer of aluminum oxide forms which protects the material up to 1370°C. Above this temperature bulk oxidation occurs.

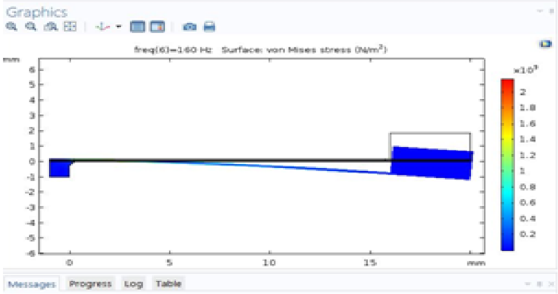

Fig.2 stress on Aluminium nitride material

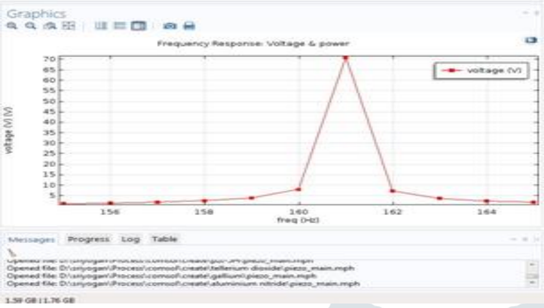

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Fig.3 Aluminium nitride voltage and frequency response

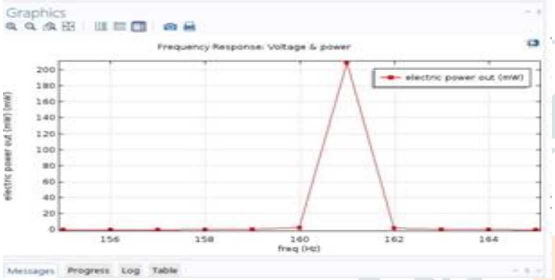

Fig.4 Aluminium nitride electrical power

Gallium Arsenide (GaAs) is a compound semiconductor: a mixture of two elements, Gallium (Ga) and Arsenic (As). Gallium is a by-product of the smelting of other metals, notably aluminium and zinc, and it is rarer than gold.

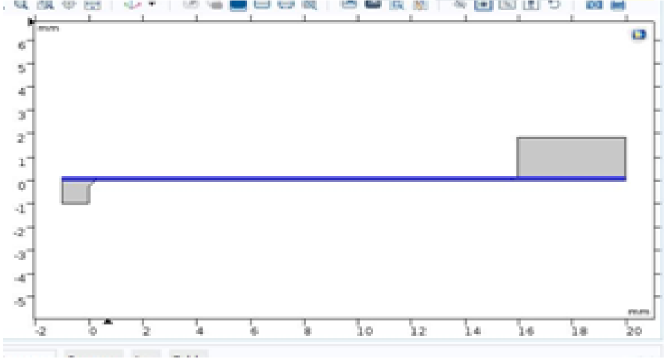

Fig.5 Gallium Arsenide material

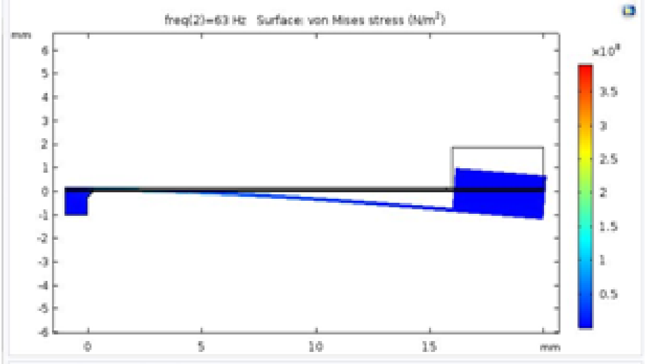

Fig.6 stress on Gallium Arsenide material

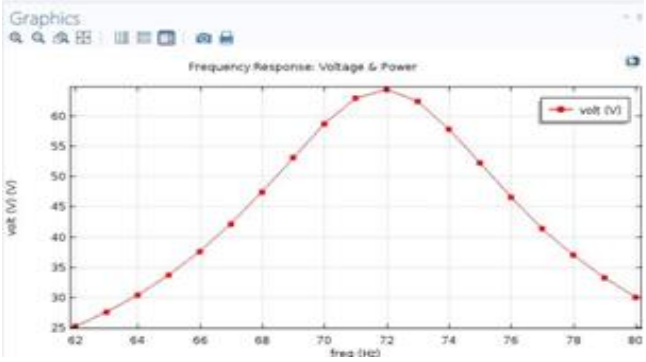

Fig.7 Gallium Arsenide voltage and frequency response

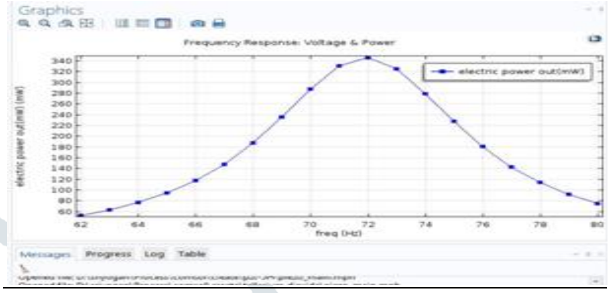

Fig.8Gallium Arsenide electrical power out

Lithium Niobate:Lithium niobate is a ferroelectric material suitable for a variety of applications. Its versatility is made possible by the excellent electro-optic, nonlinear, and piezoelectric properties of the intrinsic material. It is one of the most thoroughly characterized electro-optic materials, and crystal growing techniques consistently produce large crystals of high perfection Throughout this investigation, multiple specimens of each composition were tested at each condition, and the average value of each property was determined A Bimorph has been designed with dimensions 100mm × 30mm × 4mm in COMSOL Multiphysics 3.5. Then providing it boundary conditions as one side fixed and other side free constraints. A force of 20N/m2 along Y direction is made on the top side. Table 1 shows the results of analysis 1 to analysis 6. This analysis has been done with three different piezoelectric materials PZT-5, PZT-5A and PZT-5H with Aluminum as base material for obtaining modal analysis from these three models with same dimensions as 100mm × 30mm × 4mm. Modal analysis is done for five modes in COMSOLThe design of piezoelectric cantilevers to effectively convert ambient vibrations and flows into electricity. Such devices provide affordable, sustainable and maintenance-free power solutions for low power wireless and portable devices. Upon review of published literature in this field, it was found the current design of the piezoelectric cantilevers needs to be modified with an effective way of converting mechanical energy into electricity, from piezoelectric cantilevers. From Analysis 1 to 6 it can be concluded that for designing a unimorph with low resonant frequency the preference should be given to Tellurium Dioxide, Aluminum Gallium Arsenide, PZT materials respectively.. As gold is much costly than Aluminum therefore when cost doesn't matters much with the results Aluminum can be preferred over gold.

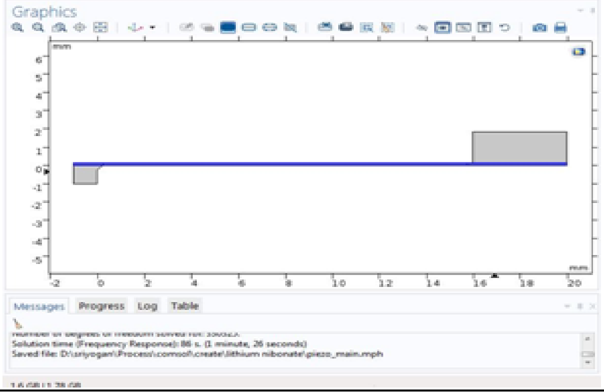

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Fig.9 Lithium Niobate material

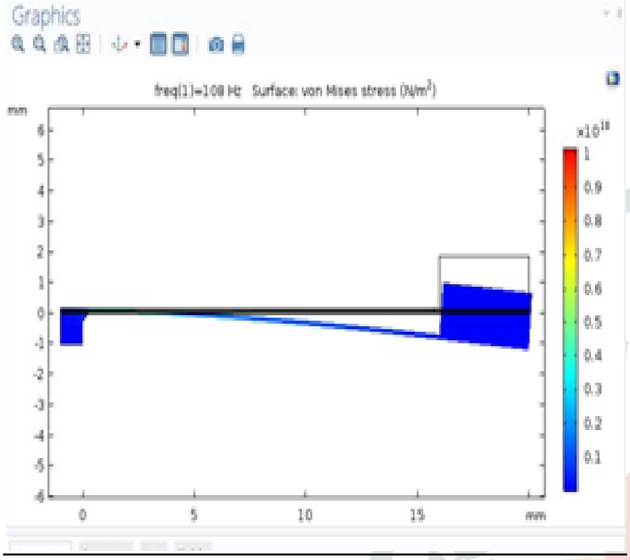

Fig. 10 Lithium Niobate material

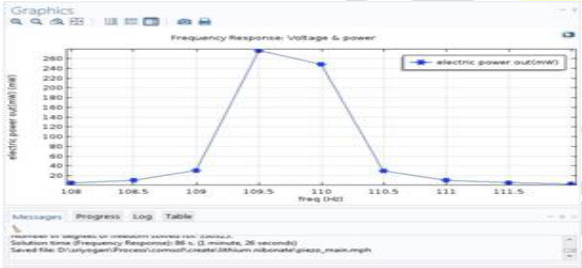

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Fig.11 Lithium Niobate electrical power out

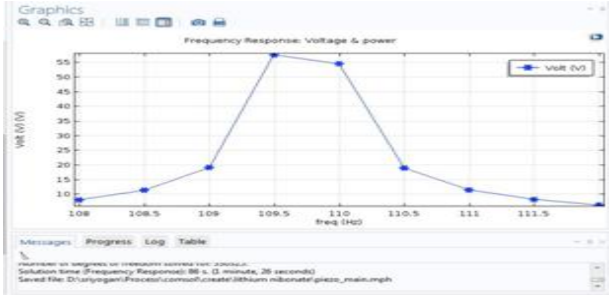

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Fig12 Lithium Niobate voltage and frequency response

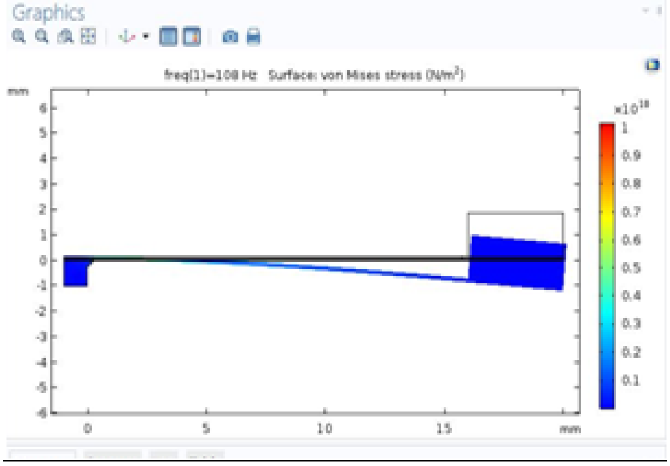

Fig.13 stress on Lithium Niobate material

PZT-5A is used for low power systems and in others applications where is required high di-electric constant, high voltage sensitivity, volume resistivity and stability over a wide temperature range. It is most suitable for making the low power transducers, acoustic sensing elements, flaw detection probes, Piezo Igniters, medical applications etc

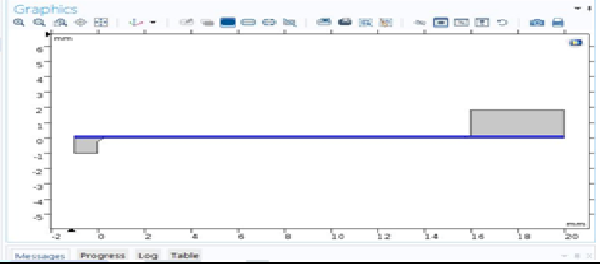

Fig.14 PZT-5A material

Epitaxial PZT thin films grown on silicon substrates are receiving a lot of interest for many applications because their excellent properties are promising for the realization of novel electronic and MEMS devices [22-25]. In general, epitaxial PZT thin films exhibit piezoelectric and ferroelectric properties superior to polycrystalline films [26]. It is also known that the epitaxial PZT thin films exhibit not only excellent piezoelectric coefficients but also low dielectric constants due to the high *c*-axis orientation [27, 28], properties that are known to enhance the performance of piezoelectric energy harvesters, as it was mentioned above. In spite of this positive advancement, the research focused on vibration energy harvesting devices based on epitaxial PZT thin

Stress

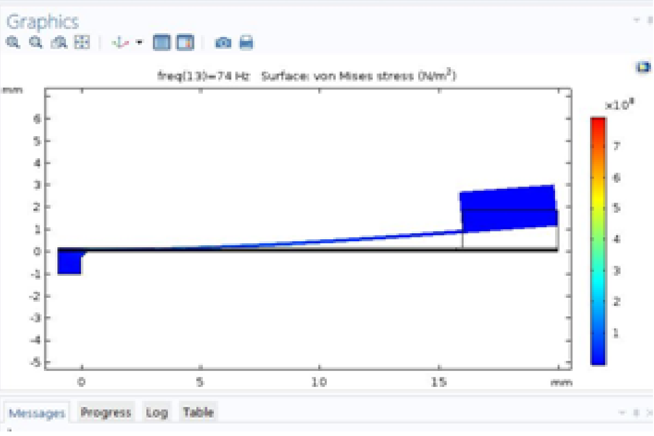

Fig.14 stress on PZT-5A material

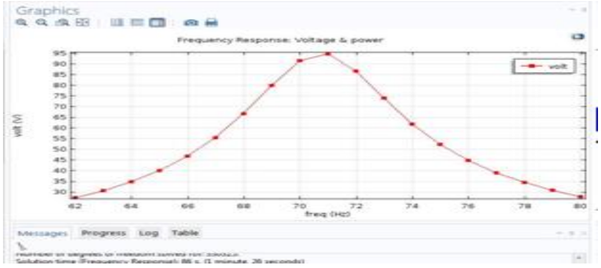

Fig.15 PZT-5A voltage and frequency response

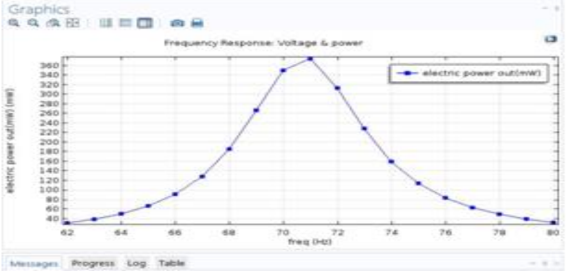

Fig.16 PZT-5A electrical power out

PZT 5H is again used for low power applications where extremely high permittivity, coupling co-efficient and piezoelectric charge coefficient required. It is an excellent material for field sensors, Level sensors, Actuator & Accelorometers, Buzzers ultrasonic NDT applications and material imaging applications.

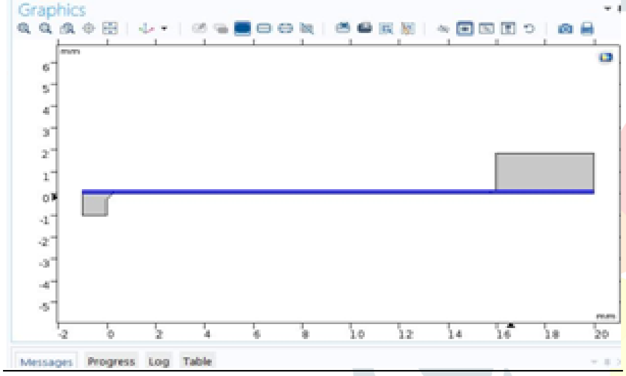

Fig.17 PZT-5H material

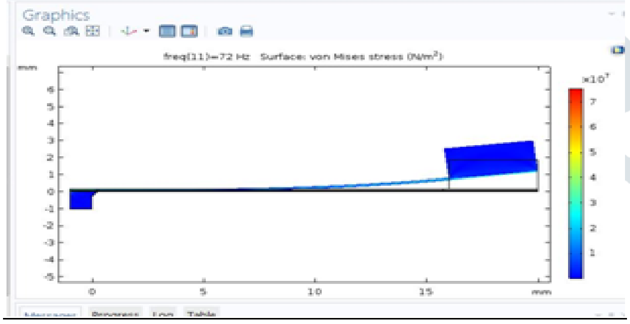

Fig.18 stress on PZT-5H material

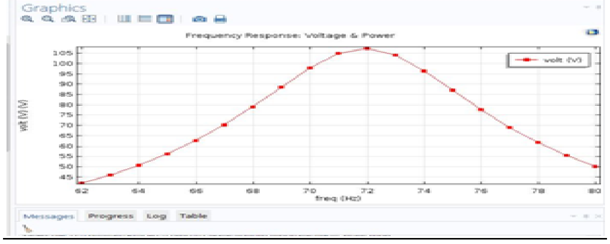

Fig.19 PZT-5H voltage and frequency response

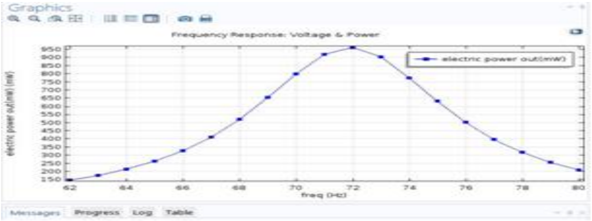

Fig.20 PZT-5H

The focus is placed on the fundamental short-circuit resonance frequencies of these cantilevers in order to compare their electrical performance results. For excitations at these frequencies, the variations of the voltage and current outputs with load resistance are shown in Figures, respectively.

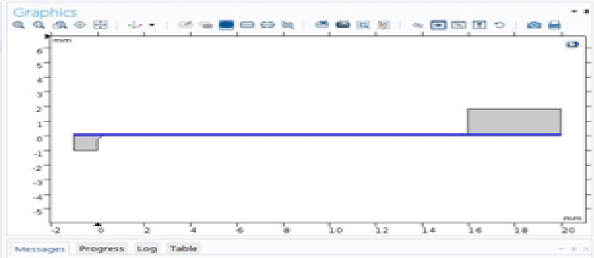

Fig.21 Tellurium Dioxide material

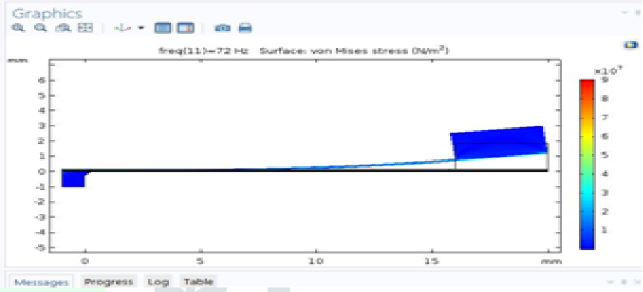

Fig.22 stress on Tellurium Dioxide material

For resonant excitation (which is often the case considered in the literature for the maximum power output), the mechanical quality factor becomes a very critical parameter. Therefore, hard ceramics should be preferred to soft ceramics, and hard crystals should be preferred to soft crystals under resonant excitation.

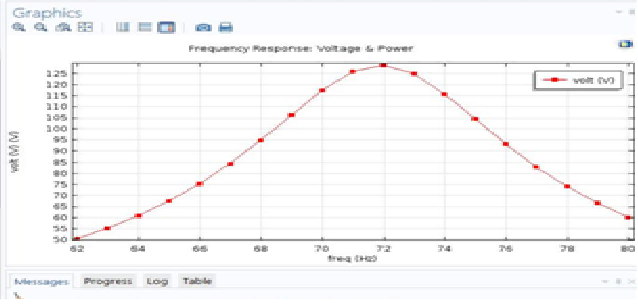

Fig.23 Tellurium Dioxide voltage and frequency response

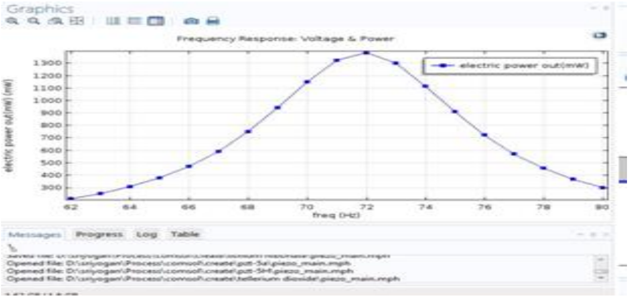

Fig.24 Tellurium Dioxide electrical power out

Table 4.1 : Results of analysis 1 to analysis 6

Piezoelectric Material	Resonant Frequency (Hz)	Potential (Volts)	Electric Power (Mw)	Total Deflection (M)
Aluminium nitride	155 to 165	70.8	209	1.2e9
Tellurium Dioxide	62 to 80	129	1385	3.8e7
Lithium Niobate	108 to 112	57.65	277	0.6e10
Gallium Arsenide	62 to 80	64.5	346	2e8
PZT-5A	62 to 80	95	375	4.2e8
PZT-5H	62 to 80	107	962	3e7

CONCLUSION

Throughout this investigation, multiple specimens of each composition were tested at each condition, and the average value of each property was determined A Bimorph has been designed with dimensions 100mm × 30mm × 4mm in COMSOL Multiphysics 3.5. Then providing it boundary conditions as one side fixed and other side free constraints. A force of 20N/m2 along Y direction is made on the top side. Table 1 shows the results of analysis 1 to analysis 6. This analysis has been done with three different piezoelectric materials PZT-5, PZT-5A and PZT-5H with Aluminum as base material for obtaining modal analysis from these three models with same dimensions as 100mm × 30mm × 4mm. Modal analysis is done for five modes in COMSOLThe design of piezoelectric cantilevers to effectively convert ambient vibrations and flows into electricity. Such devices provide affordable, sustainable and maintenance-free power solutions for low power wireless and portable devices. Upon review of published literature in this field, it was found the current design of the piezoelectric cantilevers needs to be modified with an effective way of converting mechanical energy into electricity, from piezoelectric cantilevers. From Analysis 1 to 6 it can be concluded that for designing a unimorph with low resonant frequency the preference should be given to Tellurium Dioxide, Aluminum Gallium Arsenide, PZT materials respectively.. As gold is much costly than Aluminum therefore when cost doesn't matters much with the results Aluminum can be preferred over gold.

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