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Research paper

Comparative analysis of MEMS piezoelectric cantilever beam for energy harvesting application based on mechanical vibrations

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Abstract

One of the significant application of microelectromechanical systems is energy harvesting. In recent years cantilever beam based on piezoelectric materials have garnered paramount interest for mechanical vibration to electric energy conversion. Research work are being carried out to harness maximum amount of power out of vibrations. This research work is based on the design and simulation of cantilever beamwith eight different piezo-materials for energy harvesting from ambient vibrations and comparison of observed parameters. This cantilever beam consist of fixed end made of stainless steel, a movable end with piezo-material, a proof mass at the movable end. Simulations were performed using COMSOL multiphysics software. In the analysis, specific load, acceleration and dimensions were considered and simula-tion was done for five different characteristic features like stress distribution, surface potential distribution, frequency response, acceleration dependence and load dependence. Barium Titanate gave a maximum surface potential of 2.75V at hinges. Quartz, barium titanate both gave equal and maximum power output of 5.3mW.

Keywords:*Barium Titanate; Cantilever Beam; COMSOL Multiphysics; Energy Harvesting; Microelectromechanical Systems.*

1. Introduction

The method of obtaining energy from surrounding places and transforming it into usable electric form is called as power or energy harvesting (scavenging). Recent development of VLSI and wireless technology has enabled rapid increase in the methods of power harvesting. The field of energy scavenging from vibrations encapsulates material science, mechanics and electrical circuitry. Many sources of providing ambient energy are available like ambient incident light, human body functions, vibrations, acoustics, electromagnetism,etc each of these sources has its own drawbacks and advantages. Moreover storing the harvested energy is also a prime challenge.

The development of MEMS technology has made a remarkable achievement in integrating the sensors and thereby reducing down the size. Also they are more convenient due to batch processing even at reduced unit cost.

Few of the energy harvesting sources that utilize MEMS include harvesting from human limb motions [1], human jaw movements [2], human heartbeats from self powered pacemakers [3], computer mouse clicks [4], human walking [5], walking with loads [6], knee motion during walking [7-8], energy harvesting from shoes [9], heel strikes [10-11], folded elastic strip based triboelectric nanogenerator [12], shrinking and enlarging of rib cage during respiration [13]. Other research works also involved the ways of storing such harvested energy [14-16]. Wearable energy harvesters have manifested with features like less battery weight, less maintenance and continued longevity [17].

Three modes of vibration to electric energy conversion mechanism are available they are electromagnetic [18][19], electrostatic [20][21] and piezoelectric [22][23]. Many of the research work involving experimental findings on all energy conversion procedures for low power generations from surrounding vibrations have indicated that the piezoelectric transduction mechanism have got good remarks in recent years [24]. The general representation of piezoelectric MEMS energy harvester is shown below:

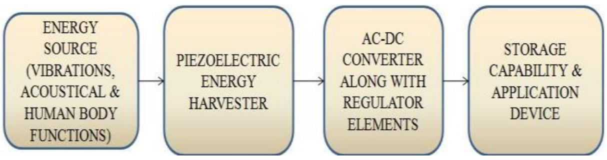

Fig. 1: General Representation of Piezoelectric MEMS Energy Harvesting Device.

2. Piezoelectric cantilever beam

The piezoelectric effect occurs in two ways. One is piezoelectric effect occurring in direct way which involves materials capability to change applied electrical potential into mechanical strain. This conversion of electrical charge into mechanical movement can be used for actuating. The general equations governing piezoelectricity is given by:

$$D=dT+\varepsilon E$$

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where, 'D' refers electrical polarization (c/m^2), 'T' refers stress vector (N/m^2), 'd' refers piezoelectric coefficient matrix, 'ε' refers electrical permittivity (F/m), 'E' refers electric field vector (V/m). Inverse piezoelectric effect is governed by equation:

s=ST+dE

where, 's' refers to strain vector, 'S' refers to Compliance matrix, 'T' refers to stress vector (N/m^2), 'd' refers to piezoelectric coefficient matrix, 'E' refers to electric field vector (V/m).
Cantilever beams as shown in fig. 2 are rigid beams or bar that are fixed at one point and freely suspended at the other point. It creates a bending effect to a certain limit. Beams embedded with piezoelectric material when subjected to mechanical deformation or bending results in charge generation.

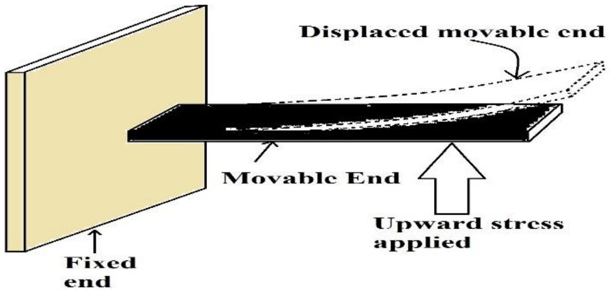

Fig. 2: Basic Cantilever Beam Structure.

Plenty of research works are carried out in this beam. Two cantilever beams with PVDF (Polyvinylidene fluoride) and PZT (Lead ZirconateTitanate) layers were subjected to ambient vibrations using simulation which gave a maximum output power of 14.85µW under 1g (g=9.81 m/s^2) acceleration [25]. Modeling and analysis of multiple cantilever beams have exhibited harvesting of broadband energy from mechanical vibrations [26]. Utilizing T-shaped cantilever beam, the maximum displacement obtained was 2.47mm [27]. Stepped cantilever beam energy harvesting device using PZT material was designed and the simulation results have shown to displace more [28] than the other models. Right angled cantilever beam [29] energy harvester subjected to wind produced a power output of 1.3mW that is twice more than the power output harvested using conventional cantilever beam. Piezoelectric material Potassium Niobate ($KNbO_3$) used such beams produced 7V output voltage [30], Thin walled beam shown output voltage of 1.82V with 10m/s^2 acceleration [31]. Multiple cantilever beams were implemented in roadways to harness energy [32] and changing position of mass upon the beam have profound influence on the output voltage harnessed [33]. Increasing the temperature of the beam subjected upto 160^{0}C can drop power by 60% to 67%. [34] based on acceleration. Inclusion of proof mass can increase the power responsiveness of the harvester [35].
This research work is based on the simulation analysis of MEMS energy harvester based on cantilever beam using eight different piezoelectric materials.These materials are selected based upon their effective nature in generating power. The following table 1 shows the materials used and their properties like relative permittivity, young's modulus, density and coupling factor (k) [36-39].

Table 1: Properties of Materials Used for Analysis

Sl.No	Material used	Coupling factor (K)	Relative permittivity (Dielectric Constant)	Youngs Modulus (GPA)	Density (Kg/m^3)
1	ZnO	0.075	8.5	210	5600
2	ADP-ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	0.30	55.9	67.3	1803
3	PDMS (Poly dimethyl siloxane)	0.055	67	360-870	965
4	PZT-5A (PbZrTio3)-Lead ZirconateTitanate	0.66	1730	48-135	7750
5	Quartz (SiO_2)	0.09	4.52	107	2650
6	Barium Titanate ($BaTiO_3$)	0.35	2920	67	6020
7	PVDF	0.2	13	3	1880
8	Lithium Niobate ($LiNbO_3$)	-	44	245	4640

3. Experimental analysis

The output power is calculated as a function of frequency, magnitude, load impedance and acceleration magnitude after applying acceleration in sinusoidal pattern upon the energy harvester structure. The acceleration applied is 1g (g=9.81 m/s^2), load resistance used is 10kΩ and width of the pate is 14mm. The overall structure in two dimension is shown below:

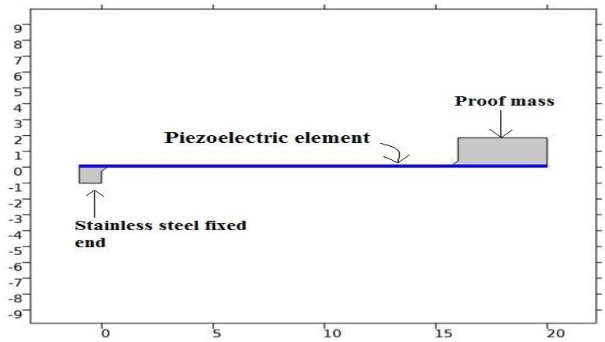

Fig. 3: Energy Harvester Using Piezoelectric Cantilever Beam.

The fixed end is made up of stainless steel and the other point is made up of proof mass. Mechanical deformation in the form of stress is applied at the proof mass end. The piezoelectric material is present the layer in between both and the materials are changed and its characteristic feature is analyzed using simulation.
Assuming the load is exerted upon the free end, the equations governing deflection include the following:

$$\text{Angle of deflection, } \theta = \frac{Pl^3}{2EI} \quad (1)$$

Where 'l' refers length of cantilever beam, 'I' refers moment of inertia of beam, 'E' refers modulus of elasticity, 'P' refers applied load.

$$\text{Maximum Deflection is given by, } \delta_{\max} = \frac{Pl^3}{3EI} (2)$$

Deflection at any side of the beam from a distance 'x' from free end is given by:

$$y = \frac{Px^2}{6EI}(3l\text{-}x) \quad (3)$$

4. Results and discussion

a) Stress distributions:

Simulation work for the above cantilever beam energy harvester is done for eight different piezoelectric materials and the following results are obtained.

Table 2: Maximum Pressure Obtained

Piezoelectric material	Maximum pressure obtained(N/m^2)
ZnO	$1.7x10^7$
PZT-5A (PbZrTio3)-Lead ZirconateTitanate	$1.7x10^7$
LiNbO3 (Lithium Niobate)	$1.2x10^7$
PVDF	$1.7x10^7$
ADP-ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	$1.7x10^7$
Barium Titanate ($BaTiO_3$)	$2.5x10^7$
Quartz (SiO_2)	$3.75x10^7$
PDMS (Poly dimethyl siloxane)	$1.7x10^7$

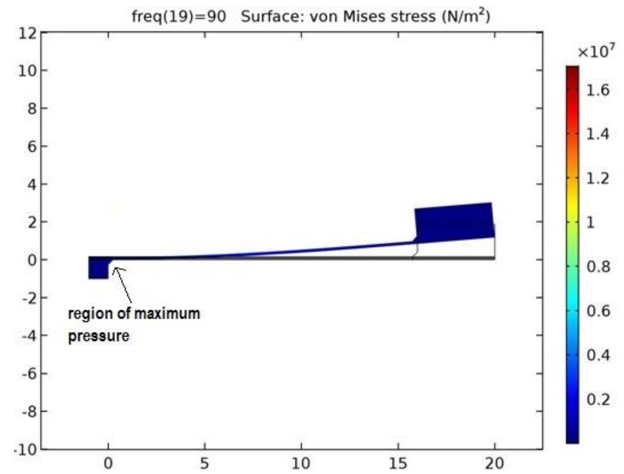

Fig. 4: Stress Distribution Pattern of ZNO.

Maximum pressure is experienced at the hinges of the interface between the stainless steel fixed end and the beam. The reason is that the hinges are placed adjacent to fixed end. From the analysis it is found that the highest pressure is experienced by Quartz and least pressure at the hinges is experienced by $LiNbO_3$.

b) Surface potential distribution:

Upon application of force, deformation takes place and it leads to development of electric potential on the surface of the piezoelectric material. Following table shows the maximum potential developed for the chosen piezomaterials.

Table 3: Maximum surface potential obtained

Piezoelectric material	Maximum surface potential obtained (V)
ZnO	-1.1
PZT-5A (PbZrTio3)-Lead Zirconate Titanate	-1.1
LiNbO3 (Lithium Niobate)	0.8
PVDF	-1.1
ADP-ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	-1.1
Barium Titanate ($BaTiO_3$)	2.75
Quartz (SiO_2)	1.75
PDMS (Poly dimethyl siloxane)	-1.1

The maximum voltage generated is for Barium Titanate 2.75V. Moreover close observation of the potential distribution is also not uniform. As shown in fig. 5, potential is least or not at all generated at the fixed end, but they are maximum generated at the hinges and the surface of the piezomaterial nearby fixed end but gradually reduces as it moves towards the proof mass.

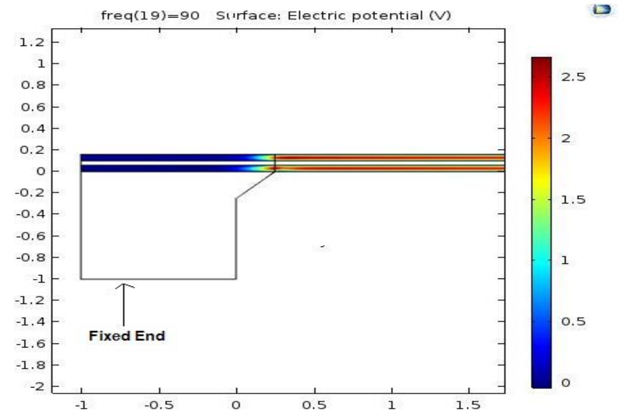

Fig. 5: Surface Electric Potential Distribution of Barium Titanate highlighting the Potential Is Zero or Very Less at the Fixed End but gradually increases Beyond the Hinges.

c) Frequency response characteristics:

For the frequency response characteristics, different piezomaterials are simulated for its output voltage generated, mechanical power and electrical power output parameters for varying frequency between 60Hz and 90Hz and it is found that at 75.5Hz, all the three parameters obtained are at its maximum for ADP, PDMS, PVDF, PZT-5A &ZnO. Following table shows the maximum voltage observed for the selected frequency of observation.

Table 4: Maximum Voltage Observed for Varying Frequency

Piezoelectric material	Maximum voltage obtained for specific frequency of observation(V)
ZnO	5.5 V at 75.5Hz
PZT-5A (PbZrTio3)-Lead ZirconateTitanate	5.5 V at 75.5Hz
LiNbO3 (Lithium Niobate)	0.00625V at 90Hz
PVDF	5.5 V at 75.5Hz
ADP-ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	5.5 V at 75.5Hz
Barium Titanate ($BaTiO_3$)	0.425V at 90Hz
Quartz (SiO_2)	0.045V at 81 Hz
PDMS (Poly dimethyl siloxane)	5.5 V at 75.5Hz

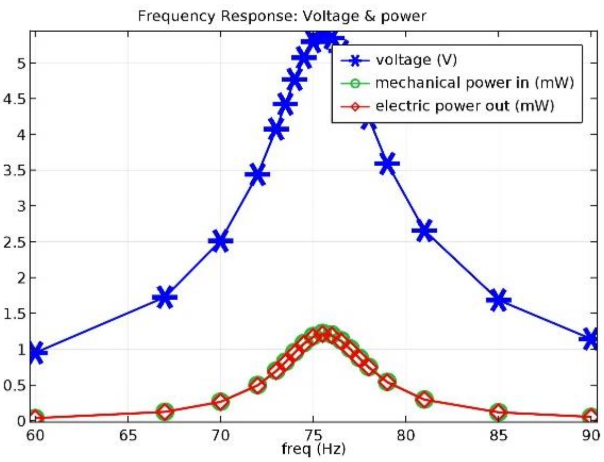

Fig. 6: Frequency Response versus Voltage, Electrical and Mechanical Power Output for Polydimethylsiloxane (PDMS).

This frequency is the resonant frequency of that particular piezomaterial for this dimension of cantilever beam structure. The maximum voltage, mechanical and electrical power obtained at 75.5Hz forpolydimethylsiloxane (PDMS) is shown above in figure 6.

d) Load dependence characteristics

The dependence of voltage, electrical and mechanical output power on load varying between $10^2\Omega$ and $10^5\Omega$ is analyzed at resonant frequency 75.5Hz for different piezomaterials embedded upon the cantilever beam. Simulation results obtained showed a constant

6.25V output power at the maximum $10^5\Omega$ load and 1.5mW electrical power output for almost all selected piezomaterials.
Load dependence characteristics of Lithium Niobate ($LiNbO_3$) is shown below:

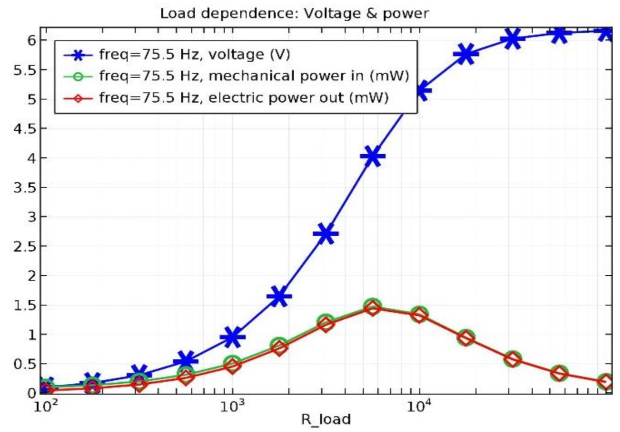

Fig. 7: Load Dependence Characteristics of $LINBO_3$.

e) Acceleration dependence characteristics

Acceleration given on the flexible end is varied between 0g to 2g and the piezoelectric cantilever beam energy harvesters characteristic feature for voltage, electrical and mechanical power output is analyzed at the resonant frequency 75.5Hz. Values obtained for electrical power output (mW) for different piezoelectric materials is tabulated below and fig 8 shows the characteristic curve for quartz.

Table 5: Maximum Electrical Power Output Observed

Piezoelectric material	Maximum electrical power output (mW)
ZnO	0.0001
PZT-5A (PbZrTio3)-Lead Zirconate Titanate	5
LiNbO3 (Lithium Niobate)	5
PVDF	1
ADP-ammonium dihydrogen phosphate ($NH_4H_2PO_4$)	0.0001
Barium Titanate ($BaTiO_3$)	5.3
Quartz (SiO_2)	5.3
PDMS (Poly dimethyl siloxane)	0.001

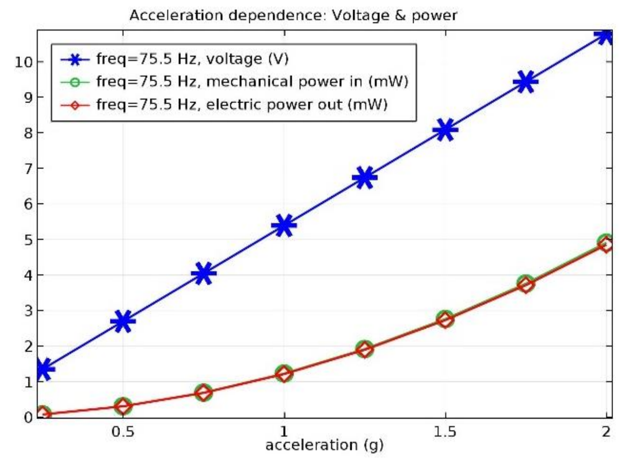

Fig. 8: Acceleration Dependence Characteristics of Quartz.

5. Conclusion

This research work focuses on the simulation analysis and characterization of eight different piezoelectric materials embedded upon a cantilever beam energy harvester of a specified dimension. Maximum pressure is exerted upon the hinges near the fixed end for all materials upon any force exerted. Barium Titanate produces more surface potential and also it exhibits high dielectric property and due to this reason they are used as capacitors in storing the developed charge. Vibrating frequency also profoundly influences the cantilever beams output power. The resonant frequency varies for different dimension of the cantilever beam and applied force. In application point of view MEMS devices based on this cantilever beam can be optimized for better results. However other parameters like sensitivity, S/N ratio, maximum displacement, environment also need to be considered and optimized to achieve a better energy harnessing device.

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