Volume 3, Issue 11, November 2013 ISSN: 2277 128X
International Journal of Advanced Research in Computer Science and Software Engineering
Research Paper
Available online at: www.ijarcsse.com

Design and Analysis of Micro-cantilevers for Energy Harvesting

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Abstract- Micro Electro Mechanical Systems (MEMS), are generally considered as micro systems consisting of micro mechanical sensors, actuators and microelectronic circuits. MEMS technology is replacing batteries due to their limitations in Wireless Sensor Node applications such as large volume, limited lifetime and environmental pollution. Energy harvesting from ambient vibration can be one of the reliable alternatives by using PMPG (Piezoelectric Micro Power Generator) which is simply a cantilever structure tuned to resonate at environmental frequencies. At resonance, strain is induced in a layer of the beam made from the piezoelectric material resulting in the generation of electricity. Recent studies have found that the most available environmental frequencies are on the order of 100 Hz. This paper emphasize on design issues of the basic component i.e. micro-cantilevers. Different shapes of cantilevers are designed in ANSYS 10 for decreasing operating frequency. Resonance frequencies are observed for modal analysis and frequency analysis with different substrate materials, varying shim length and width of cantilever. A design having resonant frequency of 147Hz is obtained as the optimal modal in low vibration ambient. Structure of unimorph is designed with PZT-5A layer in COMSOL 3.5 Multiphysics generating voltage of the order of 2.7 volts.

Keywords- MEMS, PMPG, Resonance frequency, micro cantilevers, unimorph

I. Introduction to MEMS Technology

Microelectromechanical systems (MEMS) is the technology of the very small systems, and merges at the nano-scale into nanoelectromechanical systems (NEMS) and nanotechnology. MEMS are made up of components between 1 to 100 micrometers in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 micrometers to a millimeter [2]. It is the integration of mechanical elements, sensors, actuators and electronics on a common silicon substrate through micro fabrication technology. While the electronics are fabricated using integrated circuit (IC) process sequences (e.g., CMOS, Bipolar, or BICMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices[3].

MEMS fabrication technology is inspired from Microelectronics techniques like photolithography, thin film deposition by chemical vapor deposition (CVD) or physical vapor deposition (PVD), thin film growth by oxidation and epitaxial, doping by ion implantation or diffusion, wet etching, dry etching, etc have all been adopted by the MEMS technologists. Moreover, MEMS has spurred many unique fabrication techniques introducing surface micromachining, bulk micromachining, LIGA (a German acronym for lithography (**LI**thographie), electroforming (**G**alvanoformung), and molding (**A**bformung)), etc. [4].

PMPG

The Piezoelectric Micro Power Generator uses a cantilever beam structure When the generator is subjected to vibrations in the vertical direction, the support structure will move up and down in synchronism 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 [5].

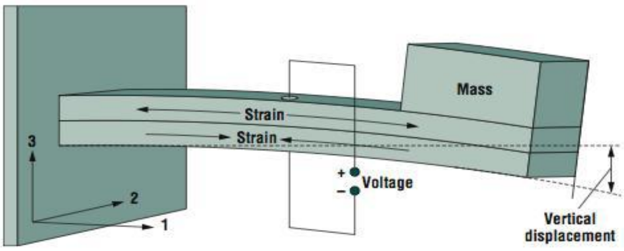

Figure1: Shows that strain is generated along the length of the beam, 3-1 mode

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. A portion of the cantilever beam is covered by electrodes that conduct the electric charges produced to an electrical circuit.

Piezoelectric Materials

A majority of piezoelectric generators use some variation of lead zirconate titanate (PZT). Typically, PZT is used for piezoelectric energy harvesters because of its large piezoelectric coefficient and dielectric constant, allowing it to produce more power for a given input acceleration[6]. Another less common material is aluminum nitride (AlN). Other materials are Ammonium Dihydrogen Phosphate, Zinc Sulfide, Zinc Oxide, Tellurium Dioxide, Gallium Arsenide, Cadmium Sulfide, Bismuth Germanate, Rochelle Salt, Quartz, Lithium Tantalate, Lithium Niobate, Barium Sodium Niobate[7].

Coupling Modes:

Piezoelectric materials have a built-in polarization, and therefore respond differently to stresses depending on the direction. There are two primary modes of electromechanical coupling for piezoelectric materials: the 3-1 mode and the 3-3 mode. In the 3-1 mode, the electric field is produced on an axis orthogonal to the axis of applied strain, but in the 3-3 mode the electric field produced is on the same axis as the applied strain [8].

Unimorph:

A piezoelectric unimorph has one active (i.e. piezoelectric) layer and one inactive (i.e. non-piezoelectric) layer.

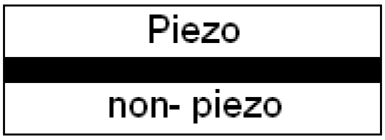

Figure 2: A Unimorph

In the case where active layer is piezoelectric, deformation in that layer may be induced by the application of an electric field.This deformation induces a bending displacement in the cantilever. The inactive layer may be fabricated from a non-piezoelectric material[9].

Bimorph:

A bimorph is a cantilever that consists of two active layers: piezoelectric and metal.

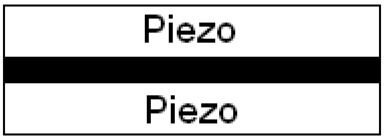

Figure 3: A bimorph

These layers produce a displacement via:

1) Thermal activation (a temperature change causes one layer to expand more than the other).

2) Electrical activation as in a piezoelectric bimorph (electric field causes one layer to extend and the other layer to contract)[9].

Cantilever: Cantilevered beams are the most ubiquitous structures in the field of microelectromechanical 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:

$$\delta = \frac{3\sigma(1-\nu)}{E}\left(\frac{L}{t}\right)^2$$

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 dc-coupled sensors.

The second is the formula relating the cantilever spring constant k to the cantilever dimensions and material constants:

$$k = \frac{F}{\delta} = \frac{E\omega t}{4L^3}$$

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

$$\omega_0 = \sqrt{\frac{k}{m}}$$

A change in the force applied to a cantilever can shift the resonance frequency.

Analysis options:

In this work modal and harmonic analysis are performed on micro cantilevers.

Modal Analysis: The goal of modal analysis in structural mechanics is to determine the natural mode shapes and frequencies of an object or structure during free vibration.It is also possible to test a physical object to determine its natural frequencies and mode shapes. This is called an Experimental Modal Analysis.

Frequency Response Analysis: This analysis is used to study the displacements, stresses, and strains that result in a 3D body given applied loads and constraints. It is used here to determine the displacement of cantilever due to a known applied force.

II. Results And Observations:

Basic cantilever structure has been designed with 2D and 3D view with rectangle and block respectively. Modal analysis is run with five different modes and different analysis is as follows:

1). A cantilever of dimensions 500µm × 10µm is designed with different materials. Element type used is Shell93 with real constant thickness at all nodes I,J,K,L of .01µm.

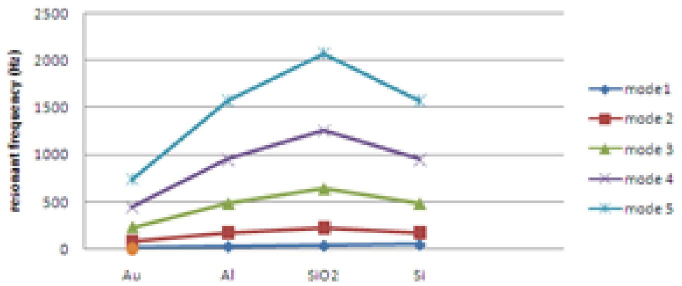

Figure 4: Mode frequencies for cantilever with different materials

From figure4 it is observed that lower resonant frequencies are obtained from a micro cantilever with material preference as gold, aluminum, silicon dioxide, silicon respectively.

2). Secondly the variation of cantilever length with fixed width of 10µm is observed as shown in figure5. This simulation shows an important characteristic of cantilevers that higher the cantilever length higher will be the deflection and lower the frequency response.

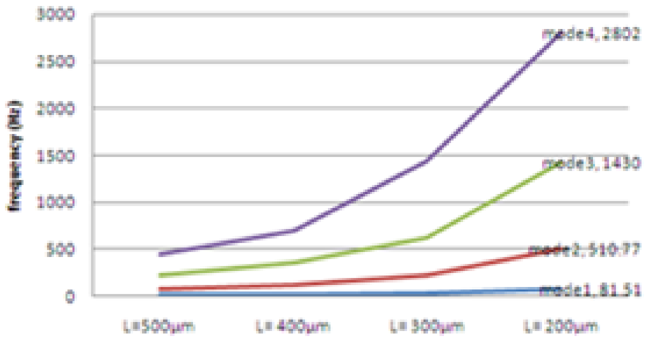

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Figure 5: Mode frequencies for Au cantilever with fixed width

3). Next observation was made by varying the cantilever length fixed at 500µm and varying width. Subspace modal analysis was performed on gold cantilevers with shell 93 element type of 0.01µm node thickness at nodes i, j, k, l.shown in figure6.

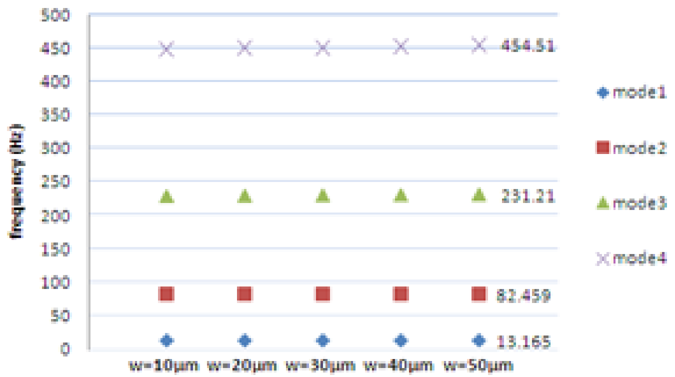
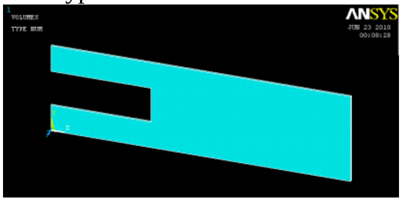


Figure 6: Mode frequencies for Au cantilever with fixed length.

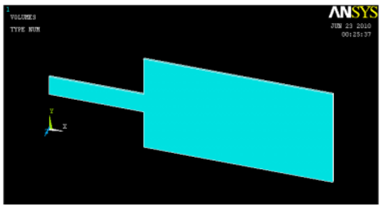
Above simulation shows that the variation in width of cantilevers doesn't affect very much on mode frequency and deflection, as mode frequencies varies a very little with increase in the width.

4). In this analysis type some other shapes of cantilever are designed other than the basic structure as shown in figure6.Silicon is the material used here with solid 95 as the element type.

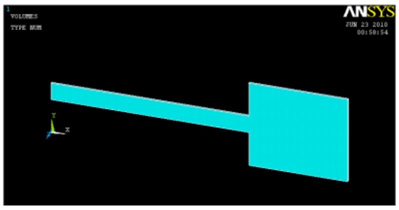
DESIGN 1



DESIGN 2



DESIGN 3



DESIGN 4

Figure 7: Different shapes of silicon cantilevers

The dimension details of above said models is:
DESIGN 1; 30mm×10mm×0.2mm
DESIGN 2: A block of 10mm×4mm×0.2mm is taken out from centre of design1 structure.
DESIGN3: Two blocks of 10mm×4mm×0.2mm is taken out from both edge of design1 structure.
DESIGN4: Two blocks of 20mm×4mm×0.2mm is taken out from both edge of design1 structure.

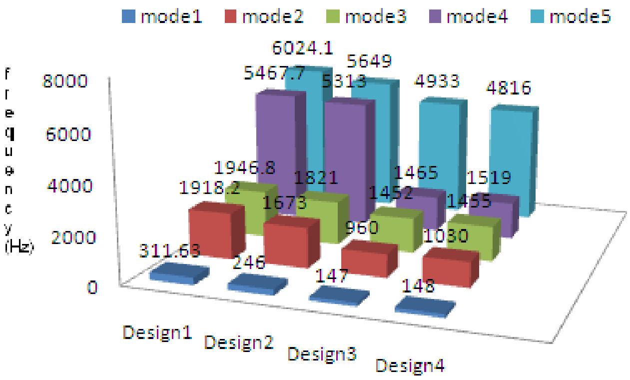


Figure8: Mode frequencies for all four design

Observing above results it can be said that design shape 3 offers lowest resonant frequency and can be used for shim formation of piezoelectric generator. Its nodal solution in mode1 is shown in figure9 with a maximum deflection of 162.661µm.

Figure9: Nodal analysis for Design3 (mode 1)

5). A 30mm×10mm×400µm unimorph was designed in COMSOL 3.5 with gold as shim material and PZT-5A as the piezoelectric layer then, modal analysis was performed to obtain the natural frequencies of such design as shown in figure 10.

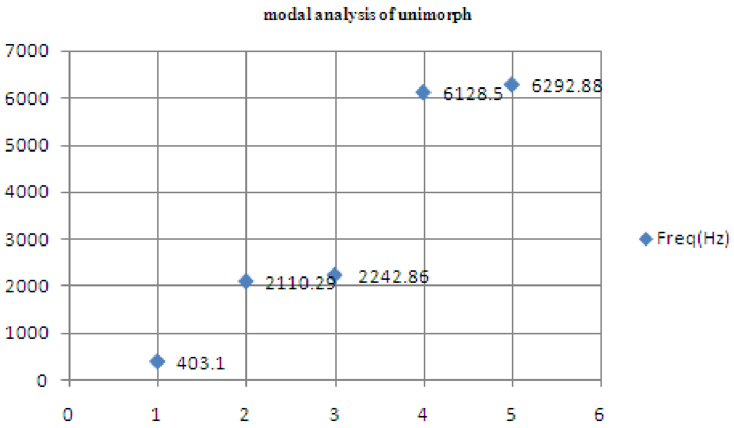


Figure10: Modal analysis of unimorph(30mm×10mm×0.4mm)

The modal analysis shows that the unimorph will have a minimum mode frequency of 403 Hz and maximum displacement in Z direction is 124µm.

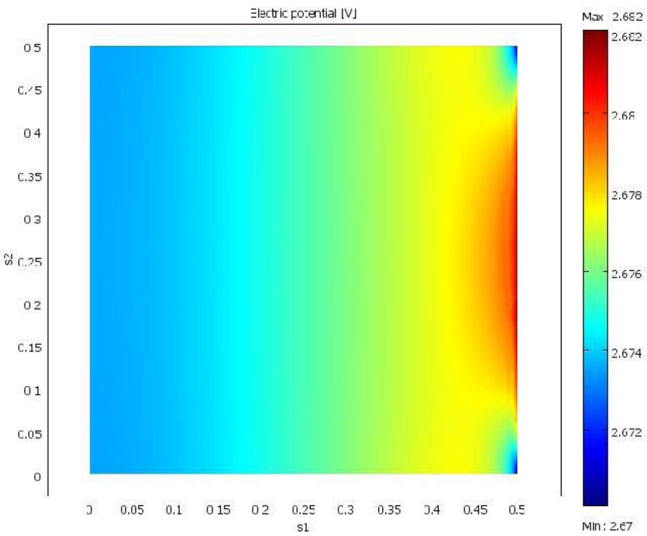


Figure11: Contour showing electric potential generated by unimorph due to 10N/m3

Figure11 shows that the piezoelectric generator generates a power of around 2.682 volts when a force of 10 N/m3 was applied on the PZT-5A layer.

III. Conclusion and Future work:

All above results and analysis will become the basic understanding for designing a PMPG with low resonant frequencies, so as to harvest environmental energy into electrical power. It can be concluded that variation of cantilever length makes large deflection. And variation in width of cantilevers doesn't affect very much on mode frequency and deflection, as mode frequencies varies a very little with increase in the width. Harvesters delivering sufficient power for sensors operating in an industrial environment have been developed, but difficulties are encountered when the devices to be powered are located on the human body. So Future work can be design based on the impact of moving mass on piezoelectric bending structures in which a mass is made to be float between the two piezoelectric micro-cantilevers with the effect of human limbs, therefore the designed cantilevers should respond to lower frequencies i.e. below 1KHz.

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