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Research Article

DESIGN AND ANALYSIS OF A MICROCANTILEVER SYSTEM FOR A VIBRATION BASED MEMS PIEZOELECTRIC ENERGY HARVESTER

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A B S T R A C T

A piezoelectric based MEMS energy harvester has been designed as a replacement for the conventional rechargeable batteries/cells, where frequent replacements and maintenance of power source are being required in remote applications. In the recent years, cantilever-based designs are gaining popularity in the field of MEMS piezoelectric vibration energy harvester, due to its small size, simple design, power efficiency and stability. In cantilever-based vibration energy harvesters, the active piezoelectric area near the clamped end can accumulate maximum strain-generated electrical charge due to the conversion of mechanical vibrations into electrical energy, while the free end is used to house the proof mass to improve stable power output without compromising the effective area of the piezoelectric generator. This work deals with the design and simulation of the MEMS-based energy harvester using COMSOL Multiphysics. In this work, two designs were modeled and analysed for their mechanical and electrical properties. In the Design-I, four variable-size cantilevers were fixed on a diagonally-mounted beam on a square fixture, whereas in Design-II four equal-size cantilevers were mounted on a Z-shaped frame fixed diagonally on a square fixture. In both the designs, Aluminium Nitride and gold layer were used as a piezoelectric material and voltage tapper, respectively. Both the designs were characterized for the Von Mises stress, displacement and output voltage. The results of this study exhibited that the design-II was found to be a better design for energy harvesting than the design-I, which is evident from the maximum output voltage, stress withstanding capacity and maximum displacement characteristics. This simulation work will be realized into practical energy harvesters, after optimizing the various design parameters during the fabrication phase. The results of this simulation study will find future scope of MEMS piezoelectric harvesters in the fields of power MEMS and Green Technology.

INTRODUCTION

In recent years, lot of effort has been deployed to study self-powered electronics for developing efficient renewable power sources or energy scavengers to replace traditional batteries as a promising solution and has attracted noticeable research interests. Therefore, novel energy harvesting techniques have been endeavored to collect and convert ambient energy into usable electrical power. Energy harvesting is an enabling technology to capture small amount of energy, which would be wasted as heat, light, sound, vibration or movement, but attempts have been made to make energy efficient devices[1]. Out of various possible energy harvesting technologies, piezoelectric vibration energy harvesting has emerged as a method of choice for powering micro scale devices[2]-[5] as well as its ability to fabricate themicro-sensors and micro-actuators using MEMS technology that attracted many researchers to work in this field. For example, many pressure sensor designs have been designed based on various physical properties like piezo-resistive, piezoelectric, capacitive, magnetic, and electrostatic. In piezoelectric energy, cantilever geometry is one of the most widely used component in deciding the efficiency of the piezoelectric energy harvesters, especially for mechanical energy harvesting from vibrations, since a large mechanical strain can be produced within the piezoelectric material using vibration. Vibration-based energy harvesters (EHs) using MEMS technology were reported to generate electricity based on piezoelectric mechanism[6]-[9]. Analysis of the different geometries of micro-cantilevers and their performances in terms of deflection and shift in resonance frequency due to addition of mass were simulated to increase the sensitivity of those devices[10]-[13]. Finite Element Analysis is used to find the most critical location for

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highest stress concentration, since certain mechanical phenomenon applied on the object and its reaction could be visualized in FEA[11], [13]-[17]. These results were analysed in terms of von Mises stress. The distribution of von Mises stress along the cantilever gave the point of highest stress. The same analysis methods were used to find the point of fracture, in case the structure is not able to withstand the given load [14]. The improvement of mass detection sensitivity using a new method of analysis was applied to piezoelectric coupled sensor. First, the performances of an original method of analysis were proved based on the structures resonance amplitude, which significantly increases the mass detection sensitivity and improves the response time. Second, the advantage of coupled micro-cantilevers with a piezoelectric detection was proved that leads to a relative voltage variation. Piezoelectric application was used in ultrasensitive detection of highly diluted biological fluids[18].

Mounika Reddy and Sunil Kumar were carried out the design, analysis and simulation of MEMS based piezoelectric micro-cantilevers of various shapes to analyze their sensitivity[19]. The micro-cantilever beams were made up of single crystal silicon. The analytical simulation of design was done by FEM (COMSOL Multiphysics). The analytical model of the cantilever beam was analyzed and found that the changes in the sensitivity of a cantilever beam with respect to change in shape for the applied force was optimized. Ashish kumar et al. studied the cantilever based MEMS pressure sensor using different piezoelectric materials for micro-cantilever and analysed the output characteristics in terms of displacement and varying applied pressure. Further, it was observed that the induced voltage found to be almost linear with the applied force. Thus, these comparative studies of simulation and modeling could be used as the guidelines for a design and optimization of performance of the different piezoelectric micro-cantilever pressure sensors.For simulating the cantilever design, microcantilever movement is one of the key factors that influence the performance characteristics of the piezoelectric devices. There are two types of cantilever movement viz. static and dynamic. In the static type, the bending of the structure occurs due to an attached mass or force acting upon it, whereas in the dynamic type the resonant frequency shifts due to the mass getting attached to it. In the present work, we simulated two microcantilever designs viz., Design-I and Design-II and studied their characteristics in terms of design compatibility, break-down point and displacement of the microcantilever. Further, the sensitivity of the microcantilever was calculated and compared for both the Design - I & II, which exhibited that the Design-II characteristics was found to be better choice for energy harvester applications.

MATERIALS AND METHODS

The constitutive laws in a mathematical model involve physical properties of the materials and the properties may depend on the modeled variables (the "dependent variables"). For example, in the analysis of vibration, mechanical properties often depend on the stress applied. There a stress with standing material, of which the designer can select a better choice for the proposed designs. In this work, Silicon (Si) was used as a substrate material due to its good restoring properties and structural integrity. Further, the breakage frequency is very high at150 GPa, which suggests that the silicon will be a suitable material for MEMS designs.There are materials like zinc oxide and lead zironate titanate, which are commonly used for nearly all-thin film and bulk piezoelectric MEMS applications. In the proposed designs, Aluminum Nitride (AlN) and Gold (Au) were chosen as piezoelectric and charge carrier materials. AlN was chosen for the proposed designs due to its compatibility with the standard MEMS processing techniques, excellent crystallinity and flexible orientation-reproduction capability on various kinds of substrates. AlN exhibits both moderate electromechanical coupling in conjunction with high acoustic and surface velocities. Additionally, AlN has low dielectric losses and high breakdown field, therefore, the figure of merit for AlN will be 24 times higher that is comparable with that of lead zirconate titanate.

Device Modeling

The multiple microcantilevers based piezoelectric energy harvester was designed and modeled by the following assumptions and reasons:

1. Microcantilevers are very sensitive to small disturbances and produces measurable deflections.
2. Creating a piezoelectric layer on the surface of the microcantilevers develop piezoelectric effect under the application of small force/mass.
3. In this work, Aluminum Nitride piezoelectric layer was used to convert the mechanical stress/strain into electric charge/voltage using direct piezoelectric effect.
4. When the microcantilever experiencing a small disturbance/vibration on the surface, it undergoes mechanical strain and changes crystal orientation of the piezoelectric material. Then, the change of crystal orientation produces dipole moment and develops the electric charge. The output of the electric charge is directly proportional to the force experienced from the surface of the cantilever.
5. Developing this kind of energy harvesters can produce electric energy from the vibration and wind therefore, it can be used for renewable energy source for smart city developments.

Polla and Francis [20] outlined the basic physical principles for the design of piezoelectric MEMS and they are governed by the following relationships:

$$S_i = s_{ij}^E T_j + d_{ki} E_k \tag{1}$$

$$D_l = d_{lm} T_m + \varepsilon_{lm}^T E_n \tag{2}$$

where *S, D, E, and T* are the strain, dielectric displacement, electric field, and stress, respectively. Here $i,\ j,\ m\ =\ 1,\ldots,6;\ k,\ l,\ n\ =\ 1,\ 2,\ 3;\ d\ and\ \varepsilon$ are the elastic compliance, piezoelectric constant, and dielectric permittivity, respectively.

In this simulation, finite element analysis was employed to study the effects of stress on the structure of the cantilever designed using COMSOL Multiphysics. Simulation in COMSOL involves several steps which include selecting physics, defining geometry, choosing materials, defining meshing, simulation, and analysis of results. Further, the structural mechanics has to be selected according to the mode defined for the cantilever.

Dimension of the proposed microsensor

The Design-I has six microcantilevers fixed with the diagonal support beam having the dimensions of 32 µm length, 2 µm width and 1.5 µm height. The diagonal beam was fixed with a square shaped outer frame having the dimensions of 28 µm length, 6 µm width and 1.5 µm height. Four microcantilevers of 1µm width and 5 µm length are placed 2 at each end and each side of the center support and 2 microcantilevers dimension of 1 µm width and 8 µm length are placed at the center of the diagonal support on either side of the support.

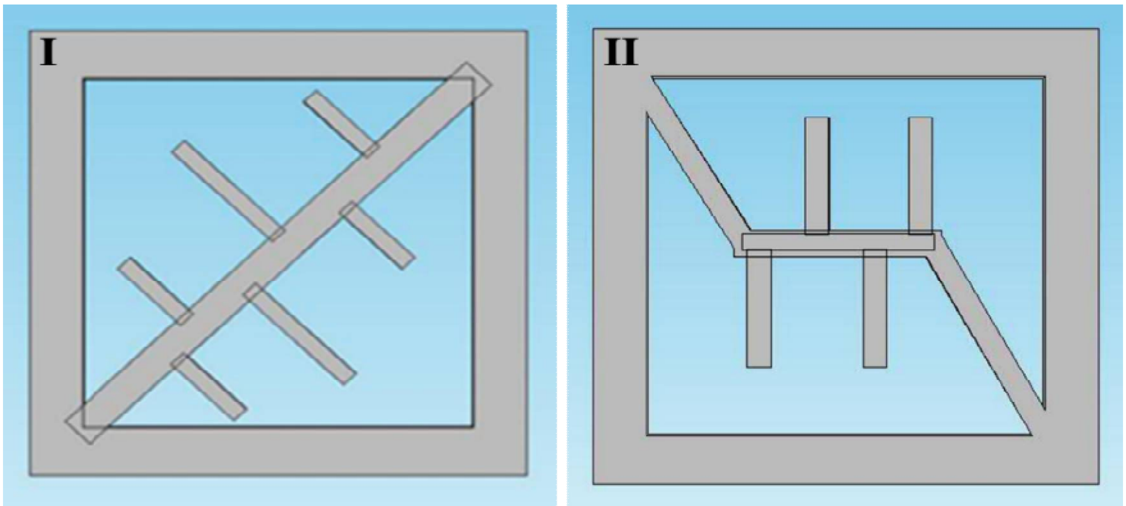

Figure 1 2D view of the proposed piezoelectric energy harvester Designs I & II.

The Design-II has 4 microcantilevers having the dimensions of 8 µm length, 2 µm width and 1 µm height. Each cantilever was fixed with z-shaped supporting frame and the frame was fixed with a square shaped outer frame having the dimensions of 28 µm length, 6 µm width and 1.5 µm height. Figure 1 shows the 2-D view of the proposed microcantilever Designs I and II.

Mesh

Mesh is a partition of the geometry into small units of a simple shape called mesh elements to study the properties, size, shape and boundary conditions of the proposed energy harvester using FEA tools. In the proposed model, a free tetrahedral mesh was used in all dimensions and a total number of 198543 and 215511 elements were employed for Design-I and Design-II, respectively. Figures 2(a) and 2(b) show the mesh partition of Design-I and Design-II of the proposed energy harvester system.

RESULTS AND DISCUSSION

Total Displacement of the Microcantilever

Figures 3 (a & b) show the line graph between the arclength of the cantilever and displacement of the microcantilever Design-I and II, respectively. From the graphs, the displacement was found to be maximum at the arclength of 8 µm (free end) and minimum where the arclength is 0 µm (fixed end) of the cantilever. It is obvious that the arclength of 8 µm is free to deflect, when a force is applied on it, and hence a large deflection and less stress were noticed. Even though, the large deflection at the free end can change the crystal orientation of piezoelectric material, which can develop the charge carriers, but the stress value was found to be zero at the free end that generated a very little potential at the free. Conversely, the stress was found to be maximum at the fixed end and thereby it generated maximum potential at the fixed end. Comparing the two Designs I & II, the Design-I generated 20 times higher displacement than Design-II at the free end, which exhibited better stability of the Design-II over Design-I.

Von Mises stress analysis

Figure 4 shows the Von Mises stress analysis for a uniform boundary load of 100Pa applied to the entire structure of Design-I in the vertical direction. In Figure4(a), red color indicates maximum stress experienced in the cantilever

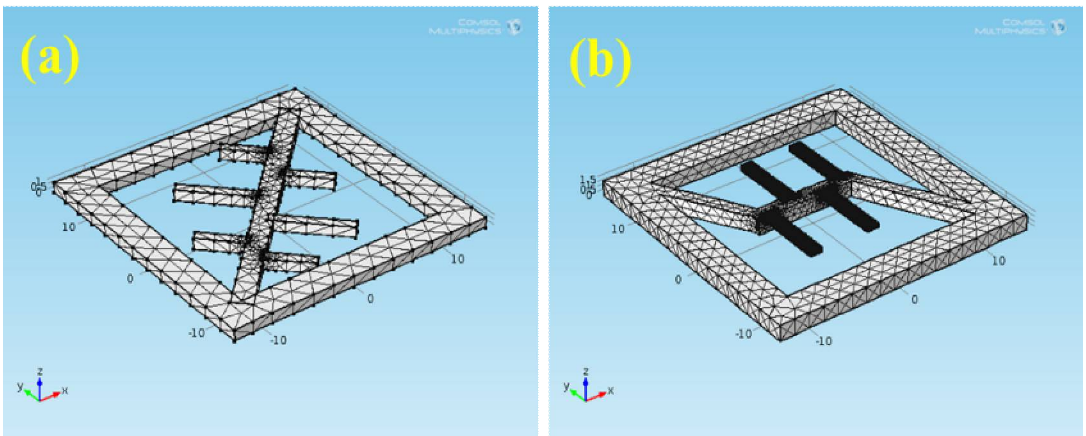

Figure 2 Meshing for Design-I (a) and Design-II (b)

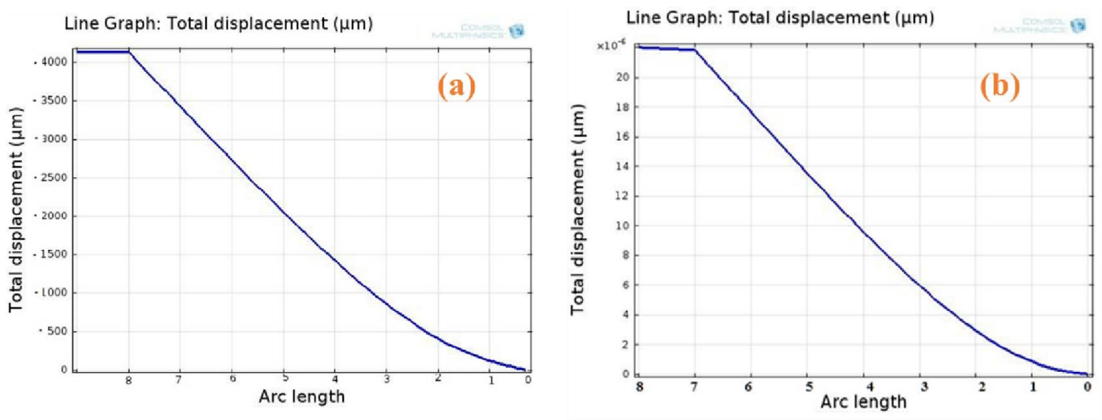

Figure 3 Total displacement of the microcantilever Design-I (a) and Design-II (b)

(which is of the order of 180GPa) and the blue color represents minimum stress experienced (0 in our case).From Figure 4(b), it is further evident that the maximum stress was found to be 180 GPa at the fixed end and the stress distribution was gradually decreasing towards the free end of the cantilever. As per Von Mises equation, the stress applied should be less than or equal to yield strength of the material. But, in the Design-I, the stress created due to the applied force of 100 Pa was found to be greater than the yield strength of Silicon (150 GPa). As a result, the cantilever arm may be broken, which indicated that the Design-I may not be suitable for the MEMS energy harvester.

Figure 5(a) indicates the distribution of the Von-Mises stress along the surface of the cantilever using the color indicator (Red for maximum and Blue for minimum). The maximum and minimum stress values were found to be 55 kPa and 0 kPa, respectively for the fixed and free ends. As per the Von Mises equation, the maximum stress (55 kPa) at the fixed end is well within the recommended yield strength of silicon (150 GPa) and hence the cantilever arm can withstand the force applied. Therefore, cantilever structure (Design-II) can be suggested as a suitable structure to measure force of very high value.

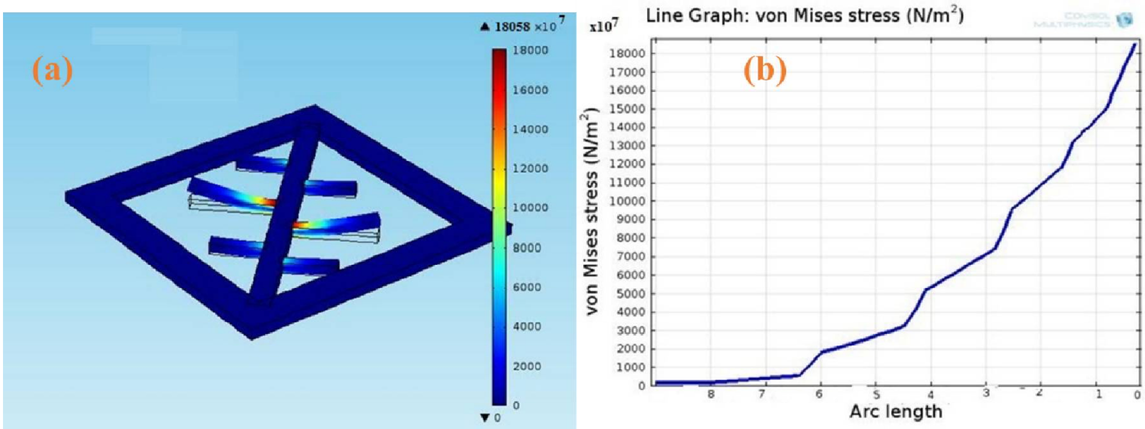

Figure 4 Von Mises Stress analysis of Design-I (a) 3D view and (b) line graph

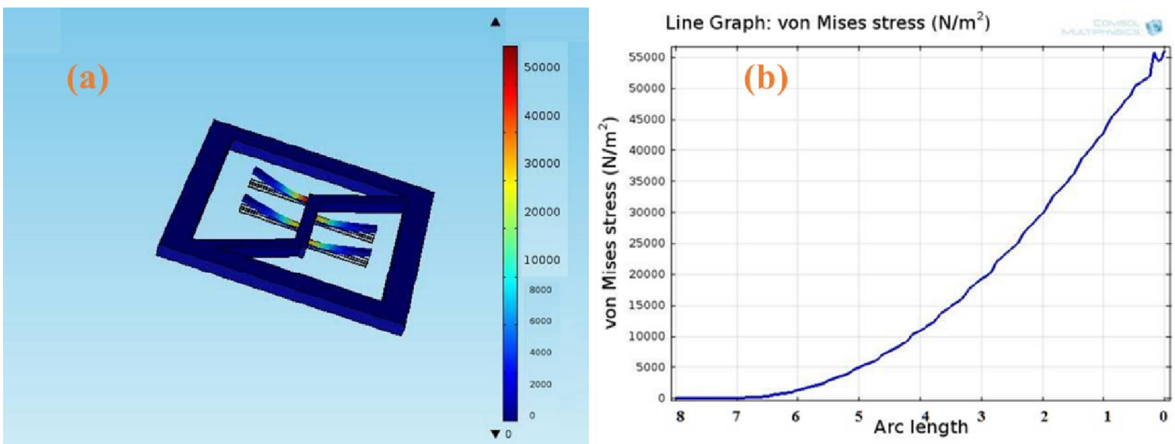

Figure 5 Von Mises Stress analysis of Design-II (a) 3D view and (b) line graph

Similarly, Figure 5 shows the Von Mises stress analysis for a uniform boundary load of 100Pa applied to the entire structure of Design-II in vertical direction.

Also, both the designs were tested for various stress conditions and analyzed their dynamic behavior like displacement and von Mises stress. The estimated values of the displacement and von Mises stress are given in the Table 1 for comparison.

Table 1 Von Mises stress and displacement values estimated for different applied force

Force Applied (Pa)	Von Mises Stress (N/m^2)		Displacement (µm)	
	Design-I ($\times 10^7$)	Design-II	Design-I	Design-II
5	900	2800	18	1
10	1800	5500	40	2
20	3600	11000	80	4
50	9000	28000	100	10
100	18000	55000	200	20

From the Table 1, it was inferred that the Design-II von Mises stress was found to be well within the maximum value of 150 GPa (Silicon) for the maximum applied force of 100 Pa and the displacement was found to be 20 µm. On the other hand, Design-I yielded von Mises stress of 180 GPa and displacement of 200 µm for the same applied force of 100 Pa. This clearly noticed that the Design-II can be suggested as a better structure for the design for microcantilever for energy harvesting applications.

Further, the Design-II was tested for potential generated due to the piezoelectric effect. The potential generated by the microcantilever Design-II was found to be 0.25 mV and few microvolt, respectively for the fixed and free end as shown in Figure 6. This once again confirmed that the fixed and free ends experienced maximum and minimum stress values, respectively. The cumulative potential generated by the entire structure of Design-II was found to be 1.167 mV, which is sufficient enough for self-powered devices.

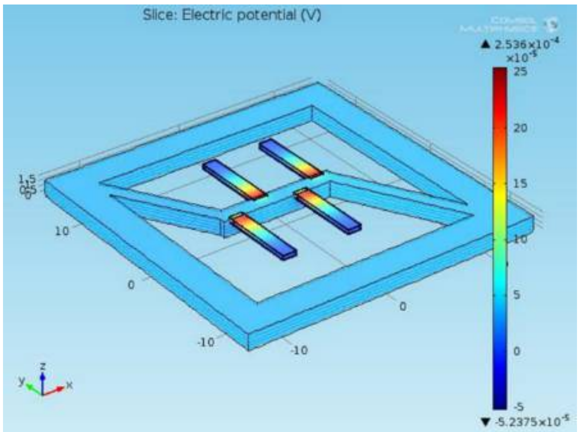

Figure 6 Potential generated in the microcantileverDesign-II

CONCLUSION

In this simulation and modeling of MEMS based microcantilever structure for energy harvesting applications, two different structures (Design-II and Design-II) were modeled with different size, shape and fixing structures using COMSOL Multiphysics. The structures were characterized through FEA analysis and parameters such as von Mises stress, displacement, voltage generated were estimated. The structures were tested for different force or pressure conditions. The results of these analysis revealed that the Design-II was found to be an optimized structure for energy harvesting, due to its withstanding and working capacity well within the recommended standards. Therefore, the Design-II micro-cantilever structure can be suggested as a better candidate for the fabrication of energy harvesting devices for the implementation of self-power sources in MEMS devices.

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