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Design optimization and simulation of micro-electro-mechanical system based solar energy harvester for low voltage applications

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In this paper, the design of a micro-cantilever based solar energy harvester is proposed. Solar energy is converted to electrical voltage using a MEMS solar cell that uses the principle of coefficient of thermal expansion and piezoelectric effect. Initially, the bilayer cantilever made of two different materials (Al and SiO_2) is displaced at the free end by absorbing the solar radiation that develops the stress at the fixed end and thus the solar radiation is converted to mechanical energy. Also, the developed mechanical energy (stress) is converted to electric potential by using the piezoelectric material that is positioned at the fixed end of the cantilever. Different shapes of bilayer cantilevers are designed and analyzed for maximum stress distribution. Experimental study on different shapes is also carried out in an INSTRON 8800 compression testing machine with the prototype made of aluminium. The results obtained prove that the triangular beam shows larger displacement and stress when compared with other shapes. Then the optimized structure with maximum stress is evaluated computationally for maximum voltage generation by placing different piezoelectric materials at the fixed end. The size of the designed solar cell is very small (4000 μm^2) when compared to the conventional photovoltaic cell which ultimately reduces the cost by the batch fabrication process. *Published by AIP Publishing.* https://doi.org/10.1063/1.5034074

I. INTRODUCTION

In today's world, energy plays a vital role in every scenario we face. One of the important problems in micro-energy harvesting is supplying power to remote devices with an automated power system from ambient energy.[1–3] Useful forms of ambient energy are thermal, light, air, etc. Many researchers have worked on micro-energy harvesting by using one of these ambient sources. Out of these sources, thermal energy from the sun is the promising source of energy as sun is one of the natural stable sources of heat.[4,5]

Solar energy is considered to be the recent trend among all the renewable energies for most consumables. Hence, we focus our research on proposing the design for solar devices. Conventional solar energy harvesting is based on photovoltaic cells (PVCs) that provide power to small scale applications.[5,6] These PVCs generate electrical energy by absorbing only photons from the visible [ultra violet (UV)] bands of sun and photovoltaic cells have no ability to absorb all the solar spectrum bands. Also, they are not economical and their sizes are very large. Therefore, in the last decade, there has been an increase in research to develop other cost effective technological systems for harvesting solar energy by utilizing more bands of sun light. One of the alternative solutions for producing solar energy is using a piezoelectric based system. Many researchers reviewed piezoelectric based energy generation systems.[7–9] Piezoelectric materials convert mechanical energy into electric potential and vice versa. When the piezoelectric

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material is positioned at the place of mechanical stress, the stress polarizes the piezoelectric material and generates the voltage at the surface that can be used to power the devices.

The design of a piezoelectric bilayer cantilever based solar energy harvester that can absorb an entire spectrum band is carried out and reported here. The solar radiation is converted to mechanical energy by absorbing heat thus generating mechanical stress. The generated mechanical stress is converted to electric potential by the piezoelectric effect. Experimental study is also performed to compare different shapes of the cantilever beams to get the optimum shape with larger displacement for larger efficiency. The proposed design can replace conventional photovoltaic cells and its size is very small and cost effective because of its simplicity in the fabrication process.

II. DESIGN OF THE SOLAR ENERGY HARVESTER

The solar energy harvester is designed by using a bilayer micro-cantilever. One end of the cantilever beam is fixed while another end is left free.[10] The two layers of the beam are made of two different materials with different thermal expansion coefficients (CTEs). The two layers coupled together along the longitudinal axis form a single solar structure.[2,11] Another third layer, made of the piezoelectric material, is placed at the fixed side of the cantilever beam to generate the potential. The proposed cantilever is shown in Fig. 1. The temperature of the cantilever rises when placed under solar energy (radiation). As the two materials have different coefficients of thermal expansion, two layers are deflected in different sizes under the effect of heat. As the materials are coupled together, unavoidably, the micro-cantilever is deflected along the material with a low coefficient of thermal expansion. Due to the deflection, stress is induced at the fixed end where the piezoelectric material layer is placed. Due to the induced stress, the piezoelectric material is polarized and electric potential is generated on its surface.[12] This generated electric potential is extracted by connecting the electrode with the piezoelectric layer. This potential can be used to charge a battery or to power low power electronic devices.

A. Numerical study on cantilever deflection

When the sun rays fall on the cantilever, the temperature is increased which results in the deflection of the cantilever beam. This deflection produces stress which is given by[13]

$$\sigma = E\alpha\Delta T, \tag{1}$$

where σ is the stress, α is the coefficient of thermal expansion (CTE), E is the young's modulus, and ΔT is the temperature difference. Two layers with different materials have different CTE and E. Hence, stress produced will vary for the two layers and results in the deflection of the cantilever. The maximum deflection of the bilayer is given by[13]

$$\delta = (\alpha_1 - \alpha_2)\Delta T \frac{3L^2}{t_1}\left(\frac{t_1}{t_2} + \frac{t_1^2}{t_2^2}\right)\left[3\left(1 + \frac{t_1}{t_2}\right)^2 + \left(\frac{E_1 t_1}{E_2 t_2} + \frac{t_1^2}{t_2^2}\right)\left(1 + \frac{E_1 t_t}{E_2 t_2}\right)\right]^{-1}, \tag{2}$$

where L is the length, t_1 and t_2 are the thickness, and E_1 and E_2 are the elastic modulus of the two layers.

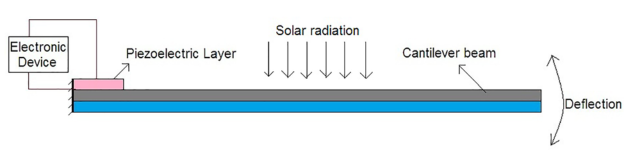

FIG. 1. Micro-cantilever based solar cell.

B. Numerical study on the piezoelectric layer

The mechanical stress is produced due to deflection in the cantilever beam. This mechanical stress is converted into electric potential with the help of the piezoelectric material.[13] The constitutive equation for the piezoelectric material is

$$D = d\alpha + \varepsilon E, \tag{3}$$

where D is the electric polarization, d is the piezoelectric coefficient, α is the mechanical stress, ε is the electrical permittivity, and E is the electric field. Electric polarization can be due to mechanical stress and electric field. In this present work, D is due mechanical stress as the electric field is not involved. Electric potential generated from the piezoelectric material is given by[13]

$$V_{oc} = T_{ij} g_{ij} G_e, \tag{4}$$

$$g_{ij} = \frac{d_{ij}}{\varepsilon_r \varepsilon_0}, \tag{5}$$

where G_e is the distance between the electrodes, ε_0 is the permittivity, ε_r is the relative dielectric constant, and d_{ij} is the piezoelectric coefficient in which i and j denote the direction of deflection and polarization. A majority of the piezoelectric material works in two modes: d_{13} and d_{33}.[14] In the d_{13} mode, the electric field is perpendicular to the stress produced and uses the top and bottom electrode to extract the electric potential. Whereas in the d_{33} mode, the electric field is parallel to the stress produced and uses interdigitated electrodes to extract the potential.

III. DESIGN OF THE MICROCANTILEVER BASED SOLAR CELL

The aim of the proposed solar cell is generating high electric potential that can be used for charging batteries or can be used to power low power electronic circuits. Maximum voltage generation is achieved when the stress generated due to solar energy absorption is high. From Eq. (2), the coefficient of thermal expansion should be high to have a large displacement for the material used. The coefficient of thermal expansion of different materials is listed in Table I, which shows that aluminium (Al) has the highest coefficient of thermal expansion. Hence, aluminium is used for designing the solar cells. Also, SiO_2 is used as the second layer in the bilayer cantilever because the coefficient of thermal expansion is 0.5. The coefficient of thermal expansion of SiO_2 which is very small compared to Al and the difference in CTE between the two materials is large which is suitable for efficient solar energy generation.

The dimension of the bilayer cantilever beam is chosen in such a way that it operates in the elastic region. This denotes that the stress produced should be less than the yield point (breaking point). Also, the elastic modulus of Al and SiO_2 is the same ($E = 70$). Thus, the

TABLE I. Thermal expansion property of different materials.

Material	Coefficient of thermal expansion (α) $\times 10^{-6}$ (1/K)
Silicon (Si)	3–5
Nickel (Ni)	13.0
Copper (Cu)	16–16.7
Aluminium (Al)	21–24
Gold (Au)	14.2
Silver (Ag)	19–19.7
Platinum (Pt)	9.0
Iron (Fe)	12.0

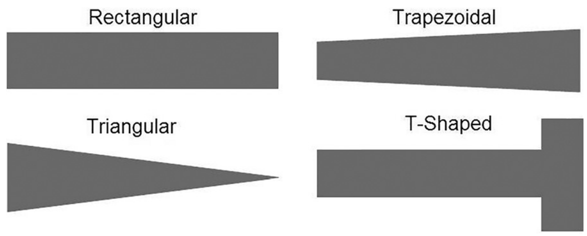

FIG. 2. Different shapes of the cantilever beam.

dimensions of the two layers are considered to be the same. In this design, dimensions of the bilayer cantilever such as length, width, and thickness are chosen to be 200 μm, 20 μm, and 2 μm, respectively. Cantilever shapes also influence in producing more potential, because different shapes produce different displacements for the same input which simultaneously affects the stress produced at the fixed end.[8,15] Hence, different shapes of the cantilever beam such as rectangular, triangular, T-shaped, trapezoidal, etc., are designed and compared for maximum stress distribution. Different shapes of the cantilever beam are shown in Fig. 2. The piezoelectric material is positioned on the fixed side of the cantilever beam where stress is high and dimensions of the piezoelectric material are $10\,\mu m \times 20\,\mu m \times 1\,\mu m$. As the feature size of the designed solar harvester is $200\,\mu m \times 20\,\mu m$, it can be batch fabricated with the standard micromachining process on the silicon substrate which ultimately reduces the cost of the individual device.

IV. SIMULATION RESULTS AND DISCUSSION

A. Analysis of different shapes of the cantilever beam

Initially, the bilayer micro-cantilever is analyzed. For analyzing the beam, the heat flux amplitude is considered to be 1050 W/m^2 which is the heat energy value of sun on earth. Different shapes of the bimaterial cantilever beam such as rectangular, triangular, trapezoidal, T-shaped, etc., are designed and analyzed for stress distribution for an applied heat flux of 1050 W/m^2. Due to heat flux, the temperature rises. This results in deformation of the structure and gets deflected in the z direction. Deflection of different cantilever shapes is shown in Fig. 3 and the von misses stress is computed, compared graphically, and it is shown in Fig. 4.

From Fig. 4, it is observed that the triangular shaped bimaterial cantilever beam has the maximum stress value within the elastic region which is required for energy harvesting. The deflection of the triangular bilayer cantilever beam with maximum stress is shown in Fig. 5. It can be observed that the stress is high at the fixed side of the cantilever which is very important in the solar cell design. The piezoelectric layer should be placed where the stress is high. Hence, the piezoelectric material is positioned on the top of the fixed side of the cantilever beam.

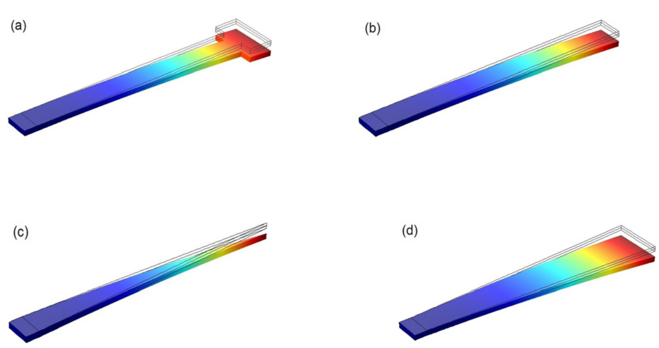

FIG. 3. Simulation results of different shapes of the cantilever beam showing displacement due to absorption of heat: (a) T-shaped, (b) rectangular, (c) triangular, and (d) trapezoidal.

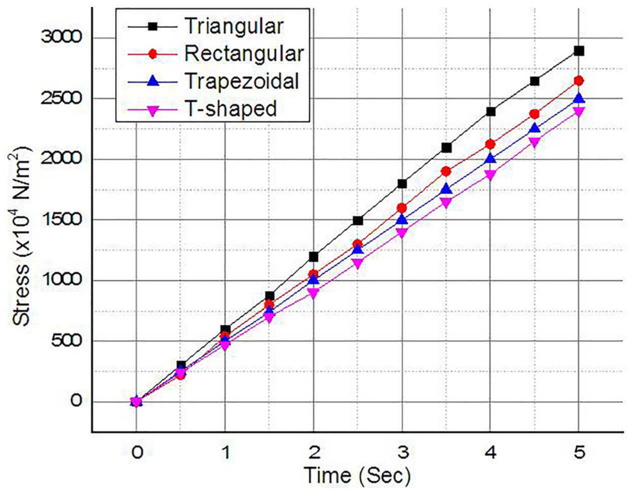

FIG. 4. Von misses stress of different shapes of the cantilever beam.

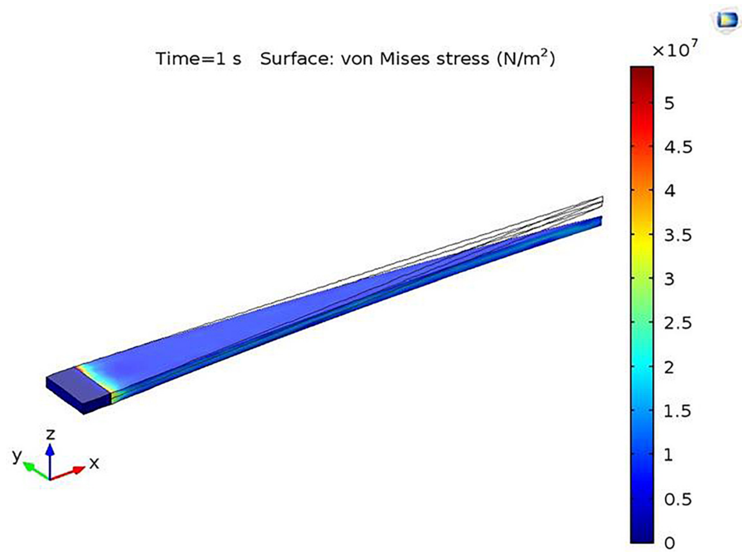

FIG. 5. Stress distribution in the triangular shaped cantilever beam.

B. Experimental study on different shapes of beam cantilever

Prototypes for different shapes of the cantilever beam such as rectangular, triangular, t-shape, and trapezoidal are made from commercially available 500 μm thick standard aluminium sheets. The proposed solar energy harvester's thickness is 2 μm which is not possible to develop without the standard micromachining process. Hence, the harvester's prototype size is magnified around 400 times and the size is made up to 100 mm $\times$ 10 mm with a thickness of 0.5 mm. The machined samples are analyzed for maximum displacement in a INSTRON 8800 compression testing machine. One end of the beam is fixed with a metal fixture and the load is applied at a point on the top surface of the beam as shown in Fig. 6. The input load is fixed at a 1 mm/min movement rate and the corresponding displacement and load acting at the fixed end of the beam are observed with a computerized measurement unit.

The displacement results achieved using four different shaped cantilevers are graphically represented in Fig. 7. From the figure, it is observed that the triangular beam gets deflected to 16 μm for 480 s whereas it is 8 μm, 6.4 μm, and 5.6 μm for rectangular, trapezoidal and t-shapes, respectively. The corresponding load experienced at the fixed end is measured with an

FIG. 6. Sample loaded in the INSTRON 8800 testing machine and the rounded area shows the point where a load is applied.

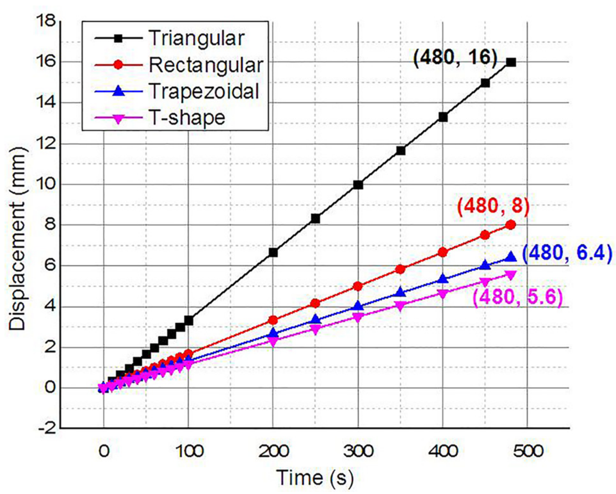

FIG. 7. Displacement of different shaped cantilever beams observed from the INSTRON 8800 testing result.

automatic computerized measurement unit and the relative stress is calculated by dividing the load with the area of the used cantilever beams. The calculated stress is plotted against the extension (displacement) and it is shown in Fig. 8. The stress experienced by the triangular beam for 16 μm is 5.26 kPa which is large compared with other shapes. From this, it is evident that the cantilever beam with triangular shape produces more displacement with large stress for the same applied input when compared with other shapes. This is the needed requirement for cantilever based energy harvesting applications. Hence, in this work, further studies are carried out in the triangular shaped beam rather than other shapes.

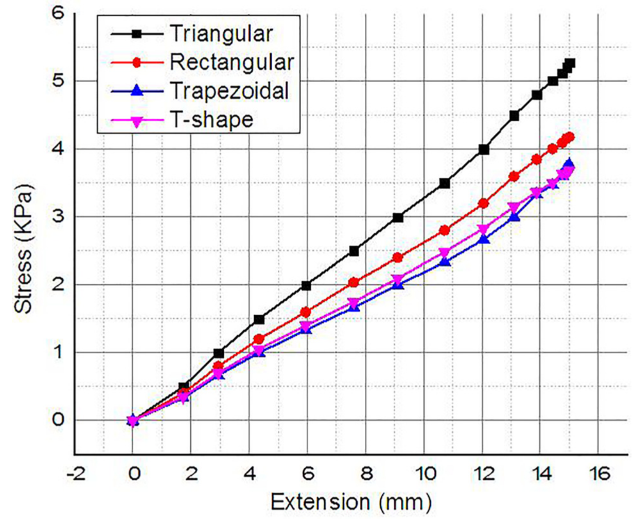

FIG. 8. Stress versus extension plotted for different shaped cantilever beams.

C. Analysis of different piezoelectric materials for large potential generation

In the next step, a triangular cantilever based solar cell is analyzed with different piezoelectric materials for large potential generation. Due to heat flux, the cantilever beam deforms and gets deflected. This produces stress at the fixed end as exhibited in Fig. 5. When the piezoelectric material is positioned at the fixed side where the stress is high, the piezoelectric layer is polarized and continuous voltage is generated on its surface that can be extracted with the electrode to power the electronic circuits. The generated voltage varies depending on the piezoelectric material used. Different piezoelectric materials such as bismuth germanate, aluminium nitride, zinc oxide, lead zirconate titanate, barium titanate, lithium nicobate, polyvinylidene fluoride, etc., are designed on the cantilever beam, simulated, and analyzed for the voltage generation. The potentials of different materials on the beam are graphically compared as shown in Fig. 9. From the figure it is clear that aluminium nitride (AlN) generates more voltage for the applied input heat flux of 1050 W/m^2. Also AlN has a high Curie temperature and stability of the piezoelectric coefficient varies for the input stress.

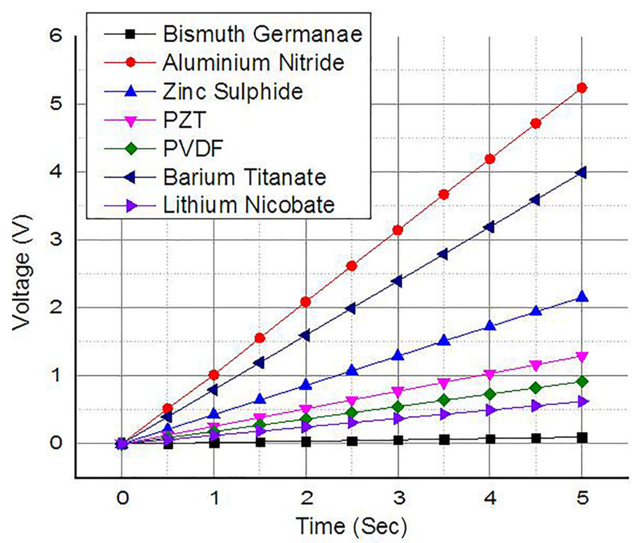

FIG. 9. Potential generated from various piezoelectric materials.

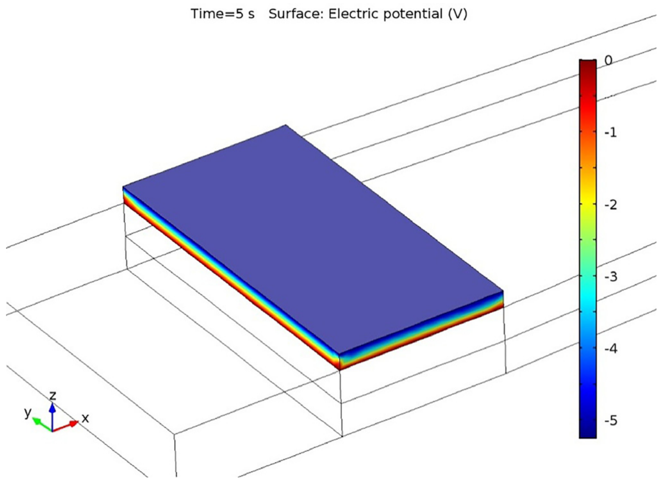

FIG. 10. Surface potential generation of the AlN piezoelectric layer.

Additionally, as the stress increases, the voltage generation also increases which is also depicted in Fig. 9. Voltage generation at the surface of the AlN piezoelectric layer is shown in Fig. 10. The objective of this work is to design a micro-cantilever based solar cell that generates more potential from the solar radiation. Thus the designed triangular bimaterial cantilever made of Al and SiO_2 with the AlN piezoelectric material can generate more voltage compared to other structures and other piezoelectric materials.

V. CONCLUSION

Sun is the natural stable source which is important for getting solar energy. One of the important tools to extract solar energy from solar radiation is the solar cell. Conventional photovoltaic solar cells are large in size, require an inverter, and are less economical. But the cantilever beam based solar cell for effective voltage generation is proposed in this paper. Various different structures are compared among which the triangular shape has more stress for an input heat flux of 1050 W/m^2. Structural analysis is also experimentally performed with an aluminium prototype in the INSTRON 8800 compression testing machine which proves that the triangular beam shows better displacement with large stress when compared to other shapes. Then the different piezoelectric materials are compared from which AlN is chosen as it generates more potential. The proposed solar cell made of the piezoelectric cantilever replaces the conventional solar cell in terms of size, cost effectiveness, and voltage generation.

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