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Simulation of Nuclear Radiation Based Energy Harvesting Device using Piezoelectric Transducer

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Abstract:

MEMS based energy harvesting is process of extracting energy from natural resources in small amounts. Here, number of (millions) small energy harvesting modules lead to substantial energy. Since conventional batteries have limited life time power, one needs a device which generates power for longer period. Many systems such as, wireless sensor networks, portable electronics, cell phones, etc., can use this technology as a power source. This will be essentially a clean, free and maintenance-free energy source throughout the lifetime of the device [1-4]. A MEMS based energy harvesting device is designed and modeled to convert beta particle energy to electrical energy via piezoelectric effect. The length, width and thickness of cantilever are 500μm x 100μm x 2μm [1]. This Cantilever beam resonates at a frequency of 110 KHz and an output voltage obtained is 0.0956 V. The proposed device is found to be suitable for beta particle energy harvesting and can be used as potential micro-generator.

Key Words: Energy harvesting, piezoelectric transducer, micro battery.

1. Introduction:

The micro cantilever tip is exposed to nuclear radiation from lower side with piezo material attached at the top cantilever as shown in Figure.1[2]. Hence its lower surface becomes negatively charged because of emission of electrons from radioactive element underneath. Thus there is an attraction between base and the tip. Once, sufficient numbers of electrons are collected, gradually the cantilever bends and discharges the electrons by physical contact. Now the electrostatic attraction disappears and setting cantilever into oscillation. The piezo attached to it also oscillates and the mechanical stress in the piezoelectric plate creates an imbalance in its charge distribution, resulting in an electric current or voltage. In such devices radioisotope like nickel-63 or tritium (milli curie range), which contains enough energy to power a MEMS device for decades can be used [2]. They emit so little radiation that they can be safe with only two to three millimeter of leather covering.

2. Modeling using COMSOL Multiphysics:

A MEMS based energy harvesting device is modeled to convert beta particle energy from radioactive isotope to electrical energy by piezoelectric effect. The thickness, length and width of metal and ZnO are varied to get maximum displacement and voltage. The cantilever is made of copper with dimensions 500µm×100 µm×2 µm. The copper material and its thickness 2 µm were chosen to capture most of the electrons [1].

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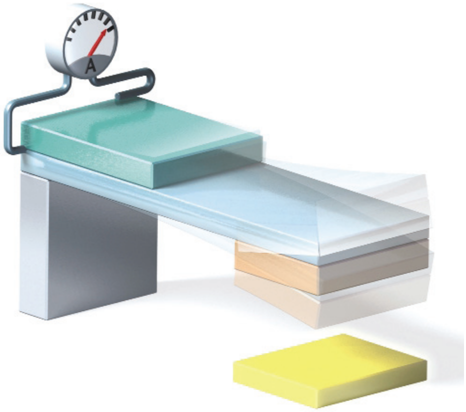

Figure 1: Basic principle of operation of nuclear radiation based energy harvesting device using piezoelectric transducer [2].

Methods

The model is developed using piezoelectric application mode for the simulation of the mechanical and the electrical behavior of the converter when a voltage is applied using electrostatic application mode. Computing the mesh deformation with the arbitrary Lagrangian Eulerian (ALE) technique.

3. Device Structure

A 3D geometry is considered for the simulations. The piezoelectric converter has a bimorph cantilever shape, as shown in Figure. 2. The device is made by a copper cantilever with a piezoelectric layer ZnO on the top with air cavity of 2µm between micro cantilever and radioactive source.

In this design, a piezoelectric material is used to scavenge energy from natural resources like radioactive source. COMSOL Multiphysics is used to model and simulate a micro cantilever with a layer of piezomaterial. The Figure.2 shows designed model of nuclear radiation based energy harvesting device using piezoelectric transducer. Piezo electric material used is zinc oxide (ZnO). The oscillating voltage is given as input to copper plate which models and simulates radioactive source. The model development and analysis is done using COMSOL Multiphysics.

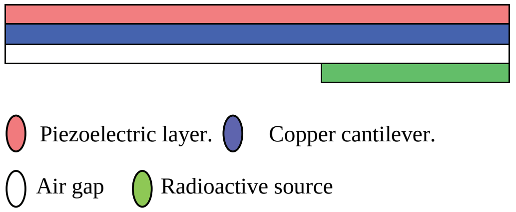

Figure 2: 3D model of nuclear radiation based energy harvesting device using piezoelectric transducer.

4. Radioactive source and its modeling

A β source made of ^{63}Ni is used as the radioisotope. The half life of ^{63}Ni is 100.2 years. The β particles (electrons) emitted have an average energy 17.3 KeV and maximum energy of 67 KeV.

$$V = \frac{q}{4\pi r \varepsilon} \tag{1}$$

Where V is the applied voltage which is equivalent to radioactive source, V=14.70V is selected such that maximum voltage is observed across the piezoelectric material with deflection of 2μm and r is initial gap between micro cantilever and radioactive source. According to this, theoretical number of charges required to generate a potential difference of 14.70 V is 20391 beta particles (electrons).

5. Meshing

The meshing done using the mapped mesh parameters by selecting sub domains of copper cantilever ,piezo and copper plate(radioactive source), with extra finer meshing between these areas where the sub domain for air is not selected to reduce the number of degree of freedom and thereby simulation time. A convert selected is considered for the meshing interior region of the selected structure and meshing for sub domain of air is done by selecting mesh remaining free tool. The mesh is composed of 3016 quad elements for 34736 degrees of freedom.

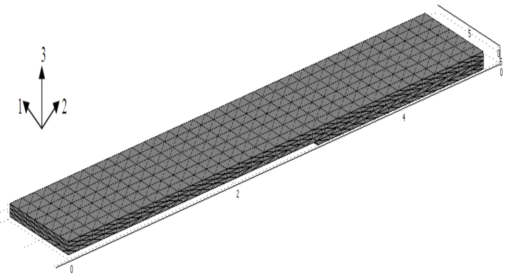

Figure 3. Nuclear radiation based energy harvesting device using piezoelectric transducer mesh.

6. Governing Equations:

In a piezoelectric energy converter based on a flexure cantilever, with the structure as shown in Figure 2 [6], the piezoelectric layer works in a transversal mode and therefore it is governed by the following equations written in the strain-charge format:

$$\begin{aligned} S &= s^{E} T + dE \\ D &= \varepsilon^{T} E + dT \end{aligned} \tag{2}$$

In eq. (2) S is the mechanical strain vector, s^E the elastic compliance tensor (Pa^{-1}), T the mechanical stress vector (Nm^{-2}), D the electric displacement vector (Cm^{-2}), ε^T the dielectric permittivity tensor (Fm^{-1}), E the electric field vector (Vm^{-1}) and d the transverse piezoelectric coefficient tensor (CN^{-1}). For the substrate layer only mechanical behavior was considered using the following stress-strain relationship:

$$S = sT$$

Analysis can be chosen arbitrarily provided it does not exceed the linear operation region of the piezoelectric converter.

7. Sub domain conditions

The geometry is made of three subdomains: One subdomain for the substrate layer, one for the piezoelectric layer and one for copper plate. The substrate was made of copper using the decoupled isotropic material which as the following value: E=120GPa, v=0.34, ρ =8960Kg/m^{-3}.

The piezoelectric material ZnO using strain charge form as following properties

Elastic Compliance matrix

$$s^E = \begin{bmatrix} 7.9 & -3.4 & -2.2 & 0 & 0 & 0 \\ -3.4 & 7.9 & -2.2 & 0 & 0 & 0 \\ -2.2 & -2.2 & 6.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 24 & 0 & 0 \\ 0 & 0 & 0 & 0 & 24 & 0 \\ 0 & 0 & 0 & 0 & 0 & 23 \end{bmatrix} \times 10^{-12} Pa^{-1}$$

Coupling matrix

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & -11 & 0 \\ 0 & 0 & 0 & -11 & 0 & 0 \\ -5.4 & -5.4 & 12 & 0 & 0 & 0 \end{bmatrix} \times 10^{-12} CN^{-1}$$

Relative permittivity matrix

$$\varepsilon_r = \begin{bmatrix} 9.16 & 0 & 0 \\ 0 & 9.16 & 0 \\ 0 & 0 & 12.64 \end{bmatrix}$$

Density

$$\rho = 5680 Kg / m^3$$

8. Boundary conditions

Piezo Solid model: one end of the cantilever is fixed while other is left free for vibration. Therefore the fixed constraint condition is applied for the vertical faces of both the layers, while all the other faces are left free for displacement. In order to pole piezo electric layer in direction 3, the electrical behavior of the ZnO must be considered and it is modeled with the electric boundary conditions. d33 mode shown in Figure 3 is selected by making floating potential for the upper face and grounding lower face of the ZnO layer and for d33 clamp vertical face and freely suspended vertical face are selected as floating and ground potential respectively. An input voltage is applied on upper face of the radioactive source (copper plate) using electrostatic application mode.

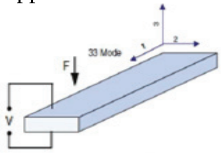

Figure 4. Operating modes of nuclear radiation based energy harvesting device using piezoelectric transducer mesh

9. Geometrical Optimization and Results:

The displacement of the free tip of the nuclear radiation based energy harvesting device using piezoelectric transducer, the open circuit voltage and the generated charge collected on the electrodes were computed for piezoelectric layer thickness varying from 2 μm to 4 μm. The obtained tip displacement is shown in Table 2 and Figure 4 and 7. Length of piezo is also varied from 500 μm to 50 μm to get a deflection of 2 μm and maximum voltage as shown in Table 1 and Figure 6 and 7

The length and thickness of piezoelectric is varied to scavenge maximum voltage developed across the piezoelectric with applied voltage of 14.7v which is equivalent to radioactive source.

Table 1: Voltage developed across piezoelectric material and deflection observed at the tip (for a fixed length of micro cantilever and varying piezo length)

SL. no	Length (μm)	Voltage (V)	deflection (μm)
1.	**500**	**0.0956**	**2.001**
2.	450	0.0963	2.011
3.	400	0.0935	2.036
4.	350	0.0916	2.149
5.	300	0.0783	2.477
6.	250	0.0679	3.092
7.	200	0.0627	4.214
8.	150	0.0506	6.125
9.	100	0.0132	8.539
10.	50	0.0654	12.05

The length of piezo is choosen to be 500 μm as it gives maximum voltage of 0.0956V and deflection of 2 μm.The optimized geometry of piezo electric material is 500 μm×2 μm. plot of applied voltage versus Z displacement is shown in Figure 8

Table 2: voltage developed across piezoelectric material and deflection observed at the tip (for a fixed length of micro cantilever and varying piezo thickness)

SL. no	Thickness (μm)	Voltage (V)	Deflection (μm)
1.	**2.0**	**0.0956**	**2.001**
2.	2.5	0.148	1.414
3.	3.0	0.164	1.032
4.	3.5	0.166	0.773
5.	4.0	0.171	0.595

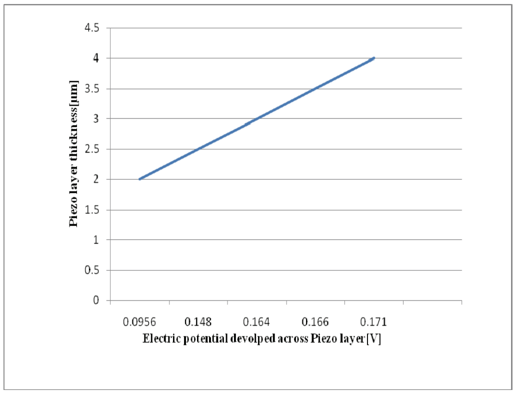

Figure 5 : plot of electric potential developed versus thickness of piezo layer.

The thickness of piezo is choosen to be 2µm as it gives maximum voltage of 0.0956V and deflection of 2µm.

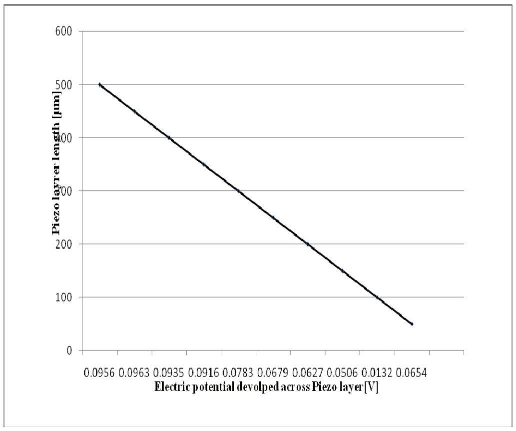

Figure 6 : plot of electric potential developed versus length of piezo layer.

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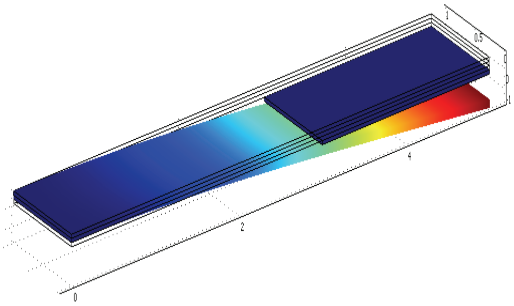

Figure 7 : Simulation result of nuclear radiation based energy harvesting device using piezoelectric transducer showing displacement.

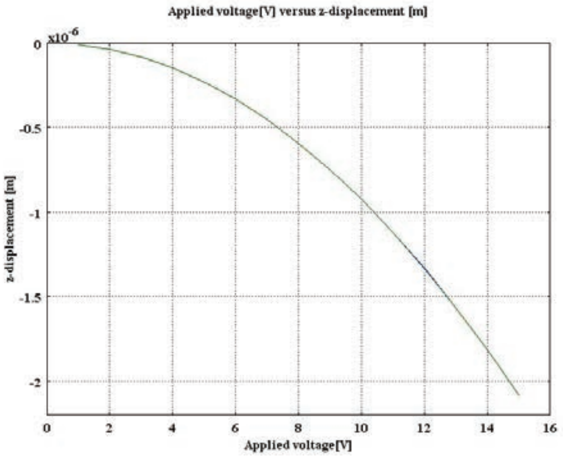

Figure 8 : plot of applied voltage versus Z displacement

11. Discussion:

The radioisotope thin film is the source of the current which is important for determining the reciprocation period. In general, radioisotopes emit alpha, beta particles and gamma rays. To avoid possible radioactive hazard with high energy alpha particles and deep penetrating gamma rays, radioisotopes that only emit low energy beta particles should be used. Table 3 shows some beta emitters with their half life and specific activity. The half life determines the useful length of time over which the described self-reciprocating actuator will work. Short lifetime sources are probably not important as chemical batteries e.g., lithium or other primary cells could effectively compete except for applications requiring high-temperature operation. However, long lifetime sources provide functionality over a period which is likely to be much larger than the shelf life of chemical batteries. Another parameter to qualify the source is the specific activity, which indicates the amount of mass needed to achieve a given activity. The smaller the specific activity, the larger the possible activity for a fixed mass. A related measure is the activity volume density listed as the last column in Table 3. Since deposition of source thin films will normally be in microns of dimensions, we can use the activity volume density to quickly estimate possible maximum activity. From the table, ^{32}P has the highest volume density; however the short half lifetime makes ^{32}P less attractive. Another figure of merit is the penetration depth of the electrons into the cantilever material, which is tabulated as the last column in Table 3. For optimum charge capture, one would like to choose a material with a small absorption depth or isotopes with low electron energy. According to the table, nickel and ruthenium are good beta emitters for thin cantilevers. In this article we concentrated on ^{63}Ni as it is easily electroplated and is commonly used in MEMS fabrication.

Table 3. Beta emitting radioisotopes, the last column is the estimated range of electron penetration in copper [9].

Radioisotope	Average energy (KeV)	Half life (Year)	Specific activity (g/mCi)	Activity Volume density (mCi/μm^3)	Estimated range in copper (mm)
^{63}Ni	17.4	100.2	1.763×10^{-5}	5.06×10^{-7}	14
^{32}Si	68.8	170.1	1.543×10^{-5}	1.15×10^{-7}	107
^{90}Sr	195.8	28.8	7.25×10^{-6}	3.50×10^{-7}	332
^{106}Ru	10.03	1.06	3.03×10^{-7}	4.08×10^{-7}	5
^{32}P	694.9	0.04	3.50×10^{-9}	5.20×10^{-7}	1344

12. Conclusions:

An electrostatic cantilever actuated by radioisotope emitted electrons has been modeled and simulated. The long half life of the source enables the cantilever to be used as an electromechanical transducer for long run applications. Furthermore, the temperature insensitivity of the radioisotope charge particle emission might enable extreme high or low temperature operation, not possible with chemical batteries. The developed and simulated model is capable of generating 0.0956 V and occupying volume of 0.3×10^{-12} m^3, 38 such cantilevers occupying a volume of 11.1×10^{-12} m^3 to generate 3.7V (mobile phone batteries).

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