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Research Paper

Energy Harvesting Using Piezoelectric Materials on Microcantilevr Structure

Engineering

KEYWORDS : MEMS, Piezoelectric, Energy Harvesting, PZT ,COMSOL

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ABSTRACT

The piezoelectric energy harvester was simulated by COMSOL Multiphysics and optimized to enhance its output power. This paper presents a microcantilever combined with piezoelectrics for energy harvesting of ambient vibrations. The cantilever structure was chosen in this study due to its large strain, and a big proof mass at the end of tip was integrated for the same reason. This paper presents results based on optimization of microcantilever that enables improved electrical power generation by discovering the optimal configurations for harvesting based on the statics of the device. The optimal device aspect ratio, thickness, length, and piezoelectric area are considered. Increased electrical output is found for geometries and piezoelectric configurations, which have not been considered previously.The Lead Zirconate Titanate (PZT) is used to fabricate energy harvesters by an optimized MEMS(Micro Electro Mechanical Sysstem)process.

I. Introduction

Although wireless data transmission techniques are commonly used in electronic devices, they still suffer from wires for the power supply or from batteries which require charging, replacement and other maintenance. The vision for the portable electronics and industrial measurement systems of the future is that they are intelligent and independent on their energy supply. The major obstacle in this path is the energy source which enables all other functions and "smartness" of the systems as the computing power is also restricted by the available energy. The development of long-life energy harvesters would reduce the need for batteries and wires thus enabling cost-effective and environment friendlier solutions for various applications such as autonomous wireless sensor networks, powering of portable electronics and other maintenance-free systems.

The motivation in this research field is due to the reduced power requirement of small electronic components,such as the wireless sensor networks used in passive and active monitoring applications[1]. The goal is to eliminate the need for battery replacement and disposal by enabling autonomous wireless electronic systems. Among the basic transduction mechanisms that can be used for vibration-to-electricity conversion(electromagnetic, electrostatic, piezo electric and magnetostrictive conversion methods as well as the use of electroactive polymers, piezoelectric transduction has received the greatest attention due to the high-power density and ease of application of piezoelectric materials.

There has been a recent dramatic increase in the use of wireless sensor networks and electronics using portable energy sources. As a result, energy harvesting methods have been developed to generate electrical energy from ambient vibrations via electrostatic generation, electromagnetic induction, and the piezoelectric effect. Priya[2] demonstrated that piezoelectrics have several advantages, including ease of integration within a system, higher strain energy densities than electrostatic and electromagnetic systems, and the simplicity of converting strain energy to electrical energy. Vibration based harvesters are often tuned to operate near resonance to maximize their power generation; however, resonant devices are not easily scalable, and performance falls significantly when operated outside their resonant frequencies. This renders linear resonant systems unsuitable for ambient conditions where vibrations generally exhibit multiple time-dependent frequencies.

In direct piezoelectric effect stress or strain applied for the piezoelectric material generates a charge on the electroded faces of the component. In vibration based harvesters deformation is produced by vibrating mass of the piezoelement itself or external mass or directly transferring deformation of external system into piezoelectric material. The natural stiffness or Young's modulus of the piezoelectric material is relatively high (typically 50-70 GPa) and therefore vibration cannot normally generate required stresses for the material. In order to overcome this problem bending type structures are typically utilised in vibration based harvesters providing extremelly compact internal leverage mechanism for the force amplification. One of the commonly used structures is a cantilever as shown in Figure 1 is chosen. The component consists of active PZT and substrate silicon layer where the PZT layer is sandwitched between bottom and top gold electrode layers.

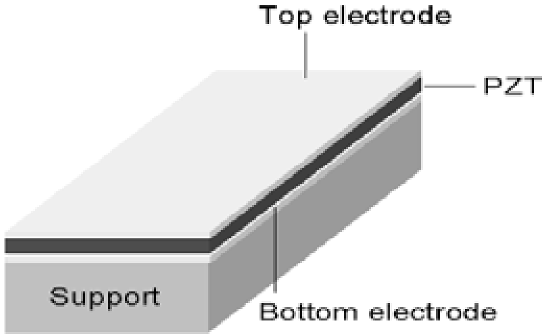

Fig 1. Piezoelectric cantilever

Since output power from piezoelectric energy harvester depends on the sensitivity of the cantilever it is desirable to optimize the cantilever sensitivity with different shapes and dimensions. Mo Yang[3] modelled a cantilever with SCR's in the elliptical structure to increase the detection sensitivity through increased surface stress. Johnny H.HE[4] has proposed that for a high sensitivity cantilever one rectangle hole positioned as close to the root has possible with its radius as large as possible produces a moresensitivity. G.Louarn[5] has modeled a V-shaped cantilever for biomedical applications.

II. Analytical Modeling

By Hooke's Law, the stress acting in the beam is equal to the beam material's modulus of elasticity, E.

$E= \sigma /\in \sigma /\in$ ----------------- (2.1)

Where, E = Young's modulus of the material, Pa(Pascals)
$\sigma\sigma$= Stress , N/m^2
$\in\in$= Strain, m/m (dimensionless)

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

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$$\delta = \frac{3\sigma(1-\vartheta)}{E}\left(\frac{L}{t}\right)^2 \text{--------------- } \mathbf{(2.2)}$$

Where υ 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 dimemsions and material constants.

$$K = \frac{F}{\delta} = \frac{EWt^3}{4L^3} \text{ ----------------------- (2.3)}$$

Where, W is Cantilever Width, L is Beam Length, F is Force applied , t is thickness, E is Young's modulus.

2.1 optimization results

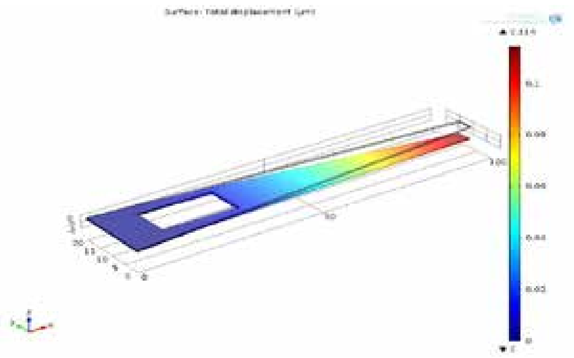
The piezoelectric cantilever was designed using comsol software. The aim is to optimize the cantilever sensitivity to obtain maximum voltage. The cantilever designed is the unimorph cantilever with piezoelectric layer mounted on the cantilever beam with gold metal layer is on two sides of PZT layer as top and bottom electrodes. The deflection of the cantilever is dependent on its size, shape, material and applied field .Hence in this work systematic investigation of influence of geometric dimensions, materials and applied field is carried out.

Within the comsol,the model was setup using the structuralmechanics->3D solid and structural mechanics- > piezo solid physics settings.The piezo solid was only active in the piezo solid domain,while the membrane was active in the 3D solid domain. Displacement can be varied by varying the applied boundary load.

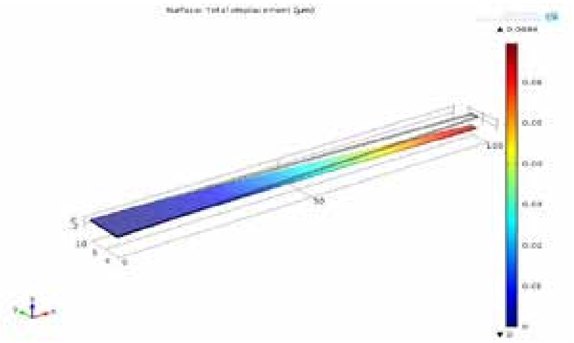
Traphezoidal cantilever

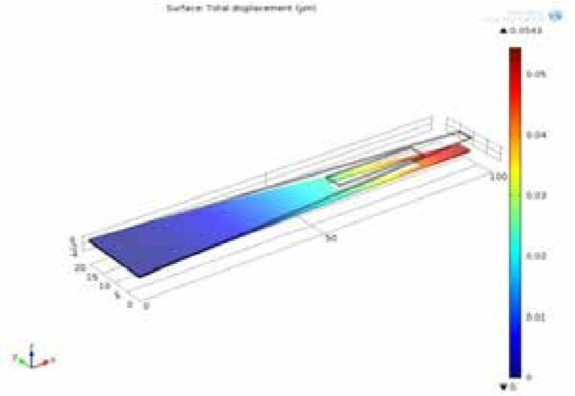
First we investigate how the effective mass of the cantilever near the free end affects the performance.As shown in fig.2.1 below,two cantilevers were choosen ,one with increased SCR region and the other with decreased SCR region

(a)



(b)





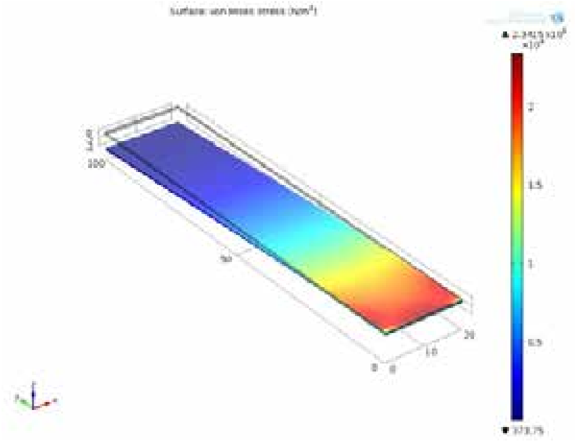
(c)

Fig 2.Traphezoid shape Microcantilever with SCR

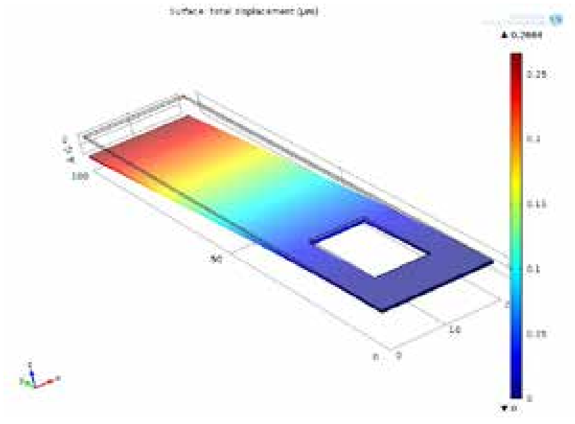
From the investigations, we can conclude that in order to maximize the sensitivity we should increase the SCR region near the fixed end.Thus,it is pretty straightforward to conclude that cantilever in fig.2.1(b) will have optimal performance with more displacement and stress.

Rectangular cantilever

As similar to class A cantilevers we have formed the stress concentration regions(SCR's) on the rectangular type of cantilevers and investigated the performance as shown in fig 2.2.



(a)



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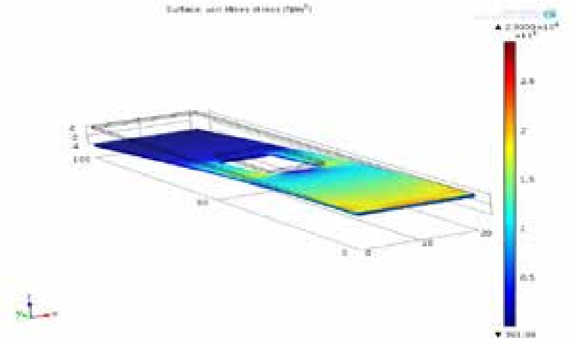

(c)

Fig 2.2.Rectangular type microcantilever

Zigzag and triangular Shaped cantilevers

From class C section cantilever we found that S-shaped cantilever is more sensitive campared to Triangle shaped cantilever with increased displacement and sress

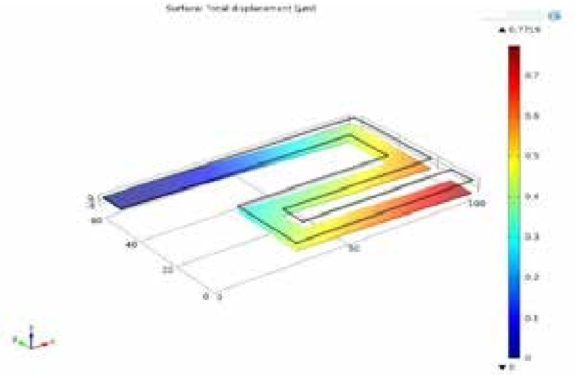

Fig 2.3.Zigzag (S shape) microcantilever

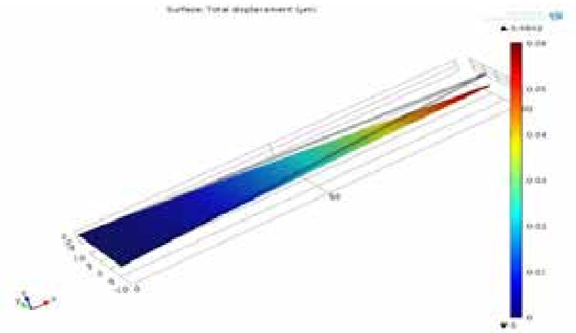

Fig 2.4.Traiangle shape microcantilever

Table 1.Comparison of different types of cantilevers

Cantilever	Displacement(µm)	Stress(N/m^2)
Traphezoidal Fig 2.1(a)	0.0694	1.0902x10^6
Fig 2.1(b)	0.114	2.9429xa0^6
Fig 2.1(c)	0.543	8.7666x10^5
Rectangular Fig 2.2(a)	0.1793	4.1518x10^5
Fig 2.2(b)	0.2664	5.726x10^6
Fig 2.2(c)	0.1864	2.9x10^6
Zigzag Fig 2.3	0.7719	9.233x10^6
Triangular Fig 2.4	0.0602	7.7931x190^5

III. Piezoelectric Energy Harvester

Piezoelectricity occurs when an electric surface charge develops on a crystalline material by mechanical stress. It was discovered by Jacques and Pierre Curie in 1880. These charges, named by polarization (*P*), are proportional to the applied stress (σ) and are expressed by equation 2.1 or equation 2.2 for the converse piezoelectric effect. The material constant for piezoelectricity is called the piezoelectric strain constant (*d*) and units are defined as *pC/N* or *pm/V*.

$$P = d\sigma \text{ ---------------------- } (3.1)$$

$$\varepsilon = dE \text{ ---------------------- } (3.2)$$

where, ε is strain and *E* is electric field. Piezoelectricity can be mathematically described by a constitutive equation given by

$$S_p = s^E_{pq}T_q + d_{kp}E_k \qquad \text{----------------- } (3.3)$$

$$D_i = d_{iq}T_q + \varepsilon^E_{ik}E_k \qquad \text{---------------- } (3.4)$$

where *S* is the strain component, *T* is the stress component (N/m2), *E* is the electric field component (V/m), *D* is the electric displacement component (C/m2), *s* is the elastic compliance constant (m2/N), *d* is the piezoelectric constant (m/V or C/N), *ε* is the dielectric constant of the piezoelectric material (F/m), *g* is the piezoelectric constant (V·m/N or m2/C), and *β* is the impermittivity components (m/F). The superscript denotes a constant and zero condition of notation for measurement.

3.1 Piezoelectric MEMS Generator System.

In piezoelectric energy harvesting from vibration, a mass is suspended by a beam, with a piezoelectric layer on top of the beam. When the mass vibrates, the piezoelectric lever is mechanically deformed and a voltage is generated. The most common energy harvesting systems are cantilever structures that are mainly designed to operate at their resonance frequencies. Such structures (unimorph or bimorph cantilevers) are popular because they enable relatively high stress levels on the piezoelectric material while minimizing the dimensions of the devices [6, 7, 8, 9]. Figure 3.1 shows such a system composed of a piezoelectric patch which is bonded to the host cantilever beam surface, which is under alternating deformation. When the beam is excited by mechanical vibration in the host structure, a large strain is induced in the piezoelectric material and an alternating voltage (AC) is generated between the electrodes. The AC voltage is then conditioned by interface circuits for proper delivery of the harvested energy to a storage element or compatibility with load specifications. Nonlinear interface circuits are the latest state of the art conditioning circuits employed to enhance the output power [10]

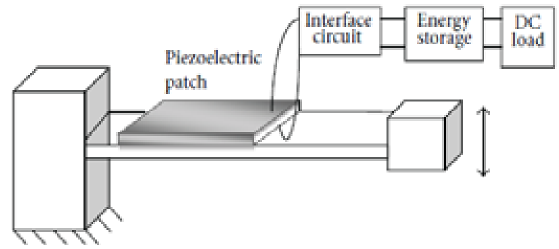

Fig 3.1:Typical piezoelectric energy harvesting system

IV. Energy Management

The generated open circuit voltage from the PZT patch can be written in terms of strain

$$V = \varepsilon_s E_{11}\, g_{31}\, T \text{ ------------- } (4.1)$$

where ε_s is the longitudinal strain of the patch. T is the thickness of the PZT ceramic layer.

Then the average energy generated in the PZT patch can be calculated based on the peak voltage output:

$$E = \frac{1}{2} CV \frac{1}{2} CV^2 \quad \text{------------ (4.2)}$$

C is the capacitance of the PZT patch which is determined by

$$C = \frac{A \varepsilon_r \varepsilon_0 \, A \varepsilon_r \varepsilon_0}{T \qquad T} \quad \text{------------- (4.3)}$$

A is the surface area of the electrode .ε_r is the relative dielectric constant between poling electrodes and ε_0 is the permittivity of vacuum ($\varepsilon_0 = 8.85 \times 10^{-12}$ farads/m).

The average available power is then:

$$P = 2 * f * Ee \quad \text{---------------- (4.4)}$$

f is frequency in Hz.

However high charge, not high voltage, is more desirable in generators. Multilayer PZT stacks are suitable for high stress environments and for harvesting large volumes of charge. The open voltage and capacitance are [Piezo Systems, Inc.]:

$$Vs\text{-}open = ss \; g33 \; Ts \quad \text{-------------------- (4.5)}$$

$$Cs = N \frac{\varepsilon_0 \varepsilon_r A_s}{t_s} \quad \text{------------------ (4.6)}$$

Ts is the total thickness of the stack. N is the number of layers. g33 is the piezoelectric voltage coefficient in the thickness direction. σ_s is the stress in the thickness direction, and σ_s= F/As . As is the cross section area of the stack. t_s is the thickness of a single layer.

Material used- PZT, L=20mm, W=5mm, T=2mm

Tip mass used silicon with L=5mm, W=5mm, t=1mm

Table 2. Summary of different piezoelectric energy harvesters

Cantilever shape	Displacement (um)	Strain (um/um)	Stress (N/m$^{2)}$	Voltage (V)
Zigzag	35	$10*10^{-4}$	$1.6*10^{7}$	80
Rectangle	1.2	$20*10^{-5}$	$1.5*10^{6}$	10
Traphezoidal	1.6	$10*10^{-5}$	$2*10^{6}$	15
Triangle	1	$5*10^{-5}$	$1*10^{6}$	5

V. Conclusion

The deflection of the cantilever increases with decrease in thickness.Using COMSOL software, two kinds of results has been explored,i.e study 1 for calculation of voltage production upon vibration of the cantilever,whereas as the study 2 corresponds to the optimization of piezoelectric energy harvester with different shapes of cantilever.The range of the frequency is given and the deformation is observed by plotting on the material.From the investigation it is found that zigzag type of piezoelectric energy harvester is more sensitive and desirable for the low frequency applications.

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