MEMS STRUCTURE FOR ENERGY HARVESTING

Shadab Rabbani, Pradeep Kumar Rathore, Gautam Ghosh and B. S. Panwar
Centre for Applied Research in Electronics
Indian Institute of Technology Delhi, Hauz-Khas, New-Delhi-110016, India
Tel: +91-11-26591107, Fax: +91-11-26596219, E-mail: shadabrabbani2008@gmail.com

Abstract: **In this paper, a piezoelectric cantilever is investigated by COMSOL FEA (finite element analysis) for the generation of electrical energy. A micro power generator was designed to convert mechanical vibrations present in the environment to electrical power. The model was studied for different cantilever dimensions. The load resistor was optimized for obtaining maximum output power for a cantilever length of 2000µm. The load was introduced to the FEM design through PSPICE netlist. The amplitude of vibration for different frequencies has been analyzed through frequency response analysis. The results confirm the possibility of PZT microcantilever power generator for wireless sensor applications. A CMOS compatible fabrication process flow is also suggested.**

Keywords: MEMS (Micro Electro Mechanical System), microcantilever, PZT (Lead Zirconate itanate), micro power generator.

1. Introduction

The energy extracted from environment to power the micro-electronics devices using MEMS based PZT structure are getting impetus for application in wireless sensor networks, geographically inaccessible temperature or humidity based sensing systems. The reduction in size, low power consumption, capability of integrating with MOS technology are the prime movers of research in the MEMS based PZT as an alternative source of energy to power system on chip[1]. The present work describes a PZT micro-cantilever structure to convert the mechanical vibrations as a source of energy for micro-electronic device applications.

A cantilever when placed in an oscillatory environment produces strain, which in turn produces stress that results in the generation of charges, and hence electric potential is developed across the piezoelectric material. The electrical power output attains a peak value if the vibration frequency of the environment matches the resonant frequency of the cantilever, and dies out dramatically when it deviates from the resonant frequency of the device. The proof mass lowers the resonance frequency of the beam to a value of the order of few hundreds of Hz which is generally the order of the frequency of vibrations present in the nature. It also increases the amount of deflection, which increases the amount of stress produced at the fixed end which consequently increases the output voltage and power.

Electrodes are used to conduct the electric charge produced to an electrical circuit. The entire MEMS structure can be modeled by an equivalent current source with capacitive source impedance. This source can be used to store energy or drive a load directly. The AC output voltage can be converted to a more useful DC voltage by using some form of rectification. DC to DC conversion schemes have also been reported to be used for enhancing the charging efficiency of the battery by allowing the device to draw more power over a short period than the harvester is able to provide[2].

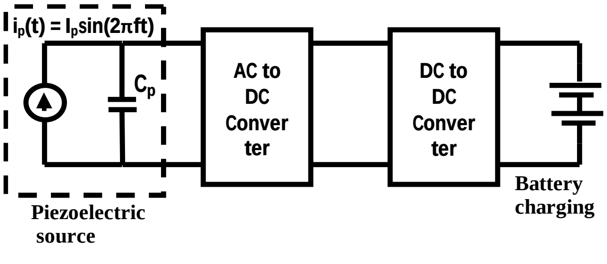

Fig.1 Energy Harvesting circuit for charging battery

2. FEM Structure

The beam configuration is a structure consisting of a silicon base frame, Si beam, a piezoelectric element (PZT) layer sandwiched between a pair of metal (Pt-electrodes), and a

Silicon proof mass at the free end. The device has been designed for different lengths and different thicknesses. An increase in length decreases the resonant frequency of the cantilever and an increase in the thickness increases it. The schematic of the designed multilayer PZT cantilever energy harvest device is shown in Fig.2. Si at the free end tip was used as the proof mass (0.5592µg; dimensions: 1000µm x 800µm x 300µm) to decrease the resonant frequency. The top Si layer of SOI (Silicon on Insulator) wafer was used as the bulk of cantilever material. SiO_2 (500nm thick) was used as the insulator between the bottom electrode Pt/Ti (thickness 300nm). Ti was used as the adhesion layer to improve the adhesion between PZT (thickness 1µm) and Pt electrode and to facilitate the growth of the PZT crystal.

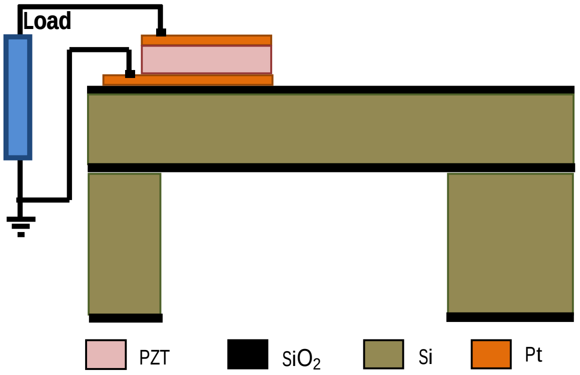

Fig.2. Lateral view of MEMS structure

3. Theoretical background

3.1. Piezoelectric effect

Piezoelectricity means electricity resulting from pressure. The piezoelectric effect can be understood as the electromechanical interactions in crystalline materials with no inversion symmetry. The IEEE standard on piezoelectricity gives different forms of piezoelectric constitutive equations. The form used here is strain-charge form, and the equations are as follows:

$$\epsilon = s^E\sigma + d^T E \qquad (1)$$

$$D = d\sigma + \epsilon_0\epsilon_{rs}E \qquad (2)$$

where, σ = Stress
ϵ = Strain
ϵ_{rs} = Relative permittivity
s^E = Compliance matrix
d = Coupling matrix
D = Electric displacement vector
E = Electric field

3.2. Mathematical analysis of cantilever

The resonance frequency of the cantilever can be theoretically estimated by assuming the cantilever to be an Euler's Bernoulli beam and the proof mass as a point load at the free end. The governing equation of Euler's Bernoulli beam is given as:

$$\frac{\partial^4\delta}{\partial x^4} + \frac{\rho A}{EI}\frac{\partial^2\delta}{\partial t^2} = 0 \qquad (3)$$

Where, 'δ' is the beam deflection, 'ρ' is the density, 'A' is the area of the cross section of the beam, 'E' is the Young's modulus, and 'I' is the area moment of inertia. The thickness of SiO_2, PZT and metal layers are small enough to be ignored while calculating resonance frequency. For a beam of rectangular cross section, A=w.h and $I=(w.h^3/12)$ where 'w' is the width and 'h' is the thickness of the cantilever.

The general solution for sinusoidal vibration is given as:

$$\delta(x,t)=\{A(x)+B(x)+C(x)+D(x)\}.\sin(\omega t) \qquad (4)$$

where, $A(x) = c1\sin\beta x$, $B(x) = c2\cos\beta x$,
$C(x) = c3\sinh\beta x$, $D(x) = c4\cosh\beta x$

and $$\beta^4 = \frac{\rho A\omega^2}{EI}$$

For a fixed-free beam with proof mass assumed to be acting as a point load at free end, the relevant boundary conditions for a beam of length L are:

$$\delta(0,t) = 0; \quad \delta_x(0,t) = 0; \quad \delta_{xx}(L,t)= 0$$
$$\text{and} \quad \delta_{xxx}(L,t)= -(m\omega^2/EI)\delta(L,t)$$

If we model the beam deflection as a 1st order spring-mass system, then the resonant frequency can be estimated as

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_{eff}}{m_{eff}}} \qquad (5)$$

The effective mass of the beam itself is approximately 0.236 times the beam’s actual mass, and if the proof mass is modeled a point load at the tip, hence, the total effective mass is approximately:

$$m_{eff} = 0.236\rho AL + m_{proof} \qquad (6)$$

The stiffness of a rectangular beam is

$$k_{eff} = \frac{3EI}{L^3} \qquad (7)$$

To model the effects of the distributed mass loading of the proof mass,

$$L_{eff} = L_{beam} - 0.5L_{proof} \qquad (8)$$

can be substituted for the length[3].

4. Simulation using COMSOL

The structure was simulated using MEMS module of COMSOL Multiphysics . The electrical circuit (a resistive load) was introduced through PSPICE netlist. The length and thickness of the cantilever were varied to obtain different resonant frequencies (summarized in Table 1). The resonant frequency increases with an increase in the cantilever thickness and decreases with an increase in the cantilever length.

Table 1: Resonance frequency of the cantilever for different dimensions.

Si Thick ness (µm)	frequency (in Hz)		
	Length(L)= 2000µm	Length(L)= 3000µm	Length(L)= 4000µm
8	471.97	202.98	116.59
12	759.63	334.68	195.41
16	1082.92	484.36	284.88
20	1427.47	648.29	382.18

The results shown here are for a 2000µm long and 20µm thick cantilever. Fig.3 suggests that maximum displacement occurs at the free end of the cantilever. Fig.4 gives the variation of the amplitude of vibration of the cantilever with frequency. The amplitude rises only for the resonant frequencies and dies out to negligible values for others. Moreover the highest amplitude is observed at 1427 Hz, which is the first resonant frequency. The second resonance occurs at 15287 Hz. The amplitude of vibration decreases for higher resonance mode.

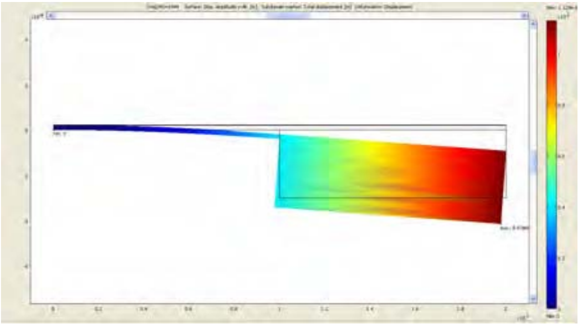

Fig.3. Displacement of different points along the length of cantilever

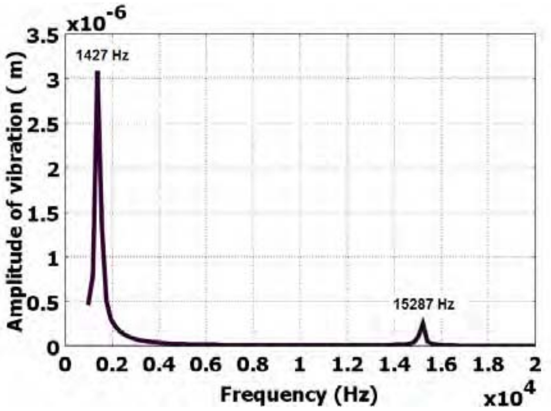

Fig.4. Variation of amplitude of vibration with frequency

Fig.5, Fig.6 and Fig.7 show the variation of electric current, voltage and power respectively for a resistive load of 5kΩ for different mechanical pressures. The maximum power is generated by the micro generator when the cantilever oscillates at its resonant frequency.

Moreover the power increases with an increase in amplitude of vibration.

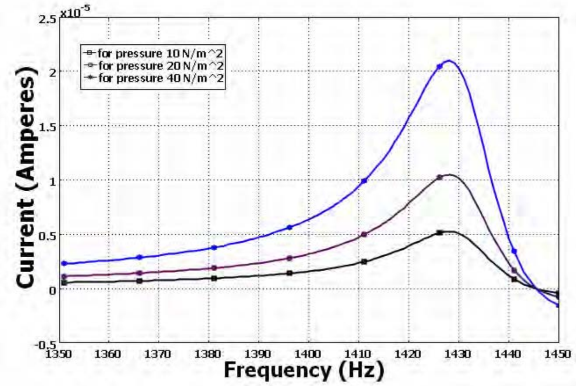

Fig.5. Variation of electric current with frequency for different mechanical pressures

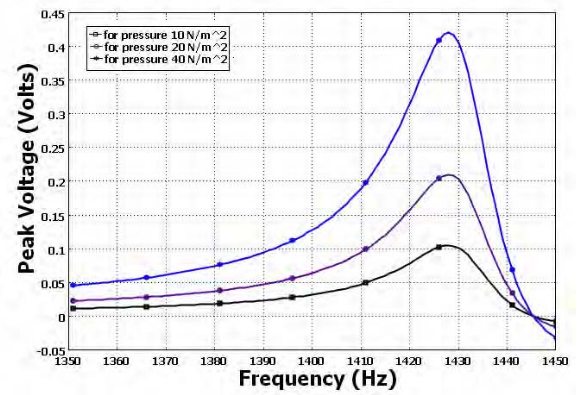

Fig.6. Variation of electric voltage with frequency for different mechanical pressures

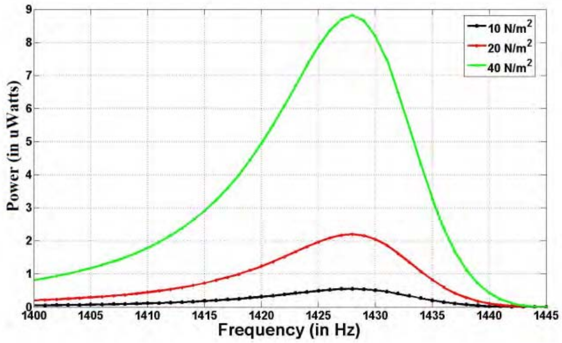

Fig.7. Variation of electric power generated with frequency for different mechanical pressures

Fig.8 and Fig.9 gives the voltage drop and power across different load resistors for a mechanical vibration of 20 N/m^2. The peak voltage increases with the increasing resistive load, and the average power shows a maximum value at a certain resistance value, which is named as the optimal resistive load. The measured optimal load is 5kΩ.

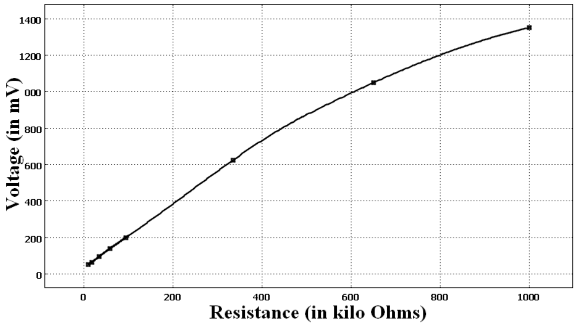

Fig.8. Variation of electric voltage generated across different load resistors

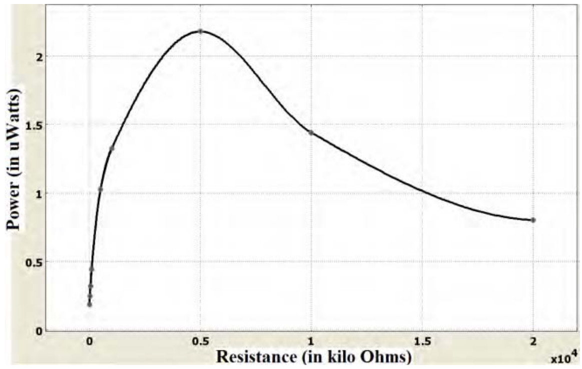

Fig.9. Variation of electric power generated for different load resistors

5. Proposed Fabrication Process Flow

The proposed CMOS compatible fabrication process flow for the designed MEMS structure for vibrational energy harvesting is shown in Fig.10. The fabrication process can be simplified by taking an SOI wafer (layered Si – Insulator – Si) rather than a conventional Si wafer as the starting material. Thin layers of PZT can be deposited over Pt/Ti/SiO_2/Si/SiO_2/Si wafer with sol-gel method and patterned through wet etching [4].

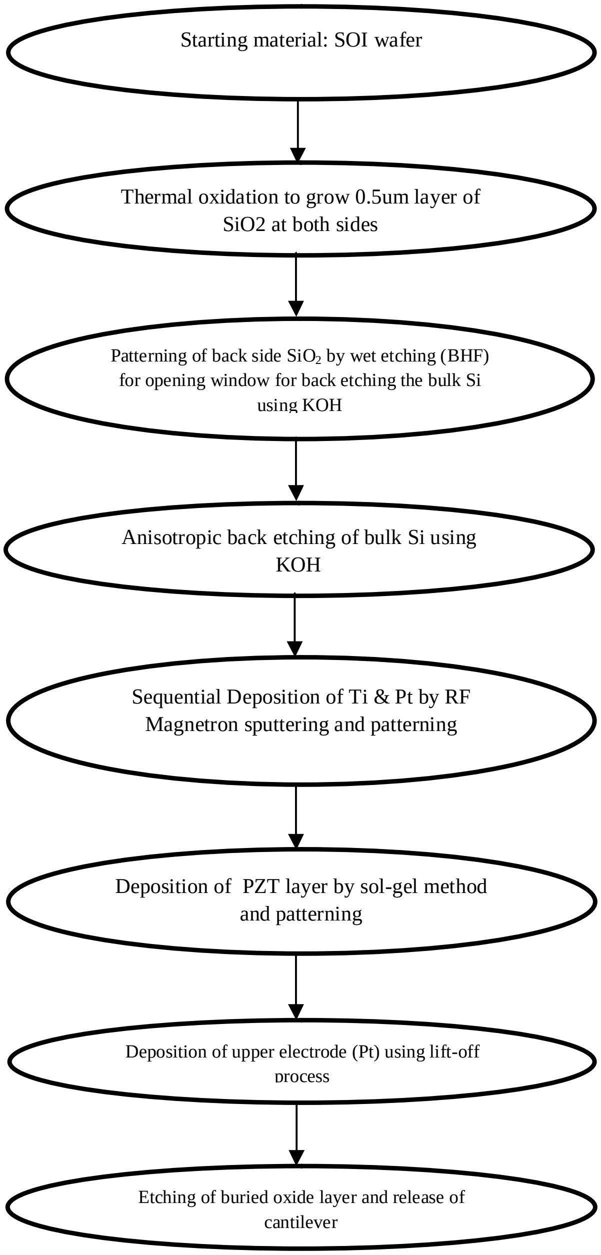

Fig.10. Flowchart for the fabrication of MEMS structure for energy harvesting

5. Conclusion

A MEMS PZT cantilever with an integrated Si proof mass is designed and simulated using a $Pt/PZT/Pt/Ti/SiO_2/Si/SiO_2$ multilayer device for vibration energy harvesting. The integrated Si proof mass at the free end tip of the cantilever is used to decrease the resonant frequency of the device. The length and thickness of the micro power generator has been changed to obtain different resonance frequencies. The width of the cantilever is 800µm. The resonance frequencies for the cantilever having dimension 2000µm ×800µm ×20µm with a proof mass of dimension 1000µm ×800µm×300µm are 1427 Hz (first mode) and 15287 Hz (second mode). When excited with a mechanical vibration of 40 N/m^2, the power generated at resonance is around 9µW. A resistive load of 5kΩ has been optimized. The simulation results suggest that such structures can be used for energy generation in wireless sensor networks.

6. References

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