ISSS International Conference on Smart Materials, Structures and Systems
July 5-7, 2017, Bangalore, India

Design and Simulations of ZnO-based Piezoelectric Energy Harvester

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Abstract: Energy harvesting devices are capable of harnessing waste ambient energy and are popularly known as green and renewable energy sources. Such devices can be used to empower electronic gadgets either by recharging the battery or by directly powering the electronic circuitry. This paper presents modeling and simulation of a piezoelectric vibration energy harvester based on a micro cantilever beam structure. The model is simulated in COMSOL Multiphysics® and a resonant frequency of 720 Hz is obtained. This energy harvester can be used to harness vibrational energy from vehicles and industrial machineries. Most importantly, the device generates a maximum power of 107 nW which can be used to operate quartz oscillators and wireless sensor and microcontrollers at standby mode.

Keywords: Energy Harvesting, Unimorph Cantilever Beam, Finite Element Modeling

1. INTRODUCTION

Amelioration of VLSI technology had resulted in production of ultra-low power wireless sensors. Micro Electromechanical Systems (MEMS) is integrating VLSI technology with micro fabrication techniques in order to realize devices such as sensors and actuators. Historically, batteries have been empowering almost every electronic gadget, but due to their bulky size and issues such as periodic replacement and limitation in size/storage density, there is a requirement of self powered devices[1]. One of the possibilities in this direction is to extract energy from ambient, either to recharge the battery or directly power the electronic device. Ambient energy sources can be broadly classified as Solar, Thermal, RF and Vibration[2]. Three techniques namely Electrostatic[3], Electromagnetic[4] and Piezoelectric[5] are available for harnessing ambient vibrations but piezoelectric energy harvesters have gained special attention of researchers due to their large power densities and compatibility with MEMS fabrication[6, 10].

2. CONFIGURATION OF MEMS CANTILEVER

The cantilever structure with a proof mass at the end has been identified as one of the most suitable structures for the purpose of energy harvesting[7]. The stress generated on the cantilever structure during vibration is harnessed using a piezoelectric layer deposited on top of the cantilever.

Generally, in simulations for piezoelectric energy harvesters, a piezoelectric layer deposited on top of silicon, which is far different from reality. Practical realization of these devices requires various other layers to be deposited and patterned on the top of silicon cantilever in order to achieve desired output. Therefore, in this work a more realistic design approach is followed, where all the layers used in fabrication are considered. Ignoring these considerations leads to an error in the estimation of important parameters like the resonant frequency of the device which are dependent on the thickness of the structure. The simulated model used in this work consists of eight layers namely: Silicon substrate / Thermal oxide / Gold electrode / PECVD oxide / ZnO piezoelectric layer / PECVD oxide / Gold electrode / Nickel proof mass (shown in Fig. 1). Each layer serves a different purpose. Silicon substrate provides mechanical strength to structure thus controlling fragility of structure. Thermal oxide acts as passivation layer. PECVD oxide provides a dielectric medium between gold electrode and piezoelectric layer ZnO. The electrode when used in such a fashion exploits mode-31 excitation which has greater advantage in MEMS[8]. Nickel proof mass is added to increase the effective mass of structure, thereby reducing resonant frequency. Finally, the cantilever is clamped at one of its end. Such a beam configuration is defined as unimorph cantilever beam in literature.

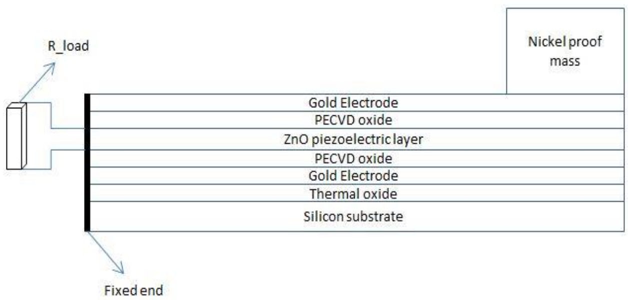

Figure.1 Schematic of proposed model of cantilever energy harvester

ZnO has been chosen as the piezoelectric material mainly because of (1) relatively high piezoelectric coupling coefficient compared to aluminum nitride (AlN) and low dielectric constant compared to PZT (2) low deposition temperature and well known standard sputter deposition technique (3) excellent bonding to silicon substrate (4) being a non-ferroelectric material it does not require post deposition annealing (5) the production of ZnO is environmental friendly and not causing serious environmental pollution compared to PZT production (6) it's high mechanical quality factor (Q_m), and being highly compatible with CMOS processing making it attractive in MEMS vibration based energy harvesting for self-powered microsystems[9].

3. SIMULATION OF PIEZOELECTRIC ENERGY HARVESTER

COMSOL Multiphysics® has been used to perform Finite Element Modeling (FEM) based simulation for obtaining performance characteristics of vibration based piezoelectric energy harvester.

3.1 Design parameters

The energy harvester is modeled using Solid Mechanics, Electrostatics and Electrical Circuit physics in COMSOL. Piezoelectric effect in Multiphysics tree is used to integrate the functionality of both Solid Mechanics and Electrostatics physics. Electrical circuit physics is used for calculating power across load resistance whose value is defined as 1MΩ. In order to model the effect of gravity, body load under Solid Mechanics physics is used. Damping effects are also considered in the simulation by introducing an isotropic loss factor of 0.01 in the model.

3.2 Dimension of different layers in the model

The 3D structure of cantilever beam consists of eight layers whose dimensions are tabulated below:

Layer Material	Length (μm)	Width (μm)	Thickness (μm)
Silicon	2100	500	10
Thermal oxide	2100	500	1
Gold electrode	2100	500	0.2
PECVD oxide	2100	500	0.5
ZnO	2100	500	2
PECVD oxide	2100	500	0.5
Gold electrode	2100	500	0.2
Ni proof mass	650	500	150

3.3 Properties of materials used in the model

The properties used for thermal and PECVD oxide are tabulated below. For the remaining layers, the in-built material library provided by COMSOL Multiphysics® is used.

Materials	Density (kg/m^3)	Young's Modulus (GPa)	Poisson's ratio
Thermal oxide	2200	70	0.17
PECVD oxide	2200	85	0.25

3.4 Meshing

The meshed model of structure consists 645392 degrees of freedom and a finalized geometry with 8 domains, 42 boundaries, 71 edges and 38 vertices. The meshed model of the structure is shown in Fig.2

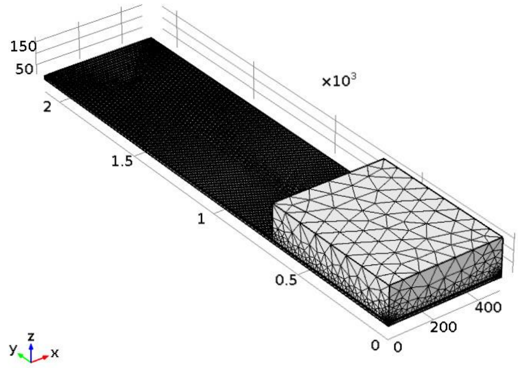

Figure.2 Meshed model of cantilever energy harvester

4. RESULTS AND DISCUSSION

The proposed structure was modelled and simulated using FEM simulator, COMSOL Multiphysics®. The first mode resonant frequency obtained was 720 Hz (shown in Fig.3), which is suitable for harvesting ambient vibrations from industrial machineries and vehicles[10].

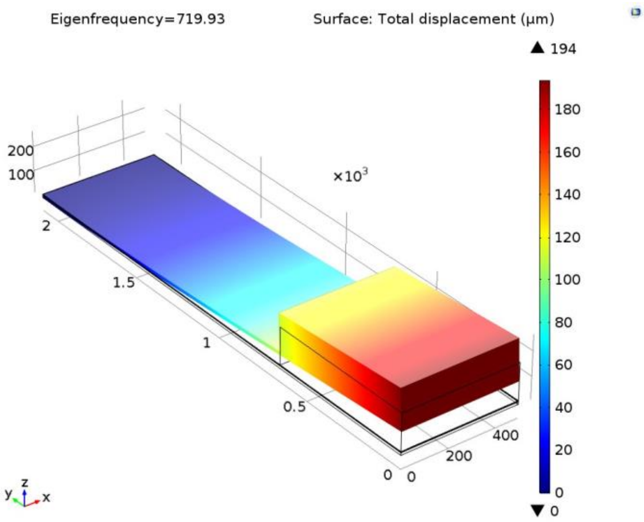

Figure.3 First resonant frequency of the structure

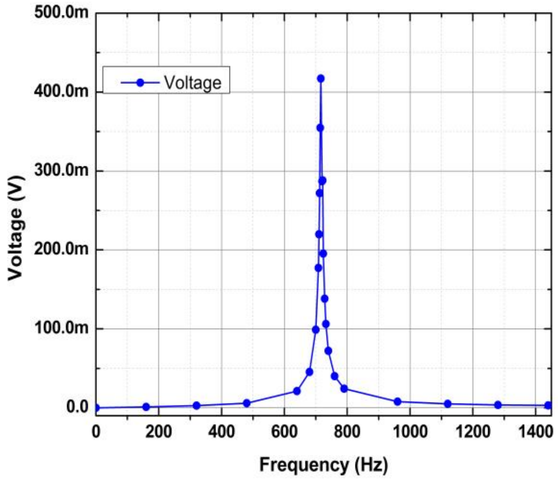

Figure.4 Voltage vs. Frequency

Fig.4 depicts the value of output voltage for first resonant frequency 720 Hz. An output voltage of 417 mV is obtained at 720 Hz.

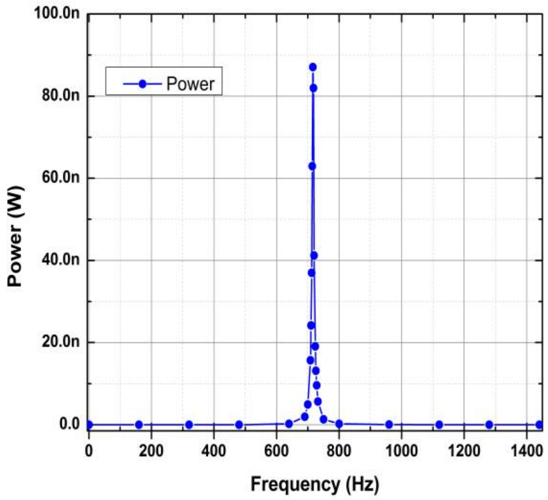

Figure.5 Power vs. Frequency

Fig.5 depicts the value of output power at 720 Hz. An output power 87 nW across a load resistance of 10 MΩ. The graphs have been plotted only for first resonant frequency because it had been proved in literatures that any device yields maximum power at its first resonant frequency.

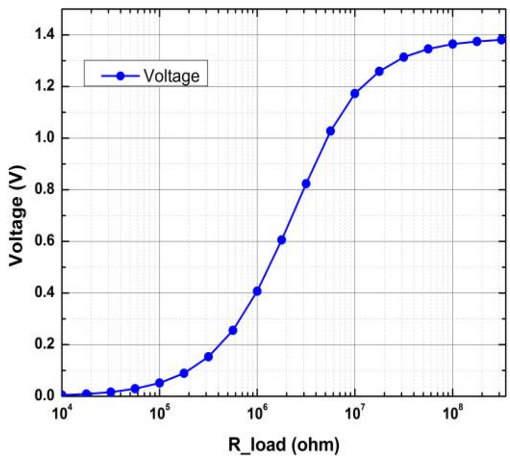

Figure.6 Voltage vs. R_load

Fig.6 shows the variation of output voltage with load resistance for the piezoelectric energy harvester, at constant frequency of 720 Hz. Nature of graphs reveals that the value of output voltage increases with increase in value of load resistance. An output voltage of 1.38 V is obtained for a load resistance of 31.6 MΩ.

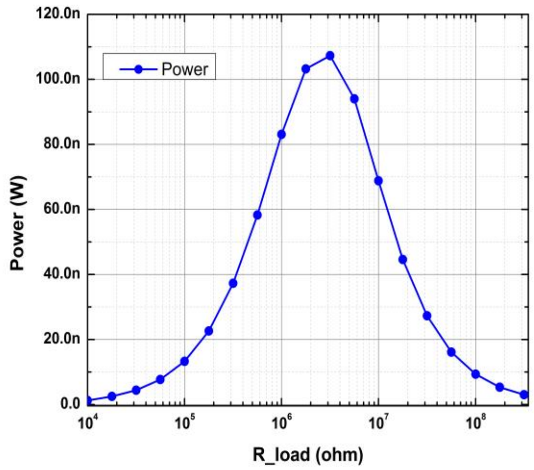

Figure.7 Power vs. R_load

Fig.7 shows the variation in power of piezoelectric energy harvester with respect to load resistance, at frequency of 720 Hz. The value of power (across load resistance) increases with increase in value of load resistance and after reaching a maximum value it start decreasing. The graph shows that device obeys the maximum power transfer theorem, to obtain maximum external power from a source with a finite internal resistance, according to which the resistance of the load must be equal to the resistance of the source as viewed from its output terminals. The maximum power of 107 nW is obtained across a load resistance of 31.6 MΩ.

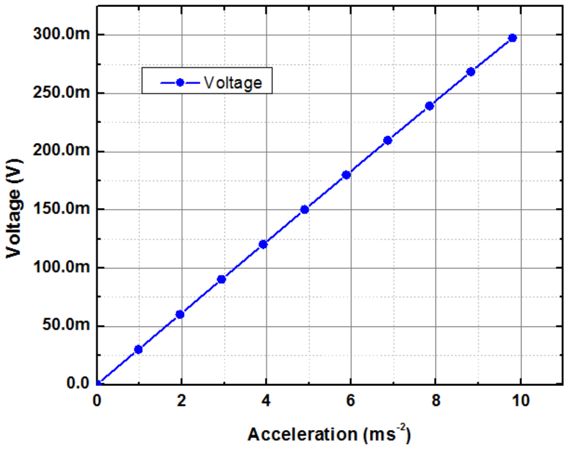

Figure.8 Voltage vs. Acceleration

Fig.8 shows the variation in voltage with acceleration. The value of voltage increases with increase in value of g. A voltage of 297 mV is obtained at 1g acceleration. The value of frequency and load resistance is held constant at 720 Hz and 1 MΩ, respectively, for this simulation.

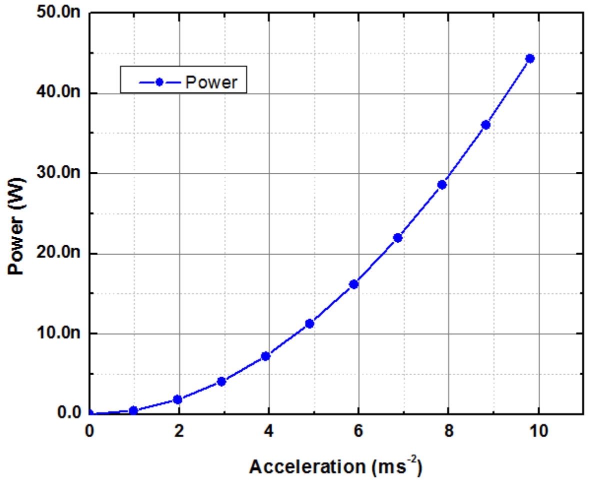

Figure.9 Power vs. Acceleration

Fig.9 shows the variation in power with acceleration. The value of voltage increases with increase in value of g. A maximum power of 44.3 nW is obtained at 1g acceleration. The value of frequency and load resistance is held constant at 720 Hz and 1 MΩ, respectively, for this simulation.

5. CONCLUSION

The ambient vibration energy can be converted to electrical energy using a MEMS piezoelectric energy harvester which would empower wireless sensors and thus will avoid the need for periodic replacement of batteries. The fabrication of proposed energy harvester would consist of several steps such as oxidation, deposition of gold electrode, PECVD oxide deposition, ZnO sputtering, top electrode formation, proof mass patterning and release of cantilever beam using DRIE. The simulated model has a resonant frequency of 720 Hz that can be used to harness vibrations from vehicles and industrial machineries. Variation of power and output voltage with respect to load resistance and g has also been studied. Simulation results indicate that the proposed structure would generate a maximum power of 107 nW. The power of such order can be utilized to operate miniaturized wireless sensors and microcontrollers at standby mode. It can also empower a 32 kHz quartz oscillator which requires 100nW to operate.

ACKNOWLEDGEMENTS

Authors would like to acknowledge the generous support of the Director, CSIR-CEERI, Pilani. The authors would also like to thank all the scientific staff of MEMS and Microsensors Group at CSIR-CEERI, Pilani.

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