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REVIEW ARTICLE

A Review of MEMS Based Piezoelectric Energy Harvester for Low Frequency Applications

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Abstract: This paper presents a review of MEMS based piezoelectric energy harvesting for low frequency and low power applications. An introduction to MEMS and its components along with the concept of energy harvesting is presented. The paper also presents a device configuration of cantilever based basic components of MEMS energy harvesters, i.e. unimorph, bimorph. Results of different designs for MEMS energy harvesters are reviewed and presented.

Keywords: MEMS, cantilever, piezoelectric materials, energy harvesting

1. Introduction to MEMS

MEMS: MICRO ELECTRO MECHANICAL SYSTEM.
MEMS are integrated micro devices or systems combining electrical and mechanical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from micrometers to millimeters [1]. These systems can sense, control and actuate on the micro scale, and function individually or in arrays to generate effects on the macro scale. MEMS are basically a combination of electronics and mechanics. The micro sensors gather information by measuring mechanical, thermal, biological, chemical, magnetic and optical signals from the environment [2].

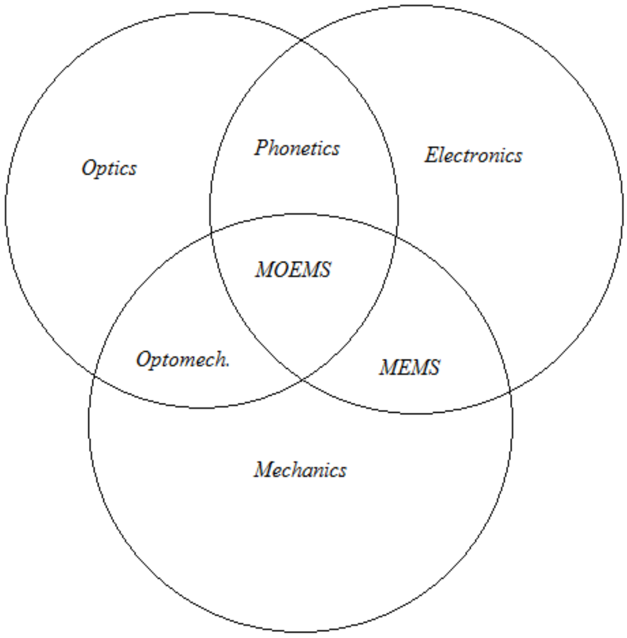

Figure 1 Basic concept of MEMS [2]

1.1 MEMS Components

In the most general form, MEMS consist of mechanical microstructures, micro sensors, micro actuators and microelectronics, all integrated onto the same silicon chip. Micro sensors detect changes in the system's environment by measuring mechanical, thermal, magnetic, chemical or electromagnetic information or phenomena [2]. Microelectronics processes this information and signals the micro actuators to react and components are usually microscopic [2].

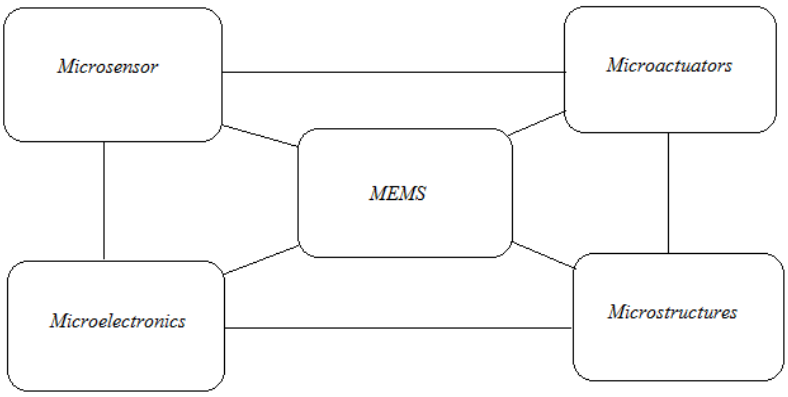

Figure 2 MEMS components [1]

1.2 Concept of Energy Harvesting

"Energy harvesting" is a technology that converts the excess energy available in an environment into usable energy for low power electronics. Many ambient energy sources have been considered for this purpose such as incident light, vibration, electromagnetism, radio frequency (RF), human body functions, temperature gradient etc. However, each of these energy sources has its own drawbacks. For example, although the solar cells offer excellent power supply in direct sun light, they are inadequate in dim office lighting. On the other hand, the circuit design for transmitting the power harvested from low level vibrations is another challenging problem. Energy harvesting also known as "Energy Scavenging", "Parasitic Energy" or "Micro generators" [1].

A. Device configuration

The vast majority of piezoelectric energy harvesting devices uses a cantilever beam structure. A cantilever beam, by definition, is a beam with a support only one end, and is often referred to as a "fixed-free" beam. When the generator is subjected to vibrations in the vertical direction, the support structure will move up and down in sync with the external acceleration. The vibration of the beam is induced by its own inertia, since the beam is not perfectly rigid; it tends to deflect when the base support is moving up and down (fig. 3). Typically, a proof mass is added to the free end of the beam to increase that deflection amount. This lowers the resonant frequency of the beam and increases the deflection of the beam as it vibrates. The larger deflection leads to more stress, strain, and consequently a higher output voltage and power. Electrodes covering a portion of the cantilever beam are used to conduct the electric charges produced to an electrical circuit, where they can be utilized to charge a capacitor or drive a load [1]-[2].

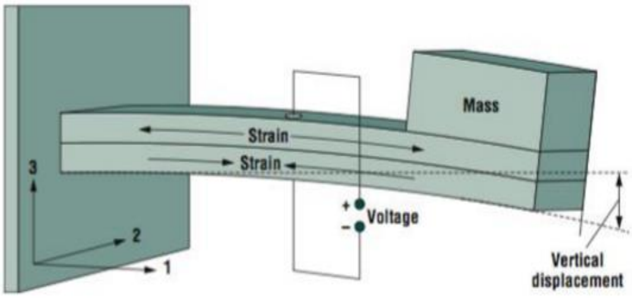

Figure 3 Strain is generated along the length of the beam (by 3-1 mode) [2]

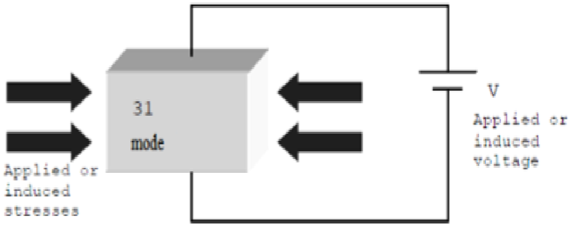

Figure 4 3-1 Mode of electromechanical coupling [1]

Lowers the resonant frequency of the beam and increases the deflection of the beam as it vibrates. The larger deflection leads to more stress, strain, and consequently a higher output voltage and power [1].

B. Cantilever

Cantilevered beams are the most ubiquitous structures in the field of micro electro mechanical systems (MEMS). MEMS cantilevers are also finding application as radio frequency filters and resonators. Two equations are keys to understanding the behavior of MEMS cantilevers. The first is Stoney's formula, which relates cantilever end deflection δ to applied stress σ [1]:

$$\delta = \frac{3\sigma(1-\nu)}{E}\left(\frac{L}{t}\right)^2 \qquad (1)$$

Where ν 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 [1].

The second is the formula relating the cantilever spring constant k to the cantilever dimensions and material constants [2]:

$$k = \frac{F}{\delta} = \frac{E\omega t}{4L^3} \qquad (2)$$

C. Unimorph

A unimorph is a cantilever that consists of one active layer and one inactive layer. In the case where active layer is piezoelectric, deformation in that layer may be induced by the application of an electric field. This deformation induces a bending displacement in the cantilever. The inactive layer may be fabricated from a non- piezoelectric material. A piezoelectric unimorph has one active (i.e. piezoelectric) layer and one inactive (i.e. non-piezoelectric) layer [1].

D. Bimorph

A bimorph is a cantilever that consists of two active layers: piezoelectric and metal. These layers produce a displacement via:

• Thermal activation (a temperature change causes one layer to expand more than the other).

• Electrical activation as in a piezoelectric bimorph (electric field causes one layer to extend and the other layer to contract) [1].

2. Review of Literature

1) Hua Yu et. Al (2014): In this paper MEMS piezoelectric power generator array for vibration energy harvesting is presented using ANSYS FEM software. A complete design flow analyzing the architecture and parameters of the energy harvester using the FEM is established. A conditioning circuit is described in this paper with the functions of impendence matching, energy storage and voltage regulation. Piezoelectric, electromagnetic and electrostatic

methods are described. A MEMS PZT cantilever array with an integrated large Si proof mass is designed and fabricated to improve the output voltage and power. An output power of 66.75 μW or a power density of 5.19 μ W is produced with an optimal resistive load of 220 kΩ from 5 m/s2 vibration acceleration at its resonant frequency of 234.5 Hz. The experimental results show that the self-supplied energy generator designed in this paper with power conditioning circuit could provide a more promising complete power supply solution for wireless sensor node loads [3].

2) E.varadrajan et. Al (2013): This paper presents an attempt to maximize the output power in the different piezoelectric materials in a unimorph cantilever configuration using COMSOL multiphysics. A macro-scale unimorph piezoelectric power generator prototypes consists of an active piezoelectric layer, stainless steel substrate and titanium proof mass was designed for frequencies 60 Hz - 200 Hz. This model is presented for three different piezoelectric materials like, PbZrTiO3 (PZT), PVDF and PMN-PT and PVDF is chosen to be an appropriate material for unimorph energy harvesting system [4].
3) Salem Saadon et. Al (2013): In this paper a model and the simulations of a new E-shaped MEMS-based piezoelectric energy harvester under ambient vibration excitation using the COVENTORWARE2010 approach is presented. This E-shaped cantilever-based MEMS energy harvester operates under ambient excitation in frequencies of 10, 12, and 13 Hz within a base acceleration of 1g produces an output voltage of 0.25 V and power of 25 microwatts at 5kΩ load. Also this paper compares the triangular, rectangular and trapezoidal shaped piezoelectric cantilever [5].
4) Monika Sharma et. Al (2013): This paper gives a brief Introduction about MEMS and its components. The concept of Energy Harvesting is introduced using PMPG circuitry Unimorph of dimension 300mm×40mm×4mm has been modeled with 2mm thin film epitaxial layer of piezoelectric material. From the simulation results Gold is preferred over Aluminum, Silicon, and Gallium Arsenide as about 1000Hz less frequency response was observed. A Unimorph with gold and PZT-5A material is considered the best model with resonance frequency of about 27120.92Hz with generated electric voltage of 2.00 volts when a load of 5 N/m 2 is applied at the tip of unimorph [1].
5) Vineet Tiwari et. Al (2013): This paper presents a bimorph actuator having piezoelectric layer of PVDF. COMSOL multiphysics software is used to design and to simulate the results. Boundary conditions are explained here to describe the deflection in bimorph beam. It is observed from this paper if thinner the piezoelectric layer, and then greater is the tip deflection because with decrease in thickness of the piezoelectric layer the electric field across it increases for constant applied potential. Also tip displacement increases with the length of the variable PVDF layer [6].
6) Deepak Poria et. Al (2012): In this paper a unimorph has been designed in 3D view using COMSOL multiphysics to decrease the operating frequency and improve the output power. In this paper Unimorph are designed with two different non piezoelectric materials as aluminum and gold. Unimorph of dimension 100mm×30mm×4mm has been modelled with 2mm thin film epitaxial layer of piezoelectric material. From the simulation results Gold is preferred over Aluminum as about 100Hz less frequency response is observed. A Unimorph with gold and PZT-5A material is considered the best model with resonance frequency of about 246Hz with generated electric voltage of 2.51 volts when a load of 20 N/m2 is applied at the tip of unimorph [2].
7) Huicong Liu et. Al (2011): In this paper the design, fabrication and measurement of piezoelectric cantilever with quite low frequency of 35.8 Hz is presented. The output voltage of different numbers of PZT patterns connected in series and in parallel are observed and discussed. It is found that the maximum power for PZT pattern connected in series and in parallel are at the same level but require different matched resistance and PZT pattern in parallel is preferred [7].

3. Conclusion and Future work

This paper concludes various models of energy harvesting devices in different design using different software to lower the resonant frequency. Cantilever beam can be of different shapes made up of different base materials and piezoelectric materials i.e. aluminum, silicon, gold. Gold is preferred over aluminum and silicon as base material and PZT-5A is selected as piezoelectric material to reduce the resonant frequency. In future low resonant frequency MEMS device can be designed to obtain better results.

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