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The effects of substrate layer thickness on piezoelectric vibration energy harvesting with a bimorph type cantilever

Jaakko Palosaari *, Mikko Leinonen, Jari Juuti, Heli Jantunen

Microelectronics Research Unit, University of Oulu, 90014 Oulu, Finland

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ABSTRACT

In this research four piezoelectric bimorph type cantilevers for energy harvesting were manufactured, measured and analyzed to study the effects of substrate layer thickness on energy harvesting efficiency and durability under different accelerations. The cantilevers had the same dimensions of the piezoelectric ceramic components, but had different thicknesses of the steel substrate (no steel, 30 μm, 50 μm and 75 μm). The cantilevers were tuned to the same resonance frequency with different sizes of tip mass (2.13 g, 3.84 g, 4.17 g and 5.08 g). The energy harvester voltage outputs were then measured across an electrical load near to the resonance frequency (~40 Hz) with sinusoidal vibrations under different accelerations. The stress exhibited by the four cantilevers was compared and analyzed and their durability was tested with accelerations up to 2.5 g-forces.

1. Introduction

As the power consumption of electronics becomes smaller while at the same time energy harvesting techniques and materials are being enhanced, interest is growing towards self-sufficient sensors [1–3]. Via piezoelectric material mechanical energy can be harvested and transformed to electrical energy. This technique requires accurate analysis of the kinetic energy experienced by the piezoelectric material so that the mechanics can be appropriately designed. Simultaneously the mechanical design has to safeguard the piezoelectric material from extreme forces that might cause cracks, while still transferring the kinetic energy efficiently. These requirements typically mean an exact energy harvest scheme for each ambient energy source at hand.

Many piezoelectric energy harvesting techniques have been developed for vibrations, including cymbal, diaphragm and cantilever type solutions [4–12]. The quantity of harvested energy outside the natural frequency of the device is still quite small and requires the optimization of the harvester dynamics to match the external vibration frequency in order to achieve usable power levels [13–15]. Not only does the harvester need to match the ambient vibrations, but also the input energy should be transmitted to the piezoelectric material as efficiently as possible. This is especially the case where the ambient vibration energy is limited and the harvesting mechanism could potentially have a major influence on the vibration source itself [16,17]. This situation demands a high efficiency of transformation of the mechanical vibration energy into electrical energy.

It is well known that piezoelectric cantilever type actuators can be optimized to convert an electrical input to mechanical vibration amplitude. This can be done by the choice of material but also by adjusting the passive-to-active material thickness

* Corresponding author.
E-mail address: Jaakko.palosaari@ee.oulu.fi (J. Palosaari).

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ratio, for example in unimorph type cantilevers [18]. With a unimorph cantilever the tip displacement varies with the passive layer thickness and determines the electromechanical coupling factor. This study was made to highlight the importance of optimization of the passive layer thickness in piezoelectric energy harvesting from ambient vibrations.

2. Materials and methods

Four bimorph type cantilevers with identical outer diameters were manufactured. Piezoelectric ceramic layers (PSI-5A4E) with a thickness of 200 μm (191 μm without electrodes) were bonded using a conductive epoxy on both sides of a steel substrate layer with thicknesses of 30 μm, 50 μm and 75 μm. One bimorph structure was bonded without the passive steel layer. All parts were laser machined (ProtoLaser U3, LPKF Laser & Electronics AG, Germany) which provided the cantilevers with precise and identical dimensions for better comparison. The cantilevers were tuned to the same resonance frequency (∼40 Hz) with different sized masses of 2.13 g, 3.84 g, 4.17 g and 5.08 g for the 0 μm, 30 μm, 50 μm and 75 μm passive steel layers respectively. Brass masses were glued on the tip of the cantilever free ends and fine-tuned to the correct weight with a blue-green sticker. The masses were glued at 2.0 mm distance from the tip. The shape of the cantilevers was slightly tapered from 9.0 mm clamping width to a free end width of 4.0 mm. The tapering will distribute the stresses more evenly across the length of the cantilever although highest stresses point will be at the clamping point. The total length of the cantilevers was 37.15 mm and the length of the clamping region was 2.28 mm. All the dimensions can be seen in Fig. 1.

A shaker was used to accelerate the cantilevers with a sinusoidal displacement near to the resonance frequency. The movement was measured on top of the clamping point with a fiber optic laser vibrometer (OFV-5000, Polytec GmbH, Germany) to calculate the acceleration applied to the harvesters. Tip displacement was also measured from the tuning mass. The energy harvester output voltage was measured across an electrical load under different accelerations as a function of frequency. Average raw power curves were then calculated from the voltage measurements using Eq. (1) where U is the root mean square (RMS) voltage and R is electrical load resistance.

$$P = \frac{U^2}{R} \tag{1}$$

A 2D model was created with Comsol Multiphysiscs 5.2 simulation software and was used to analyze and compare the stress patterns of the cantilevers with different passive layer thicknesses. Simulations were carried out as transient simulations with the clamp point boundary set to sinusoidal acceleration. All the other boundaries were free. The 2D-model was tapered using the out-of-plane dimension as a variable to create the tapered width. The meshing was done with the automatic meshing tool of the software, which created triangular elements. The piezoelectric electrode boundaries were connected to a SPICE-circuit containing the load resistor. This is also facilitated by the Comsol software. The stresses were recorded as the maxima of the stress waveforms at the top of the piezolayer at the clamp point as shown in Fig. 3.

3. Results

Firstly, the voltage (RMS) was measured with sinusoidal accelerations of 0.5 g-force (gravitational), 1.0 g-force and 1.5 g-force. The average raw power was then calculated from the measured voltage across an electrical load of 100 kΩ. Fig. 2 shows the power curves as a function of frequency for each cantilever. The power levels were quite similar between cantilevers for

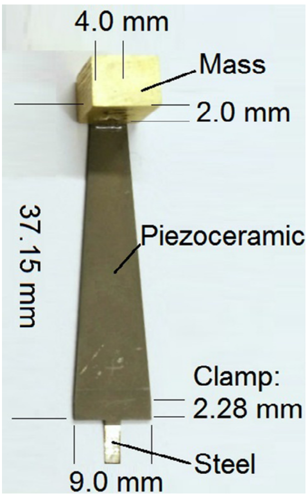

Fig. 1. Cantilever dimensions.