A Hair-cell Structure based Piezoelectric Energy Harvester Operating under Three Dimensional Arbitrary Vibrations

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Abstract. A hair-cell structure based piezoelectric energy harvester was newly developed to effectively scavenge three-dimensional vibrations. The cantilever of the proposed energy harvester, called a hair-cell structure, is deliberately elongated and curled so that it oscillates with decent displacement under not only vertically induced vibrations, but also under longitudinally and horizontally induced vibrations. The proposed energy harvester is comprised of an elongated and curled piezoelectric cantilever and a proof mass with high aspect ratio at the free end of the cantilever. The fabricated device generated the peak output voltage of 15 mV under vertically induced vibrations with an acceleration of 50 m/s^2 at its resonance frequency of 116 Hz. Furthermore, it also generated the peak output voltage of 33 mV and 10 mV under longitudinally and horizontally induced vibrations, respectively.

1. Introduction

The development of low-power wireless sensor networks has recently opened up a possibility that energy harvesters can be used to power self-sustainable autonomous sensor nodes instead of traditional batteries [1-4]. Micro electromechanical system (MEMS) energy harvesters have been actively developed to reduce size and weight and to integrate with other integrated circuits (ICs) and MEMS components. The reported MEMS energy harvesters generated several micro- watts of output power from induced vibrations and are based on the cantilever structure [4-7]. The cantilever structure is comprised of a piezoelectric thin film attached on a spring structure and proof mass at the free end of the cantilever and it is based on the spring-mass-damper system. MEMS energy harvesters that employ this cantilever structure produce their maximum output power when the frequency of the induced vibrations matches the resonance frequency of the cantilever. Furthermore, most of this cantilever structure utilized for MEMS energy harvesters is flat. Therefore, they produce their maximum output powers when the normal direction of the cantilever plane matches the direction of induced vibration, otherwise their output powers dramatically decrease [4-8]. Therefore, these MEMS energy harvesters need to be individually installed on the vibration sources to maximize their output powers.

A curled cantilever structure based MEMS energy harvester was developed for two-dimensional operation [9]. The curled cantilever structure could be interpreted as the series connections of short flat cantilevers and each short flat cantilever had each own tangential component to induced vibrations

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along the cantilever curve, which caused maximum bending momentum. Therefore, this curled cantilever successfully oscillated under both vertically and longitudinally induced vibration and generated uniform output under two-dimensionally induced vibrations. However, it is prohibited to scavenge horizontally induced vibrations.
In this paper, a hair-cell structure based piezoelectric energy harvester was newly proposed to effectively scavenge quasi three-dimensional ambient vibrations. The proposed cantilever structure, called a hair-cell structure, is based on a curled cantilever structure and deliberately elongated so that it oscillates under not only vertically induced vibrations but also under longitudinally and horizontally induced vibrations. The proposed device was successfully micro-fabricated and generated electrical power under vertically, horizontally, and longitudinally induced vibrations.

2. Design and fabrication

2.1. Design

The conventional flat cantilever structure is restricted to oscillating in the tangential direction over the neutral surface under vertically induced vibrations [4-8]. On the other hand, a curled cantilever structure was previously reported to scavenge two-dimensional vibration and its feasibility was verified [9]. A curled cantilever can be interpreted as the series connections of short flat cantilevers and each short flat cantilever has each own tangential component along the cantilever curve, which causes maximum bending momentum. The tangentially induced force at the specific point of curled cantilever is the projection of arbitrary vibrations on the tangential direction of spring component and leads to oscillate vertically and longitudinally.
In addition, a new cantilever structure that is deliberately elongated and curled around the longitudinal direction of the cantilever, called a hair-cell structure, was proposed to scavenge quasi three-dimensional ambient vibrations. The cantilever structure obtains an additional degree of freedom when the ratio of the length to the width of the cantilever is high enough. Therefore, the hair-cell structure based energy harvester can generate electrical energy from quasi three-dimensional ambient vibrations via both the typical fundamental mode and harmonic mode of torsional operation, as shown in Figure 1 (a) and (b), respectively. The proposed energy harvester is comprised of a high aspect ratio proof mass and elongated piezoelectric cantilever curled around the longitudinal direction.

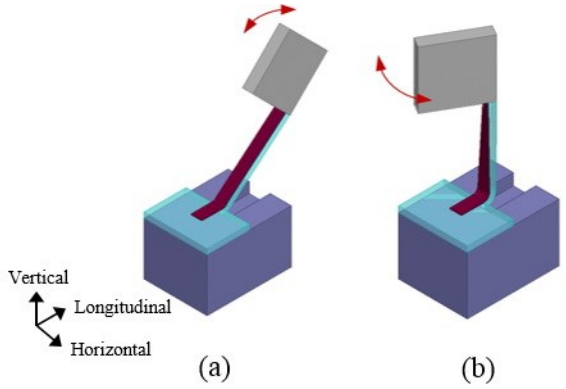


Figure 1. Operation principle of the proposed hair-cell structure based energy harvester: (a) typical fundamental mode for vertical and longitudinal vibration energy harvesting and (b) harmonic mode torsional operation for horizontal vibration energy harvesting.

2.2. Fabrication

The fabrication sequences of the proposed hair-cell structure based energy harvester are schematically shown in Figure 2. The fabrication started with the deposition of LPCVD SiNx (0.8 μm) and LTO (0.2 μm) for an elastic layer on a Si wafer. After sputtering a Ti/Pt (300 Å/1200 Å) thin film for the formation of the bottom electrode, a $Pb(Zr_{0.52}Ti_{0.48})O_3$ (3500 Å) thin film was sol-gel spin coated. A Pt thin film was sputtered for the formation of the top electrode and then Ti/Pt/PZT/Pt layers were patterned by using the inductively coupled plasma (ICP) dry etching technique. A Si_3N_4 (2000 Å) thin

film was deposited by using a PECVD and patterned by the RIE technique for the passivation between the PZT layer and NiFe proof mass. A Ti/Au (300/3500 Å) was deposited by the E-beam evaporation technique and patterned by the lift-off technique to form electrode bonding pads. The SiNx/LTO layer on the Si substrate was then patterned to form the cantilever structure. A photoresist layer was coated as a sacrificial layer and Ti/Cu (300/1500 Å) thin film was then sputtered as a seed layer for electroplating. After forming a thick photoresist mold, a $Ni_{0.8}Fe_{0.2}$ (22 μm) alloy was electroplated to form a proof mass. Finally, the XeF_2 etching technique was used to release the cantilever and the released cantilever was curled up due to the intrinsic bending deformation of multi-stacked layer.

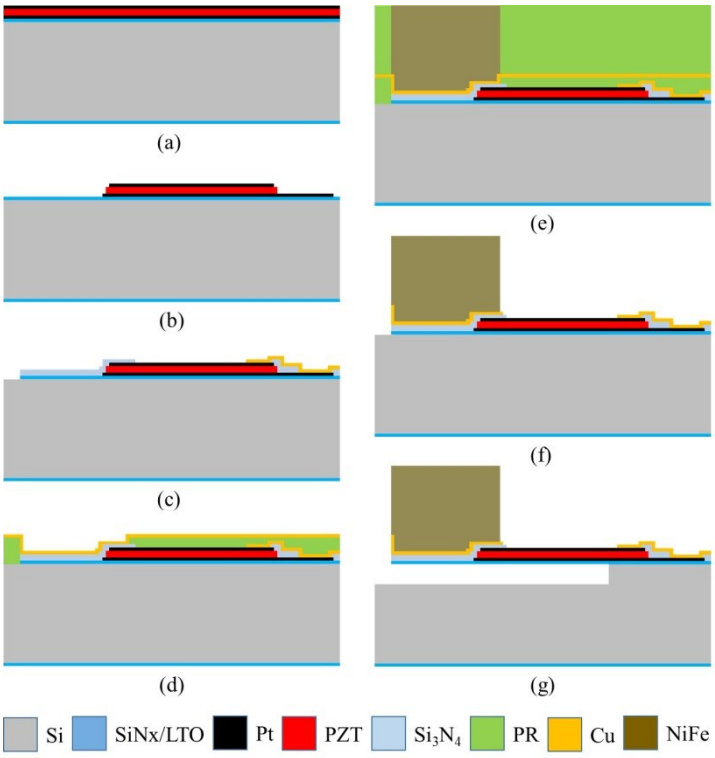
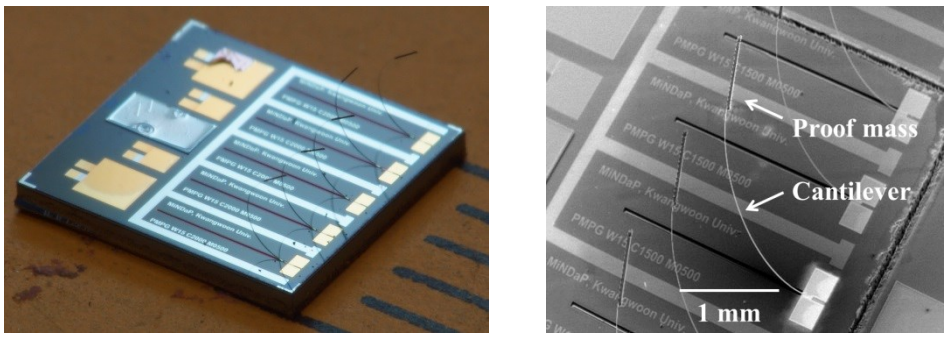


Figure 2. Fabrication sequences of the proposed hair-cell structure based piezoelectric energy harvester: (a) deposition of SiNx/LTO/Ti/Pt/PZT/Pt on a Si wafer, (b) patterning of Ti/Pt/PZT/Pt (c) deposition and patterning of Si_3N_4 as a passivation layer and Ti/Au as an interconnection layer, (d) deposition of photoresist as a sacrificial layer and Ti/Cu as a seed layer for electroplating, (e) formation of photoresist mold and electroplating of NiFe as a proof mass, (f) removal of mold, seed, and sacrificial layers, (g) XeF_2 etching of Si selectively for releasing the cantilever.

Figure 3 shows the photograph and SEM image of fabricated MEMS piezoelectric energy harvester. The ratio of length to width of the cantilever was 67:1. The PZT cantilever was curled up to the longitudinal direction of the cantilever due to the intrinsic bending deformation and the NiFe proof mass was located at the free end of the cantilever. The volumes of fabricated piezoelectric cantilever and NiFe proof mass are 1000×15×1.7 (height) μm^3 and 500×15×22 μm^3, respectively.



(a) (b)

Figure 3. (a) Photograph and (b) SEM image of the micro-fabricated hair-cell structure based piezoelectric energy harvester.

3. Experimental results

The PZT thin film of the fabricated hair-cell cantilever structure was exposed to the electric field ranging from -10 V to 10 V and its polarization curve was measured by the Radiant Precision LC system. The fabricated PZT thin film had a saturation polarization, remnant polarization and coercive field of approximately P_{MAX} = 23.15 μC/cm^2, $2P_r$ = 6.22 μC/cm^2 and 6.64 kV/cm, respectively. Figure 4 shows the experimental set-up for the fabricated device. A rotational jig between the accelerometer and fabricated device was used to apply three-dimensional vibrations to the fabricated device in order to verify the main concept that the fabricated device generated electrical energy under three-dimensional ambient vibrations.

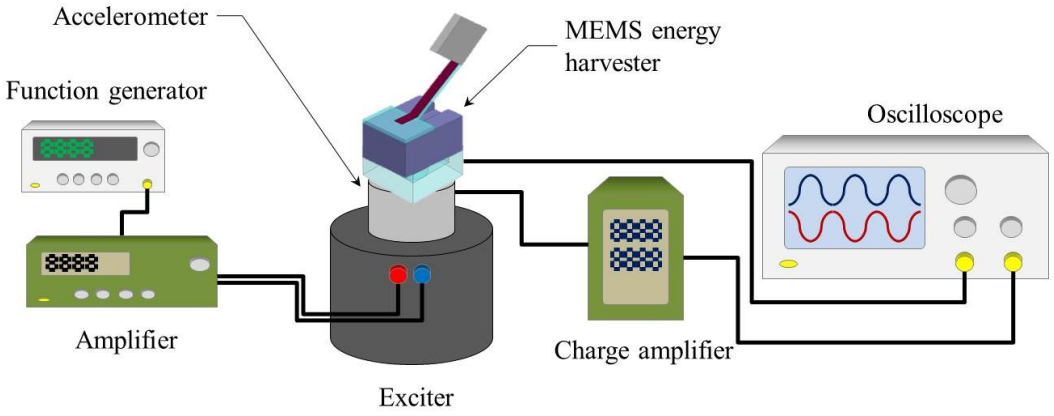


Figure 4. Experimental set-up with a rotational jig for the fabricated device.

The fabricated device was located under vertically induced vibrations at various frequencies to find its fundamental resonance frequency. The output voltage of the fabricated device was maximized to 15 mV at its resonance frequency of 116 Hz under vertically induced vibrations with frequency swept from 95 to 135 Hz and an acceleration of 50 m/s^2, as shown in Figure 5. Figure 6 shows the waveform of the generated output voltage from induced vibrations. In order to verify three-dimensional vibration harvesting, the fabricated hair-cell structure based energy harvester was placed under longitudinally and horizontally induced vibrations. As shown in Figure 7, the fabricated device successfully generated the output voltage of 33 mV and 10 mV under longitudinally and horizontally induced vibrations with a resonance frequency of 116 Hz and acceleration of 50 m/s^2, respectively. Even though the output voltage of proposed energy harvesting device was smaller than the expected value, the performance was not affected by installation angle with respect to vibration.

4. Conclusion

In this paper, a piezoelectric energy harvester for three-dimensional vibration scavenging has been presented. The cantilever of the proposed energy harvester, called a hair-cell structure, was deliberately elongated and curled so that it has a quasi three-dimensional operation with decent displacement under both the typical fundamental mode and harmonic mode of torsional operation. The output voltage needs to be improved for the practical use as a power source and it is expected to generate higher output voltage if the proof mass and PZT thin film becomes heavier and thicker, respectively.

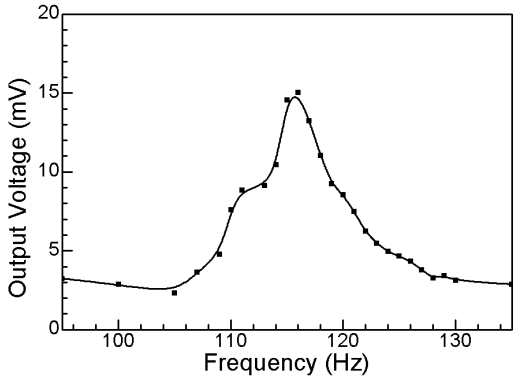


Figure 5. Frequency response of the fabricated hair-cell structure based energy harvester under vertically induced vibrations with an acceleration of 50 m/s^2.

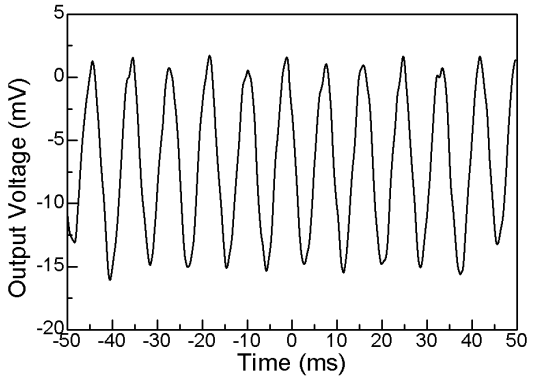


Figure 6. Output voltage waveform of the fabricated energy harvester under vertically induced vibrations with an acceleration of 50 m/s^2 at its resresonance frequency of 116 Hz.

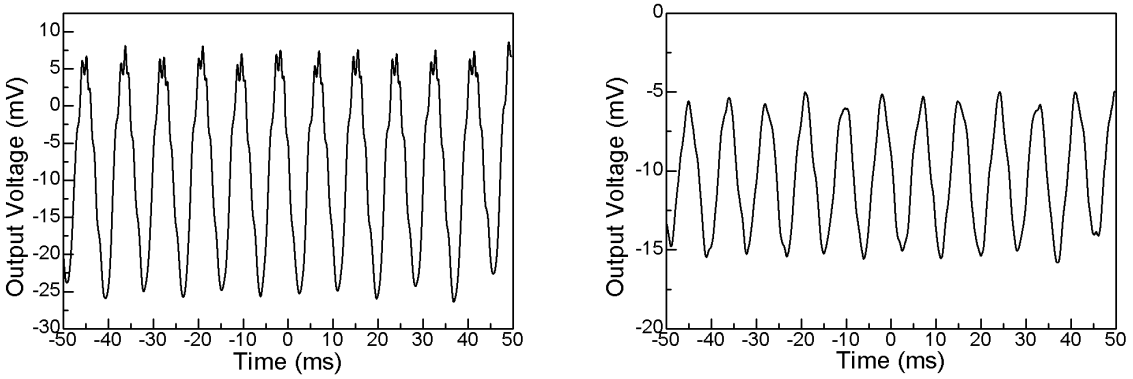


Figure 7. Output voltage waveform of the fabricated energy harvester under (a) longitudinally and (b) horizontally induced vibrations with an acceleration of 50 m/s^2 at its resonance frequency of 116 Hz.

Acknowledgements
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