MICRO-FABRICATED PIEZOELECTRIC TWO-DIMENSIONAL VIBRATION ENERGY HARVESTER

Jong C. Park, S. Khym, and Jae Y. Park
Department of Electronic Engineering, Kwangwoon University, Seoul, Republic of Korea

Abstract: A micro-fabricated energy harvester was investigated for scavenging two-dimensional vibrations. The proposed piezoelectric bent cantilever was formed by using intrinsic stress-induced bending deformation of polyimide, PZT thin film with Pt electrodes, and low stress SiNx thin film layers. The fabricated device generated an output voltage of 14mV at its resonant frequency of 89.8Hz with acceleration of $10m/s^2$. While typical cantilever based piezoelectric energy harvesters were limited to generate the maximum output powers within the installation angles ranging from -20 to 20 degrees, the proposed one exhibited its maximum output power at the installation angles ranging from -90 to 90 degrees. The piezoelectric bent cantilever was highly effective generate electricity from two-dimensional ambient vibrations.

Keywords: energy harvesting, two dimensional vibrations, PZT, ambient vibrations, bent cantilever

INTRODUCTION

Since the traditional power sources like chemical batteries have been met serious problems in their maintenances due to the self-discharge, energy harvesting technologies, which convert the ambient wasting energy of things such as light, heat, and mechanical vibrations into electrical power, have been attracted for micro-power systems. In particular, these energy harvesting devices are highly effective for the hazardous and harsh environments and autonomous system applications. In addition, since low-power ICs (integrated circuits) have also been developed with extremely low power consumption ranging from only tens to hundreds of microwatts, self-sustainable tiny wireless sensors have been developed using the vibration based energy harvesting devices integrated with low-power ICs for implantable biomedical devices, intelligent buildings and structures monitoring systems, and wireless sensor networks [1-4].

The vibration energy has great potential for micro-power generator because it has a relatively higher power density than the others, sustainability, and reliability in harsh environments due to the absence of physical connections to the outside of system. Therefore, the vibration based energy harvesting devices have been studied to generate power from mechanical vibrations via electromagnetic, electrostatic, and piezoelectric operating principles. They utilize a mass spring damper system which the mass moves in accordance with transducers and couples with external vibration. In these electromechanical devices, the maximum output power is achieved at their resonant frequencies [3-10].

The output powers of energy harvesting devices reported in literature are ranged from micro- to milliwatts. Several bulk-prototype piezoelectric energy harvesters have been developed to increase the output powers by using various structures and transduction modes [5]. To reduce their sizes and volumes, a few groups have reported micro-machined piezoelectric vibration energy harvesters. In order to present feasibility as a power source, several micro-machined power generators were also reported which generated several micro-watts of output power from induced vibration [6]-[10]. While they presented promising performances, these devices are still limited to generate electrical power from ambient vibration source [3-10]. Since the ambient vibrations are existed arbitrarily, the previously reported devices are limited for practical applications.

In this paper, the piezoelectric energy harvesting device was investigated to generate the electricity from two-dimensional vibrations. In order to harvest two-dimensional vibrations, the proposed device was designed to have a bent PZT cantilever and Si inertial mass as shown Fig. 1. The bent cantilever was formed by using intrinsic stress-induced bending deformation of multi-layered thin film structures. It was comprised of polyimide, PZT thin film with Pt electrodes, and low stress SiNx thin film layers.

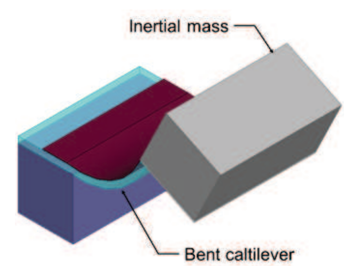

Fig. 1: Conceptual drawing of 2-dimensional vibration energy harvester using bent cantilever.

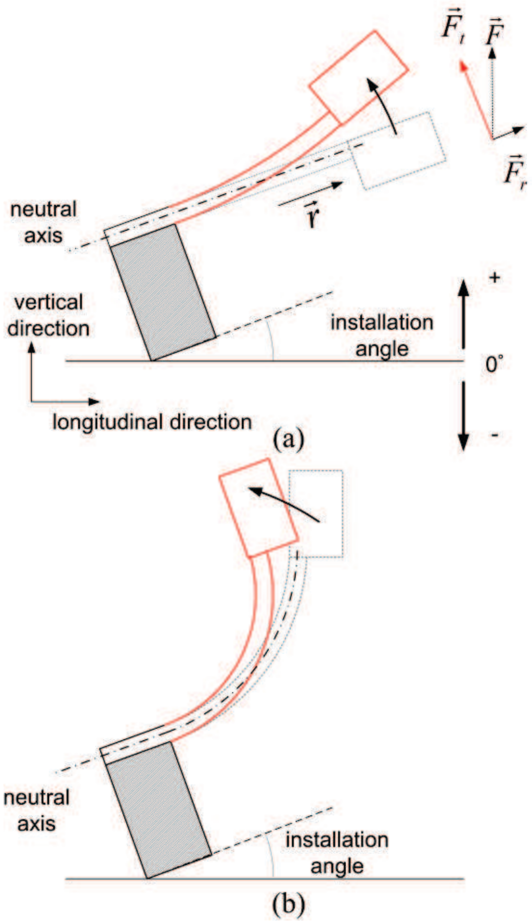

Fig. 2: Conventional piezoelectric cantilever based energy harvester (a) and proposed piezoelectric bent cantilever based energy harvester with inertial mass (b).

DESIGN AND FABRICATION

Fig. 2 shows the typical piezoelectric energy harvesting cantilever structure and proposed bent cantilever for two-dimensional vibration energy harvester. An arbitrary force can only cause a tangential oscillation of inertial mass when an inertial mass is attached at the free end of cantilever for angular oscillation as shown in Fig. 2 (a). Therefore, the bending momentum (*M*) acting on the specific point of cantilever which causes the strain in the piezoelectric thin film, is proportional to the tangentially induced force (F_t) on the inertial mass at the end of cantilever. The radial direction is not permitted by the cantilever. This tangentially induced force can be defined the angle between the flat cantilever and the arbitrary force. Thus, the bending momentum of flat cantilever is strongly sensitive in its installation orientation. According to beam theory, the output power is proportional to the bending momentum of cantilever [3, 10].

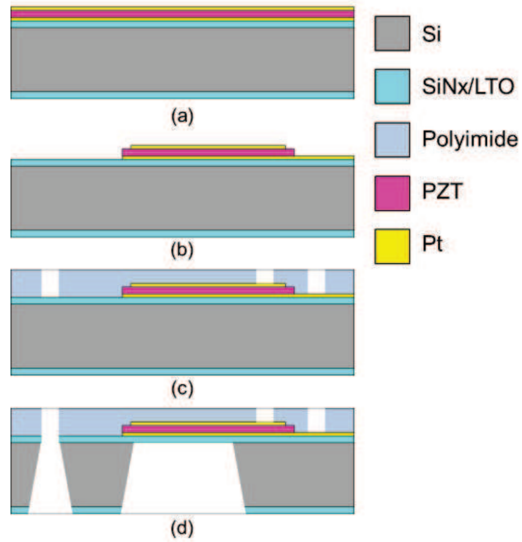

Fig. 3: Fabrication of proposed energy harvester using bent PZT cantilever: LPCVD SiNx and LTO process/ bottom Pt / PZT / top Pt deposition (a), Top Pt and bottom Pt dry-etching and PZT wet-etching (b), Photosensitive polyimide deposition (c), release via Si wet-etching (d).

The output voltage of typical energy harvester is maximized and minimized when the arbitrary vibration exists perpendicular and parallel to the longitudinal direction of cantilever, respectively. It limits the installation of typical energy harvester in practical application because the energy harvester must be installed on a perpendicular plane to the induced vibration for maximum output power.

In order to harvest arbitrary vibrations, the bent cantilever based energy harvester was investigated. The tangentially induced force at the specific point of bent cantilever leads to oscillate the inertial mass at the free end of bent cantilever. These tangential components normally existed along to the neutral axis of bent cantilever which formed as an arc, as shown in Fig. 2 (b). Therefore, the inertial mass can be angularly oscillated from both vertically and longitudinally induced vibrations. Thus, the proposed energy harvester can generate electricity at much larger installation angles than typical piezoelectric energy harvesters. To verify the proposed structure, the bent cantilever based piezoelectric energy harvester was fabricated by using the intrinsic stress-induced bending deformation of multilayered cantilever. The fabricated bent piezoelectric cantilever has a volume of 4000 × 2000 × 18 (height) μm^3. The polyimide layer was utilized as an elastic layer for leading into low resonant frequency and securing mechanical reliability. The inertial mass has a volume of 2000×2000×500 (height) μm^3.

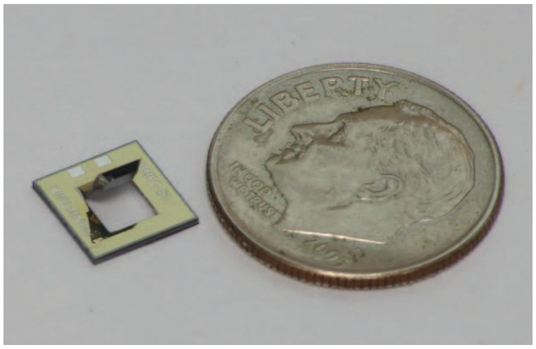

Fig. 4: Photograph of micro-fabricated piezoelectric bent cantilever based energy harvester.

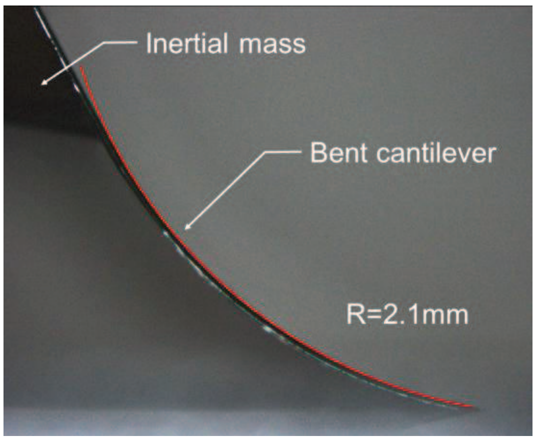

Fig. 5: Side view of piezoelectric bent cantilever through optical microscope.

Fig. 3 shows the fabrication of proposed energy harvester by using bent PZT cantilever. The fabrication of the proposed vibration harvesting device started with deposition of LPCVD SiNx and LTO with thickness of 0.8 μm and 0.2 μm, respectively. Then, a Ti/Pt bottom electrode with a thickness of 0.03/0.12 μm was deposited by sputtering and a PZT thin film with a thickness of 0.3 μm was deposited with a Zr/Ti ratio of 52/48 by using the sol-gel method. A Pt with thickness of 0.1 μm layer was sputtered to form top electrode. The top and bottom electrodes were patterned by the inductively coupled plasma (ICP) dry etching technique and PZT thin film was wet-etched by using etchant with HF/HNO_3/HCl. A polyimide was utilized as a cantilever to decrease the resonant frequency and fabricated by using HD4100 photoresist to define cantilever structure. The fabricated device has polyimide thin film with 18 μm of thickness. A SiNx to define Si inertial mass were formed by back side RIE etching. The cantilever device was released by wet-etching and dry-etching of the bulk silicon. The most of bulk silicon was carefully etched by using KOH wet-etching and the remained silicon was etched by using XeF_2 etching. Finally, the cantilever device was released RIE etching of SiNx/LTO layer. Figs. 3 and 4 show the fabrication sequences and photograph of the fabricated energy harvesting device, respectively.

EXPERIMENTAL RESULTS

Firstly, the piezoelectric properties of the PZT thin film were tested by polarization voltage measurement by using Radiant Precision LC system. The remnant polarization and coercive field of fabricated device were measured to be 2Pr = 35.4 $\mu C/cm^2$ and 2Ec = 122 kV/cm, respectively. The capacitance measured using HP4194A was 66 nF and the extracted dielectric constant was 872.

Fig. 5 shows the side view of the fabricated energy harvester measured by using an optical microscope. As a result, the free-standing cantilever undergoes bending deformation due to the internal elastic stress as shown in Fig. 5. The fabricated bent cantilever has a radius of curvature ranging from 1.9 to 2.5 mm and the inertial mass has displacement of approximately 3.1mm.

Fig. 6 shows the frequency and acceleration response of fabricated energy harvester. The input frequency was increased and decreased slowly from 85 to 95 Hz with acceleration of $6m/s^2$. As shown in Fig. 6 (a), the fabricated device generated a maximum output voltage at its resonant frequency of 90Hz. While previous work has several hundred Hz of the resonant frequency, the fabricated device has significantly reduced one by utilizing polyimide for bent cantilever. The output voltage was measured at its resonant frequency with the input acceleration ranged from 2 to 10 m/s^2. The output power was 14mV at 10 m/s^2.

Fig. 7 shows the comparison of normalized output power of proposed energy harvester to conventional energy harvester. Our previous work was utilized to compare with proposed energy harvester [10]. The output was normalized to the output power at the installation angle of zero degree and the installation angle was varied ranging from -90 to 90 degrees. As shown in Fig. 7, the conventional energy harvester generated the maximum output power at the installation angles ranged from -20 to 20 degrees. However, the proposed energy harvester exhibited the maximum output power in whole range of installation angles. Although the proposed device exhibited small output voltage of several milli-volts, it was confirmed as promising geometry to harvest electrical energy from multi- dimensional vibration sources.

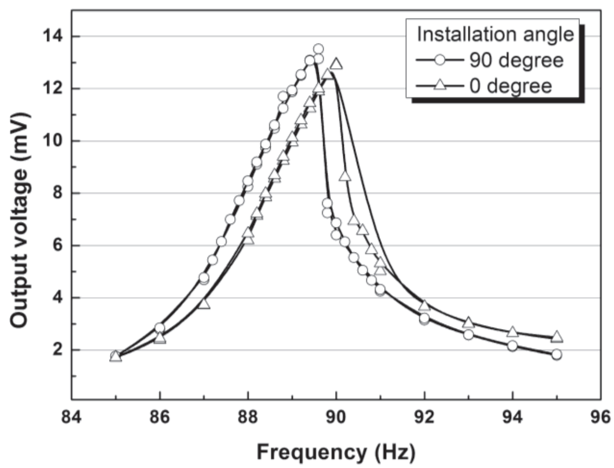

Fig. 6: Experimental results of micro-fabricated two-dimensional vibration energy harvester at vertically and longitudinally induced vibrations of 6m/s^2.

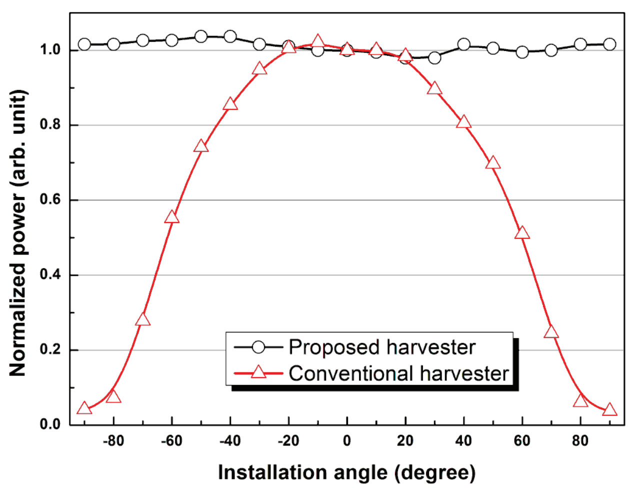

Fig. 7: Normalized output power of micro-fabricated two-dimensional vibration energy harvester at induced vibration with frequency of 89.8 Hz, acceleration of 10 m/s^2, and various installation angles.

CONCLUSIONS

In this paper, the bent cantilever based piezoelectric energy harvester has been presented to generate electricity from two-dimensional vibration sources. The energy harvester was comprised of the bent cantilever and inertial mass at the free end of cantilever. The bent cantilever was formed by using stress-induced bending deformation of MEMS based multi-layered polyimide/PZT cantilever and bulk-micromachining, respectively. The experimental results showed that the proposed device was highly effective to generate electricity from two-dimensional vibration sources.

ACKNOWLEGEMENTS

This research was supported by the Pioneer Research Center Program (2010-0019313) and Basic Science Research Program (2010-0024618) through the National Research Foundation of Korea funded by the Ministry of Education, Science and Technology. The authors thank the MiNDaP group members for their technical support and discussions.

REFERENCES

[1] T Starner 1996 Human powered wearable computing *IBM Syst. J.* **35** 618–629

[2] R Amirtharajah, A P Chandrakasan 1998 Self-powered signal processing using vibration-based power generation *IEEE J. Solid-State Circuits* **33** 687-695

[3] S Roundy, P K Wright, J Rabaey 2003 A study of low level vibrations as a power source for wireless sensor nodes *Comput. Commun.* **26** 1131–1144

[4] S P Beeby, M J Tudor, N M White 2006 Energy harvesting vibration sources for microsystems applications *Meas. Sci. Technol.* **17** R175–195

[5] S R Anton, H A Sodano 2007 A review of power harvesting using piezoelectric materials (2003–2006) *Smart Mater.Struct.* **16** R1-R21

[6] H-B Fang, J-Q Liu, Z-Y Xu, L Dong, L Wang, D Chen, B-C Chai, Y Liu 2006 Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvester *Microelectron. J.* **37** 1280-1284

[7] M Marzencki, Y Ammar, and S Basrour, 2008 Integrated power harvesting system including a MEMS generator and a power management circuit *Sens. Actuators A, Phys.* **145** 363–370

[8] M Renaud, K Karakaya, T Sterken, P Fiorini, C Van Hoof, R Puers 2008 Fabrication, modeling and characterization of MEMS piezoelectric vibration harvesters *Sens. Actuators A, Phys.*, **145** 380–386

[9] D Shen, J-H Park, J Ajitsaria, S-Y Choe, H C Wikle III, D-J Kim, 2008 The design, fabrication and evaluation of a MEMS PZT cantilever with an integrated Si proof mass for vibration energy harvesting *J. Micromech. Microeng.* **18** 1-7

[10] J C Park, J Y Park, Y-P Lee 2010 Modeling and characterization of piezoelectric d_{33}-mode MEMS energy harvester *IEEE J. Microelectromech. Syst.* **19** 1215-1222