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Fabrication and characteristic of piezoelectric bimorph MEMS generators based on stainless steel substrate for vibration generator

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Abstract

The piezoelectric micro energy harvester has received great attention for the energy conversion in the last recent decades. In this paper, we present the bimorph type of piezoelectric micro energy harvester that was fabricated by laminating two PZT thick film with double side. The device was based on stainless steel substrate, which can more efficiently capture vibration energy from environment and transformed into useful electrical energy. Two directions of polarization about the device were fabricated and evaluated. To adjust the resonance frequency was also demonstrated. The experimental results show the device at 0.5 g acceleration, which and open-circuit output voltage had 11.6 V_{P-P} and 20.1 V_{P-P} of a parallel polarization device and a serial polarization device, respectively. The output performance of a parallel polarization device that a maximum output power and voltage had 423 μW and 15.2 V_{P-P} at excitation frequency of 143.5Hz under 1.5 g externally applied vibration. For a serial polarization device, a maximum output power and voltage had 413μW and 33 V_{P-P} at excitation frequency of 140.9Hz under 1.5g externally applied vibration.

1. INTRODUCTION

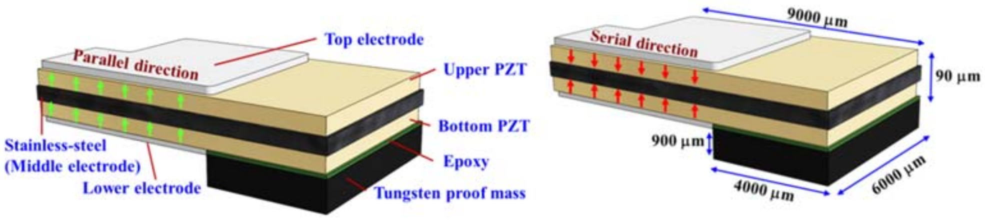
Wireless sensor network and sensors for structural health monitoring in remote locations have seen growing importance and triggers lots of researches in past two decades [1]. The power source of these sensors is powered by batteries that replacement operations and maintenance costs can be difficult and expensive. However, the power consumptions of low-power VLSI (very large-scale integration) circuits for integrated sensor devices have been down to the scale of tens to hundreds μW [2]. As a result, using the micro energy harvesters from ambient sources to power the tiny sensor devices has become more and more practical. Comparing all energy of possible ambient sources, the mechanical energy of ambient vibrations is most potential to transform it into useful electrical power through the piezoelectric, electromagnetic and electrostatic transducers types [3]. In the three energy sources, the piezoelectric types have higher energy density then electromagnetic and electrostatic types [4].

In order to improve the efficiency of the output power, the bimorph piezoelectric MEMS generator which is the PZT layer deposited on the double side (obverse and reverse side) of the stainless steel substrate is proposed. Due to its stability, good electrical conductivity and thermal expansion match to stainless steels [11], PZT thick film was selected and applied as depositing onto stainless steel substrate.

In this paper, we present the development of piezoelectric bimorph MEMS generators, which was made from a piezoelectric bimorph cantilever beam. Both PZT layers of the bimorph type MEMS generator can be used to transform mechanical vibration energy into useful electrical power. The two piezoelectric PZT layers on the bimorph generator were both fabricated using the aerosol deposition method. To fabricate the piezoelectric bimorph MEMS generator, a beam structure was constructed by laminating two layers of PZT and equipped with top, middle, and bottom electrodes. To harvest the vibration energy from its surroundings, the beam structure was designed to operate at its resonant frequency for maximum stress and strain so as to also maximize the electric power output. Two poling methods, a parallel polarization and serial polarization were achieved for the upper and the lower PZT layers of the piezoelectric bimorph MEMS generators [12].

2. DEVICE STRUCTURE

Although the bimorph mode has been well-developed for large-scale devices [4, 8-10], a bimorph piezoelectric remains difficult to fabricate for a micro-scale generator. In order to improve the efficiency of the output power, the bimorph piezoelectric MEMS generator which is the PZT layer deposited on the double side (obverse and reverse side) of stainless steel substrate is proposed. Figure 1 shows the schematic diagram of the bimorph piezoelectric MEMS generator for low-frequency power harvesting. The bimorph piezoelectric MEMS generator was mainly a micro-cantilever beam laminated with a double layer of PZT and which possessed a proof mass at the tip. The double layers PZT could be poled in different direction. The poled in parallel direction is shown in Figure 1 (a) and the poled in a serial direction is also shown in Figure 1 (b).



(a) (b)

Figure 1. Schematic diagram of the piezoelectric bimorph MEMS generator: (a) poled in a parallel direction and (b) poled in a serial direction.

The bimorph piezoelectric MEMS generator in this work was designed as a 9000×6000 μm^2 cantilever beam. It was 90 μm thick formed by laminating two 15 μm upper and lower PZT layers and comprised of stainless steel in between and the thin electrodes also at the top and bottom of the PZT layers. The areas of top and bottom electrodes were also a distance of 5000 μm from the base. The stainless steel has excellent conductivity that can be used as middle electrodes. In order to demonstrate the tuning of the resonant frequency of the device, the proof mass for the bimorph piezoelectric MEMS generator was fabricated under the beam structure at the tip with a dimension of 4000×6000×900 μm^3 for parallel poling device and serial poling device.

3. EXPERIMENTAL SET-UP AND RESULTS

The experimental setup of measurement is shown in Figure 2. The piezoelectric MEMS generator was mounted on a shaker which acted as a vibration source to the device. The data acquisition device (DAQ-NI USB-6251) had high input impedance (10 GΩ) and high sensitivity measurement accuracy. It can be assumed as an open circuit condition was used to measure the output signal. An accelerometer (B&K Type

4381) was mounted together with the piezoelectric MEMS generator to measure the given vibration condition.

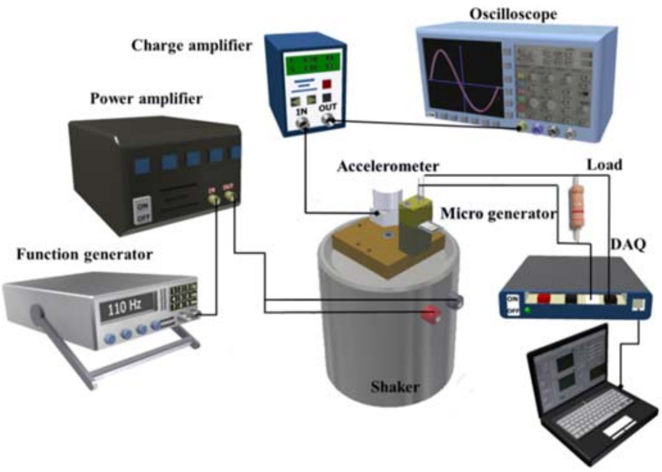


Figure 2. Experimental setup for measuring the piezoelectric MEMS generator.

3.1 Parallel polarization direction device

The maximum output power of the bimorph mode piezoelectric MEMS generator was also a function of the applied acceleration. The bimorph mode piezoelectric MEMS generator with parallel polarization was tested up to 1.5 g acceleration. Figure 3 shows the relationship of the maximum output power and the associated output voltage at different externally applied accelerations under 68 kΩ optimal load impedance. Results show our device obtained a maximum output power of 423 μW with 15.2 V_{P-P} output voltage under an impedance matching condition at a 1.5 g acceleration excitation.

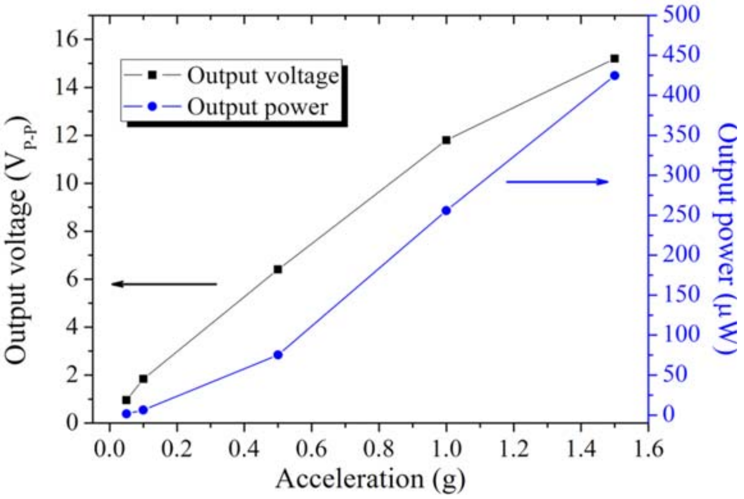


Figure 3. Relationship between maximum output power and associated output voltages at different applied accelerations under 68 kΩ load impedance for a parallel polarization device.

3.2 Serial polarization direction device

A bimorph mode piezoelectric MEMS generator with serial polarization was also tested up to 1.5 g acceleration. Figure 4 shows the maximum output power and the associated output voltage at different applied accelerations when connected to 330 kΩ optimal load impedance. Our device obtained a maximum output power of 413 μW, which corresponded to a 33.0 V_{P-P} output voltage under an impedance matching condition at a 1.5 g excitation.

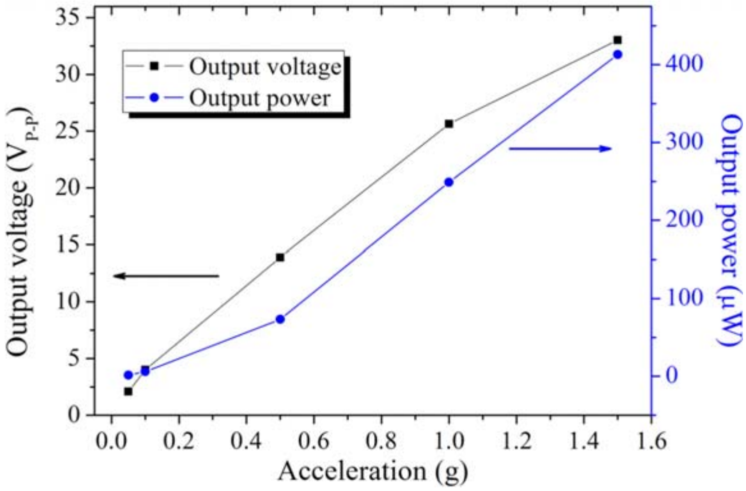


Figure 4. Relationship between maximum output power and associated output voltages at different applied accelerations under 330 kΩ load impedance for a serial polarization device.

From the experimental results of the bimorph mode piezoelectric MEMS generator with parallel polarization and serial polarization. The maximum output voltage of serial polarization device large than parallel polarization device is 33 V_{P-P}. It should be noted that even though a bimorph mode piezoelectric MEMS generator with a different polarization direction will have different output voltages, the output power remains identical [4]. To sum up, the result of all published piezoelectric MEMS generators and our piezoelectric MEMS generators has been listed in Table 1. The area of cantilever beam, excitation frequency, generated power, power density and normalized power density were usually used as useful metrics to compare their performance. The maximum power densities with area of our piezoelectric MEMS generators were calculated. The normalized power density of our piezoelectric MEMS generators were also calculated to allow a fair comparison on MEMS generators operating at different accelerations and frequencies. This results show that the power density and normalized power density of ours devices furnish a better performance.

Table 1. Comparison between all published piezoelectric MEMS generators and our piezoelectric MEMS generators.

Author	**Mode**	**Material**	**A (g)**	**f (Hz)**	**Power (μW)**	**Area^{b} (mm^{2})**	**Power density (μWmm^{-2})**	**Normalized energy density (μW g^{-1} Hz^{-1} cm^{-2})**

Jeon *et al* 2005 [5]	3-3	PZT	10.8	13.9 k	1	0.04	25	0.02
Fang *et al* 2006 [14]	3-1	PZT	1.0	608	2.16	1.2	1.8	0.3
Marzencki *et al* 2008 [6]	3-1	AlN	2.0	1495	0.8	0.96	0.83	0.03
Shen *et al* 2008 [15]	3-1	PZT	2.0	461.2	2.15	1.9	1.1	0.12
Lee *et al* 2009 [13]	3-1	PZT	2.5	255.9	2.8	4.5	0.62	0.1
Elfrink *et al* 2009 [16]	3-1	AlN	2.0	572	60	30	2	0.17
Muralt *et al* 2009 [17]	3-3	PZT	2.0	870	1.4	0.96	1.5	0.08
Hajati *et al* 2010 [18]	3-3	PZT	4.0	1.3 k	22	120	0.18	0.004
Park *et al* 2010 [19]	3-3	PZT	0.39	528	1.1	2	0.55	0.27
Lee *et al* 2010 [20]	Bimorph	PZT	2.0	168	1.8	4.5	0.4	0.12
Yen *et al* 2011 [21]	3-1	AlN	1.0	853	0.17	0.245	0.69	0.08
Morimoto *et al* 2011 [22]	3-1	PZT	0.5	126	5.3	92.5	0.06	0.09
Aktakka *et al* 2011 [23]	3-1	PZT	1.5	154	205	49	4.2	1.81
Lei *et al* 2011 [24]	3-1	PZT	1.0	235	14	35.8	0.39	0.17
Defosseux *et al* [25]	3-1	AlN	0.25	214	0.62	5.6	0.11	0.21
Kanno *et al* 2012 [26]	3-1	KNN	1.0	1036	1.1	68	0.02	0.002
Tang *et al* 2012 [27]	3-1	PZT	1.0	514.1	11.5	2.5	4.6	0.89
Xu *et al* 2012 [7]	Bimorph	PZT	1.0	250	37.1	35.75	1.04	0.42
This paper (parallel)	Bimorph	PZT	1.5	143.5	423	54	7.8	3.6
This paper (series)	Bimorph	PZT	1.5	140.9	413	54	7.7	3.6

4. CONCLUSIONS

In this paper, we presented the fabrication and evaluation of a MEMS piezoelectric bimorph generator. This device has the ability to convert ambient vibration energy into useful electrical energy. A cantilever type bimorph mode MEMS piezoelectric generator with both parallel polarization and serial polarization was fabricated and tested. Different dimensions of the proof mass at the tip of the beam structure for adjusting the resonance frequency of the device were demonstrated. The maximum output power was 423 μW with a 15.2 VP-P output voltage when excited at its resonant frequency for a parallel polarization device. For the bimorph mode MEMS piezoelectric generator with serial polarization, the maximum output power was 413 μW with a 33.0 VP-P output voltage at its resonant frequency. It confirmed that the bimorph mode MEMS piezoelectric generator with serial polarization could generate higher output voltage than that of the device with parallel polarization under identical output level. The optimal resistive load of the device with serial polarization is higher than that of the device with parallel polarization. We also compared our results with previous publications. The power density and normalized power density of our device show a better performance compared with the previous studies.

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