UTILIZATION OF DIFFERENT CHARGE POLARIZATIONS ON PZT DIAPHRAGM OF ACOUSTIC ENERGY HARVESTERS

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Abstract: This paper presents improved power generation performances of a PZT MEMS acoustic energy harvester with dual top electrodes to utilize the different polarization of charges on the surface of a vibrating PZT diaphragm. Two independent energy harvesters were defined between the peripheral top electrode, the central top electrode and the lower common electrode. The power density of the acoustic energy harvesters was increased by connecting the two energy harvesters in series, which can be simply realized by using the top electrodes as the harvester terminals. The PZT acoustic energy harvester had a diaphragm with a diameter of 2 mm, and it exhibited the generated power of 9.5x10^{-11} W and the energy density of 23.7 µW/m^2 under the sound pressure level of 100 dB (0.01 W/m^2) at 4.92 kHz. The device generated nearly two times larger power than other devices with similar diaphragm areas.

Keywords: Acoustic energy harvester, PZT, diaphragm

INTRODUCTION

Energy harvesters have attracted much attention for possible application to independently operating intelligence systems [1,2]. Pb(Zr,Ti)O3 (PZT) is an excellent candidate for harvesting power from ambient vibration sources because it can efficiently convert mechanical strain to electrical charge [3,4]. Several bulk PZT piezoelectric energy harvesters have been reported [5-9]. Also, energy harvesters using thin PZT films have recently been widely studied since they can be integrated into silicon integrated circuits (ICs) [10-15].

Horowitz et al. have recently reported on a MEMS acoustic energy harvester that contains a PZT piezoelectric film as a diaphragm [16]. They claimed that their energy harvester with the PZT (0.27 µm thick) diaphragm with the diameter of 2.4 mm exhibited the power density of 0.34 µW/cm^2 at 149 dB sound pressure level (SPL) under the first-resonance vibration mode. The reason for measuring the energy harvester at such a high sound pressure level is the need for health monitoring systems in aircrafts where noises from engines are extremely high and wireless intelligent sensor systems are needed.

Shinoda et al. [17] fabricated PZT energy harvesters with similar sizes to those of Horowitz et al., compared the performances of their energy harvesters with those of Horowitz et al. at 100 dB SPL, and reported that higher generated power could be realized by vibrating PZT diaphragms at the third-resonance frequency. Kimura et al. reported that PZT acoustic harvesters with non-wet electrode fabrication processes exhibited further improved power density at the first resonance [18]. However, these previous reports on the PZT acoustic energy harvesters did not consider to utilize the different polarity charges in the peripheral part and the central part of the diaphragms.

In this paper, we report on further improved performances of PZT acoustic energy harvesters that utilize different charge polarizations at the peripheral part and the central part of a PZT diaphragm at the first-resonance vibration.

DEVICE STRUCTURE

Figure 1(a) shows the top view of the PZT energy harvester investigated here. The two top Al electrodes cover the peripheral area and the central area of the PZT diaphragm, respectively. The schematic cross-section of the energy harvester is shown in Fig. 1(b). A piezoelectric capacitor with the diaphragm structure of Al (0.1 µm)/PZT (1 µm)/Pt (0.1 µm)/Ti (0.1 µm) was formed on 1.5-µm-thick SiO₂. The cavity of the diameter of 2.0 mm was fabricated on a 300-µm-thick silicon wafer. When sound pressure is applied from above the device, the diaphragm vibrates, resulting in the deflection of the diaphragm. The deflected PZT capacitor generates a voltage difference between the two electrodes of Al and Pt/Ti owing to the polarization of PZT. In case of exciting the first resonance, the generated charge polarizations were different between the peripheral part and the central part. This way, the dual top electrode dimensions were determined to utilize the different charge polarizations. Therefore, the independent top electrodes that covered the peripheral area and the central area to form the independent two energy harvesters were fabricated as illustrated in Fig. 1(c). The two energy harvesters were defined between the peripheral electrode and the common electrode, and the central electrode and the common electrode. A connected energy harvester was also defined between the two top electrodes. The detailed fabrication conditions have been already reported [17,18].

Figure 2 shows the strain distribution of the PZT capacitor/SiO₂ diaphragm under a static pressure. The sign of the strain changes at a radius of 730 µm. The different signs of the strain correspond to different
signs of charges. Therefore, the dimensions of the peripheral and the central electrodes were determined to cover the areas where the strains were relatively large. The area of the diaphragm that was not covered with the electrodes was where the strain was relatively small to avoid the unnecessary increase in energy harvester capacitance.

The X-ray diffraction measurements of the crystalline orientation of (111) are shown in Fig. 2. The sol-gel PZT film investigated here showed smaller peaks for the PZT (001) and (002) perovskite structures. However, the large peak of PZT (111) indicated that the PZT crystal is mostly oriented in the (111) direction. From the measured hysteresis characteristics of the PZT capacitor, the resultant PZT film exhibited ferroelectric behaviors with a coercive field of 168 kV/cm and a remanent polarization of 19.2 µC/cm² after poling at 20 V for 15 min. It also showed a relative dielectric constant of 620 and a dielectric loss of 0.05.

![Fig. 1 Structure of PZT energy harvester](image)

Fig. 1 Structure of PZT energy harvester; (a) top view, (b) Schematic cross section, (c) expected charge distribution, and (d) concept of connected energy harvester.

![Fig. 2 Calculated strain distribution on the 1-µm-thick PZT film deposited on 1.5-µm-thick SiO₂ under a static pressure. This analysis was carried out using the finite element analysis method.](image)

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![Fig. 3 XRD patterns for the 1-µm-thick PZT thin film deposited using sol-gel process.](image)

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The resonance frequencies under a sound pressure of 100 dB SPL (0.01 W/m²) were measured using the characterization system described in previous reports [17,18]. In order to measure the resonance frequency of the energy harvester, an amplifier with a gain of 10,000 was connected to amplify the output voltage signals from the energy harvester. In the case of measuring the generated power, a resistance was connected to the energy harvester, and the voltage between the two terminals of the load resistance was monitored using an oscilloscope.

RESULTS AND DISCUSSION

Figure 4 compares the frequency dependencies of the output voltages for the peripheral device and the central device under the sound pressure level of 100 dB. The output voltage, $E$, was determined by measuring the open-circuit voltage between the two electrodes of the energy harvesters. A sharp resonance for the first resonance for the peripheral device and the central device were observed at 4.29 kHz, which was also suggested by the vibration analysis using the finite element method. The frequency dependence of a device with the same diaphragm diameter but with the circular-shaped top electrode covering whole surface
of the diaphragm was also compared as a reference [18].

The resonance frequencies were measured using the same characterization system described previously [17,18]. AC sinusoidal voltage signals with different frequencies were generated by the function generator and amplified by the power amplifier. The amplifier was connected to the speaker. The gain of the power amplifier was modified to generate 100 dB SPL (0.01 W/m²) at the PZT energy harvester using a standard microphone (Buel & Kjaer Free Field 1/4 Microphone Type 4039). In order to measure the resonance frequency of the energy harvester, an amplifier with a gain of 10,000 was connected to the harvester to amplify the output voltage signals from the energy harvester. In the case of measuring the generated power, a resistance was connected to the energy harvester, and the voltage between the two terminals of the load resistance was monitored using an oscilloscope.

**Fig. 4. Frequency dependences of generated voltage, E, of PZT energy harvester with different diaphragm diameters of 2.0 mm; (a) Peripheral energy harvester, (b) central energy harvester, (c) energy harvester fabricated by Kimura et al. [18]; the whole surface of the diaphragm was covered by the Al electrode. The frequency at each arrow corresponds to first resonance.**

Figure 5 shows comparison of the output voltage wave forms measured between the load resistance terminals R connected to (a) peripheral energy harvester, (b) central energy harvester, (c) connected energy harvester, and (d) sum of (a) and (b).

**Fig. 5. Output voltage wave forms measured between the load resistance terminals R connected to (a) peripheral energy harvester, (b) central energy harvester, (c) connected energy harvester, and (d) sum of (a) and (b).**

Table I shows the comparison of the performances of the PZT power generators prepared by Horowitz et al. [16], Shinoda et al. [17], Kimura et al. [18] and in this work. The energy harvesters of this research utilized both of the charges at the peripheral and the central parts of the diaphragm. Thus, nearly double power was generated at the same energy harvester area. In conventional cases, the resistance at the maximum power and the capacitive impedance of PZT energy harvesters matches well as reported by Harigai et al. [19]. The load resistances of the energy harvesters of Kimura et al. [18] and this work at the maximum power were significantly lower than those of other researchers possibly owing to the larger capacitance of the PZT capacitors. Harigai et al. [7] have also demonstrated that their vibration energy harvesters with (001)-oriented PZT films generated a much larger power than conventional energy harvesters with (111)-oriented PZT films. Thus, further improvement of acoustic energy harvesters fabricated using (001)-oriented PZT films can be expected.
CONCLUSION

This paper presented improved power generation performances of a PZT microelectromechanical systems (MEMS) acoustic energy harvester having dual top electrodes to utilize the different polarizations of charges on the surface of a vibrating PZT diaphragm. The PZT acoustic energy harvester had a diaphragm with a diameter of 2 mm consisting of Al(0.1 \( \mu \)m)/PZT(1 \( \mu \)m)/Pt(0.1 \( \mu \)m)/Ti(0.1 \( \mu \)m)/SiO\(_2\)(1.5 \( \mu \)m). The top Al electrodes independently cover the peripheral surface and the central surface of the PZT diaphragm. The peripheral energy harvester generated a power of 5.28x10\(^{-11}\) W, and the central energy harvester generated a power of 4.25x10\(^{-11}\) W under the sound pressure level of 100 dB (0.01 W/m\(^2\)) at 4.92 kHz. A connected energy harvester was also defined between the peripheral electrode and the central electrode. The total power generated by the connected harvesters was 8.28x10\(^{-11}\) W that corresponds to the power density of 20.7 \( \mu \)W/m\(^2\). The device exhibited nearly two times larger power than the other devices with similar diaphragm areas.

REFERENCES


<table>
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<tr>
<th>Diaphragm Diameter (mm)</th>
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