PIEZOELECTRIC ENERGY HARVESTERS OF PZT FILMS DEPOSITED ON TITANIUM CANTILEVERS

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Abstract: We fabricated piezoelectric energy harvesters composed of $Pb(Zr,Ti)O_3$ (PZT) films on Ti cantilevers. PZT films with the thickness of 3.9 μm were directly deposited on the Pt-coated Ti thin plate by rf-sputtering and simple unimorph cantilevers of PZT and Ti were prepared. Because of the thin thickness of the Ti cantilever (thickness: 100 μm, length: 17.5mm), the resonant frequency of the energy harvester could be as low as 304 Hz without seismic mass at the tip of the cantilever. The averaged output power proportionally increased with the square of the acceleration, and it reached 17 μW under the acceleration of 50 m/s^2.

Keywords: energy harvesting, piezoelectric, PZT, thin film

INTRODUCTION

Recently, energy harvesting technologies have attracted considerable attention as an energy source for microdevices, especially for wireless sensor networks [1-3]. For integration into microdevices, energy harvesters must be highly efficient and capable of generating sufficient electric power in a limited space. To convert mechanical vibration to electric power, it is reported that piezoelectric energy harvesting are advantageous because of simple structure and the high energy conversion efficiency [2,4]. Piezoelectric energy harvesters generally have a bimorph or unimorph cantilever structure with a seismic mass attached at the tip of the cantilever to adjust the resonant frequency to an environmental vibration of ~100 Hz [5,6]. Recently, the microelectromechanical systems (MEMS) composed of piezoelectric thin films have been applied to integrate energy harvesters into microdevices. Commonly, piezoelectric films, especially PZT films, were deposited on Si substrates because microfabrication of Si is well-established and it is advantageous for the integration. However, Si as well as PZT is a typical brittle material, therefore the serious problems of the fracture toughness emerge, especially under large vibrations or shocks.

In this study, we deposited PZT thin films to a metal substrate to enhance the toughness of the piezoelectric MEMS energy harvesters. Because metals have excellent mechanical elasticity and strong fracture toughness compared with Si, a thin metal-based cantilever can be utilized while maintaining sufficient toughness and flexibility. In addition, it is expected that a lower resonant frequency down to around environmental frequencies can be easily achieved without a seismic mass. In previous study, we deposited PZT films on Ti metal substrates and reported large piezoelectric properties compatible with the PZT films on Si substrates [7]. In this study, we fabricated piezoelectric energy harvesters using the PZT films on flexible Ti cantilevers and examined their power generation performance.

FABRICATION

The PZT films with a composition of Zr/Ti = 53/47 were deposited on Pt-coated Ti substrates by rf-magnetron sputtering. The substrates used were beam-shaped Ti of 20 mm long, 3 mm wide, and 100 μm thick, respectively. The Ti substrate was heated to around 600 °C, and prior to the PZT deposition, $(Pb,La)TiO_3$ buffer layer was deposited on the substrate to improve the crystal growth of the PZT [7]. The PZT deposition was performed under a mixed gas atmosphere of Ar/O_2 with a flow rate of 19.5/0.5 sccm. The thickness of the PZT films was 3.9 μm. After the deposition, post annealing treatments of 650 °C for 30 min were performed for the further crystallization of the PZT films. Then, a Pt top electrode was deposited on the surface of the PZT film. Finally, one end of the beam was clamped by a vice and the 17.5 mm-long unimorph cantilever was mounted one the shaker. Fig. 1 shows a schematic of the measurement system and a photograph of the piezoelectric energy harvesters. The Pt top electrode was connected with a Au lead line, while the Pt/Ti substrate was grounded. The acceleration of the vibration was measured by an

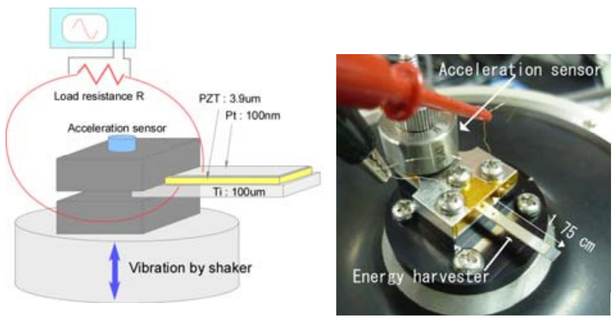

Fig. 1: A schematic and a photograph of piezoelectric energy harvester composed of PZT

acceleration pickup attached to the base of the cantilever. The output voltage between a load resistance *R* was measured by a oscilloscope under vibration.

CHARACTERIZATION OF PZT FILMS

The crystal structures of the PZT thin films were measured by X-ray diffraction (XRD), and the XRD pattern is shown in Fig. 2. The polycrystalline PZT films with perovskite structure were grown on the Pt-coated Ti substrates. Surface morphology and cross-sectional structure of the PZT film on Ti were observed by a scanning electron microscope (SEM), and the images are shown in Fig. 3. The SEM images indicate that dense PZT films were grown with the columnar structure and the grain size was around 0.1 μm.

The dielectric and ferroelectric properties of the PZT films were measured by depositing Pt dot electrodes of 0.3 mm in diameter on the PZT films. The relative dielectric constant and dielectric loss were 320 and 2.9%, respectively. Fig. 4 shows the *P-E* hysteresis loop of the PZT film, representing excellent ferroelectricity.

Transverse piezoelectric properties were evaluated from the actuator performance of the PZT/Ti unimorph cantilever. Tip displacement of the cantilever was measured by a laser Doppler vibrometer and the simplified transverse piezoelectric coefficient e_{31}^* ($=d_{31}/s_{11}$) was calculated [8]. The tip displacement increased proportionally with the applied voltage and e_{31}^* was calculated to be -3.8 C/cm^2.

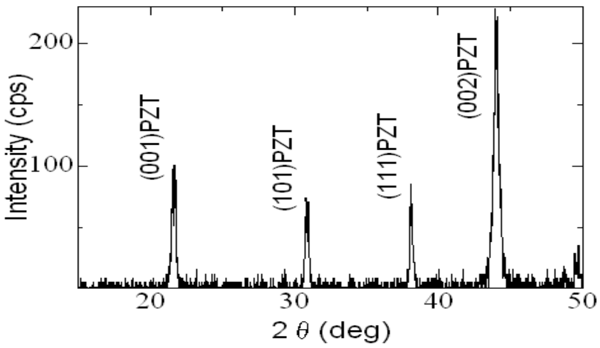

Fig. 2: XRD pattern of PZT films deposited on Ti

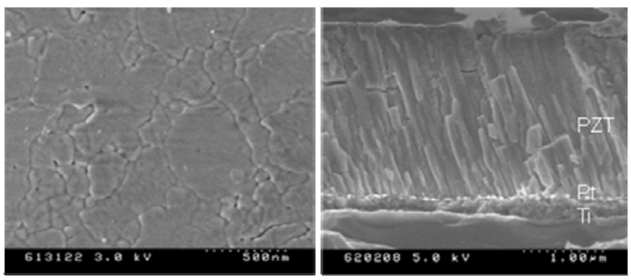

Fig. 3: Surface and cross-sectional SEM images of the PZT film grown on Pt-coated Ti substrate

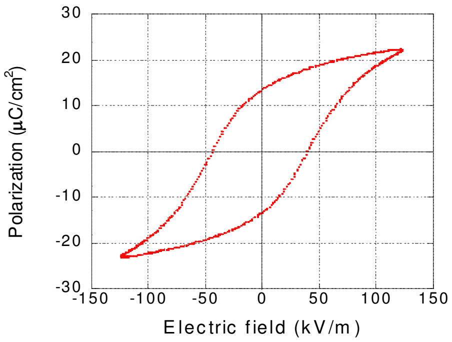

Fig. 4: P-E hysteresis curve of the PZT film on Ti

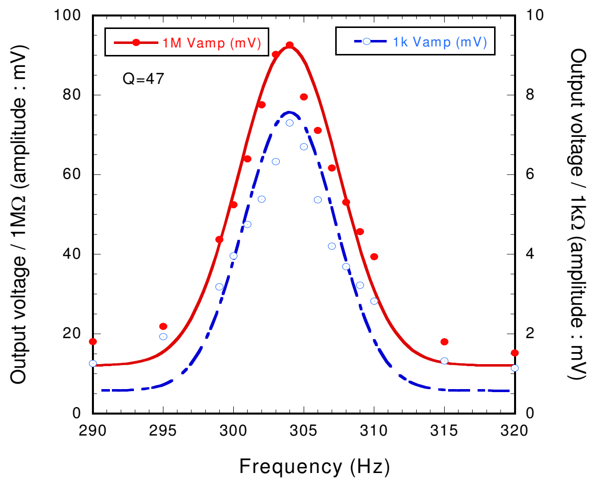

Fig. 5: Frequency response of output voltage under the acceleration of 10 m/s^2 with the load resistance of 1 MΩ and 1 kΩ, respectively.

ELECTRIC POWER GENERATION

The electric power generated by mechanical vibration was measured using the unimorph cantilever of the PZT films on Ti. First, the frequency response of the output voltage was measured under an acceleration of 5 m/s^2 with load resistance of 1 MΩ and 1 kΩ, respectively. The results were shown in Fig. 5. Clear peaks of the output voltage appear at a frequency of 304 Hz. At the resonance, the output voltage of 1 MΩ reaches 95 mV. The observed resonant frequency is almost consistent with the calculated first resonance. Because of the small thickness of the cantilever, we could achieve a low resonant frequency for a simple cantilever without a seismic mass.

Next, we measured the output voltage and averaged electric power output [$P = V^2/(2R)$] as a function of load resistance. The measurements were performed at the resonant frequency under the acceleration ranging from 3 m/s^2 to 50 m/s^2, and the results are shown in Fig. 6. For each acceleration measurement, the output voltage increases with the load resistance, and the electric output power shows a maximum at a load resistance of around 15 kΩ.

From the results as shown in Fig. 6, the acceleration dependence of the output voltage and

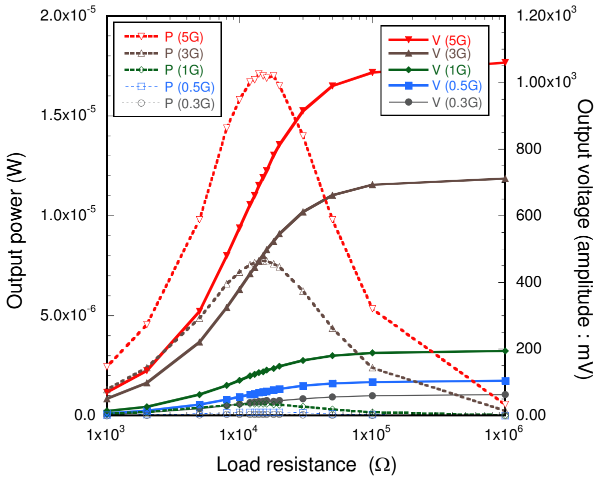

Fig. 6: Output voltage and generated power as a function of load resistance. The acceleration was varied from 3 m/s² to 50 m/s².

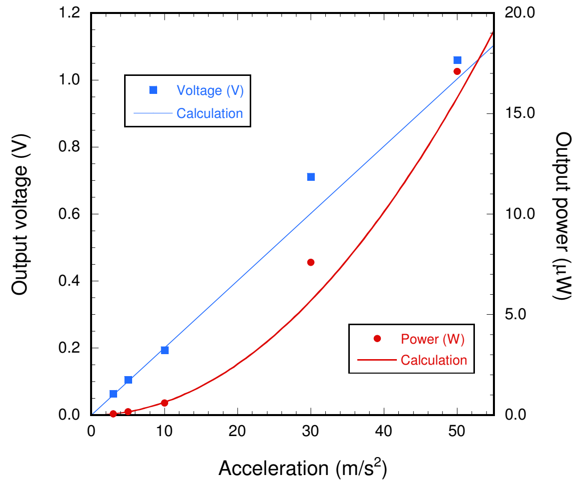

Fig. 7: Output voltage and generated power as a function of acceleration vibrated at the resonant frequency.

power were plotted in Fig. 7. The output voltage increases proportionally with the acceleration, reaching the amplitude of 1.1 V under the acceleration of 50 m/s². On the other hand, output power is almost proportional to the square of the acceleration, and maximum output power reaches17 μW at 50 m/s². It is noted that PZT film deposited on Ti could not only generate large output power with the simple unimorph cantilever, but also showed excellent mechanical toughness as well as stability of electric power generation under the large vibration of 50 m/s² without cracking or breaking of the PZT films.

We consider the characteristics of the output power on the basis of the theoretical study reported by M. Renaud [9]. The output power at the resonance is expressed by Eq. (1).

$$P \cong \frac{ma^2}{2\omega} \frac{K^2 \psi Q^2}{\psi^2 + \left(1 + K^2 \psi Q\right)^2} \qquad (1)$$

where m, a, ω, and Q are the cantilever's effective mass, acceleration, fundamental mechanical angular frequency, and mechanical quality factor. K represents the generalized electromechanical coupling factor (GEMC), and ψ is the normalized mechanical resonant frequency expressed by

$$\psi = \omega RC \qquad (2)$$

where C is the capacitance of the energy harvester. In this study, since we did not attach a seismic mass, the effective mass m of the cantilever is given by

$$m = \frac{k}{\omega^2} = \frac{3EI}{\omega^2 L^3} \qquad (3)$$

where k, L, E, and I are the cantilever's spring constant, length, Young's modulus, and momentum of inertia. On the other hand, the theoretical output power of Eq. (1) is based on lumped parameter modeling, which is valid for a piezoelectric cantilever with a large seismic mass. In this study, since we did not attach a seismic mass on the cantilever, the correction factor μ_1(=1.566) should be applied to Eq. (1) [10], and the output power

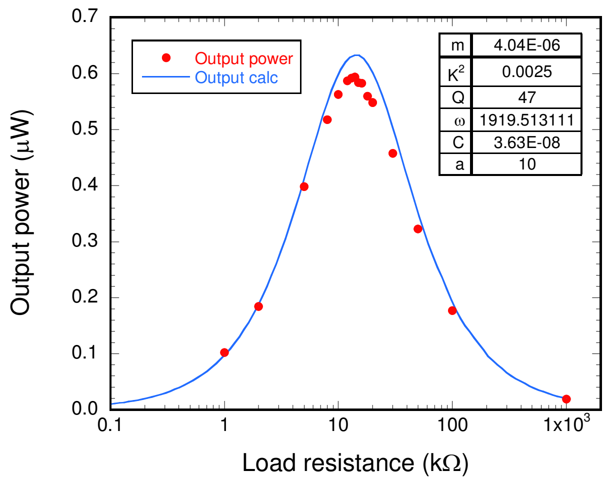

Fig. 8: Output power as a function of load resistance under the acceleration of 10 m/s². The calculated curve corresponds with experimental values.

of the piezoelectric cantilevers is written as

$$P \cong \frac{ma^2}{2\omega} \frac{\mu_1{}^2 K^2 \psi Q^2}{\psi^2 + \left(1 + K^2 \psi Q\right)^2} \qquad (4)$$

The optimal load resistance R_{opt} is also obtained as,

$$R_{opt} = \frac{1}{\omega C} \sqrt{\frac{1}{1 + Q^2 K^4}} \qquad (5)$$

If $Q^2K^4 \ll 1$, the optimal load resistance R_{opt} is approximated by

$$R_{opt} = 1/\omega C \qquad (6)$$

The GEMC (K) was obtained from the frequency difference of the resonance between open and short circuit ($K^2 = \left(\omega_{open}{}^2 - \omega_{short}{}^2\right)/\omega_{short}{}^2$). From the frequency response in Fig. 5, the quality factor Q is around 47, while the difference of the resonant frequency between 1 MΩ and 1 kΩ are very small and we can assume Q^2K^4<<1. The capacitance of the unimorph was 36 nF, then the R_{opt} is calculated from Eq. (6) to be 14 kΩ. The calculated R_{opt} is compatible with the experiment (15 kΩ).

By Eq. (4), we calculated output power and compared the experimental results with the calculation. Since the difference of resonant frequency between 1 MΩ and 1 kΩ is so small that the K^2 was determined by fitting the calculated curve with the experimental data. Fig. 8 shows the output power under the acceleration of 10 m/s^2 as a function of load resistance. The experimental results are almost consistent with the calculation if K^2 is determined as 2.5×10^{-3}. Theoretical curve of output power as a function of acceleration is also plotted in Fig. 7. These results indicate that the experimental output power almost follows the theoretical equation.

These results indicate that unimorph cantilevers made of PZT thin films deposited on Ti metal cantilevers are promising energy harvesters with sufficient toughness against severe vibration environments. In this study, we used simple unimorph structure to evaluate the fundamental characteristics of the PZT films deposited on Ti, however, it is expected that further enhancement of the power generation would be possible by optimization of the design of them.

CONCLUSION

We fabricated piezoelectric energy harvesters composed of PZT thin films directly deposited on Ti metal cantilevers. The PZT films were grown on Pt-coated Ti substrates by rf-sputtering. The PZT films have a high piezoelectric coefficient ($e_{31}^* = -3.7$ C/m^2) and excellent dielectric properties (ε_r = 166, tanδ = 0.029). The energy harvester (17.5 mm-long) showed a low resonant frequency of 304 Hz without a seismic mass. The output voltage proportionally increased with the acceleration, while output power reached 17 µW at 50 m/s^2 without any damage to the harvester. The generated output power almost follows the theoretical equation. PZT films directly deposited on metal cantilevers are promising devices for energy generation with sufficient output power and toughness.

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