

The Power Generation Characteristics and Durability of a Vibration Power Generation Device using Piezoelectric Thick Film Formed Directly by Screen Printing on a Stainless Steel Substrate

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Abstract. This paper presents a small, high-performance and novel device that generates power from vibrations, made using screen-printing to form a piezoelectric thick film directly on a stainless steel substrate. This simple and cheap method realizes a 20 - 40 μm -thick piezoelectric film, otherwise difficult to achieve using thin-film techniques or ceramic sintering, on a stainless steel substrate. A maximum output power of 1.1 mW was recorded with acceleration of 0.1 G_{op} (0.98 ms^{-2}) applied at a resonance frequency of 24 Hz. We also evaluated the durability of the device by repeatedly striking the tip of the element. Output power exceeding 100 mW under damped resonant vibration was generated at the instant of striking, with approximately 0.9 mJ of power measured per single damped vibration. No deterioration was seen in the integrity of the stainless steel substrate or the piezoelectric thick film after over 10 million strikes.

1. Introduction

We have been working on developing vibration power generation devices, which are one form of energy harvesting technology. Vibration energy has the second largest energy density after light. Efficient harvesting and power conversion of vibration energy would enable power to be generated in dark or cramped places where solar cells are impractical. Vibration power generation devices can be classified into four types based on their power generation mechanism: piezoelectric, electromagnetic, electrostatic, and magnetostrictive. The piezoelectric type can be made smaller and can generate higher voltages than the electromagnetic type, while the magnetostrictive type has certain disadvantages, such as very high internal resistance and low electric current. The piezoelectric type is thus generally regarded as the most suitable match for ICs and similar devices used in electronic circuits.

Piezoceramic materials, including PZT, are widely used in piezoelectric-type vibration power generation devices. However, piezoceramic materials need to be sintered at high temperatures to be able to exhibit their excellent piezoelectric properties. The resultant bulk materials are usually fragile and have durability concerns during harvesting of vibrational energy. The inner stress caused by the

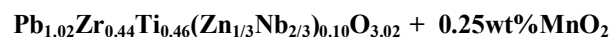


difference in thermal expansion coefficient with the electrode materials can also damage the device. Roundy *et al.* [1] have obtained an output power of 375 μW with 0.26 G (2.5 ms^{-2}) acceleration applied at a frequency of 120 Hz using a bimorph device with piezoelectric sheets integrally formed from piezoceramic and electrode materials; and Yu *et al.* [2] have achieved an output power of 66.75 μW with 0.5 G (5 ms^{-2}) acceleration at a frequency of 234.5 Hz using a MEMS device with the film thickness reduced to the level of several micrometers. However, thin-film fabricating processes such as sputtering are painstaking and require special equipment.

This report focuses on the new vibration power generation device we have developed and evaluates the materials' physical properties and their power generation characteristics. Our new vibration power generation device is able to obtain output power that is sufficient to drive a sensor circuit. It is also able to overcome the problems characteristic of conventional vibration power generation devices that use piezoceramic materials, such as mechanical durability and high manufacturing costs.

2. Preparation of the vibration power generation device

A screen-printing method is employed to fabricate our vibration power generation device: an inexpensive process that requires no special equipment. Stainless steel was selected as the base material of the vibration power generation device, as it is a readily available material, has a high resistance to fracture, and shows little loss of durability during high-temperature processing. As the piezoceramic material of the device, we used a hard PZT material with the composition shown below.



This material was pre-sintered and then pulverized to give it an average particle diameter of less than 5 μm . A solvent, dispersant, and binder resin were added to the resultant powder and kneaded together with a triple roll mill into a piezoelectric paste.

As the bottom electrode, an AgPd (90:10) paste was applied, using screen-printing, to a 0.1 mm-thick stainless steel substrate with high heat resistance. It was then dried. The piezoelectric paste was applied on top of this layer using screen printing and then dried. Lastly, as the top electrode, the AgPd (90:10) paste was printed and dried. Sintering was then applied at 900 $^{\circ}\text{C}$. The thickness of the piezoelectric layer after the sintering was approximately 30 μm . The layer was polarized by applying 120 V at 120 $^{\circ}\text{C}$ for ten minutes, and a fixing member was attached to one end of the element and a weight to the other to form the cantilever-type vibration power generation device. Figure 1 shows the appearance and structure of the device.

Beeby *et al.* prepared a vibration power generation device by forming the bottom electrode, insulation material, and PZT on stainless steel using screen-printing. A smartcard including the device realized an output power of 240 μW at 67 Hz under an acceleration of 0.4 G (3.9 ms^{-2}) [3]. Beeby *et al.* also reported, at Power MEMS 2013, on obtaining output powers of 0.1 to 0.86 μW using wind power with wind speeds of 1.5 - 8 ms^{-1} [4]. The device we have prepared does not require application of insulation materials: this has been achieved by effective matching of the materials with the sintering processes.

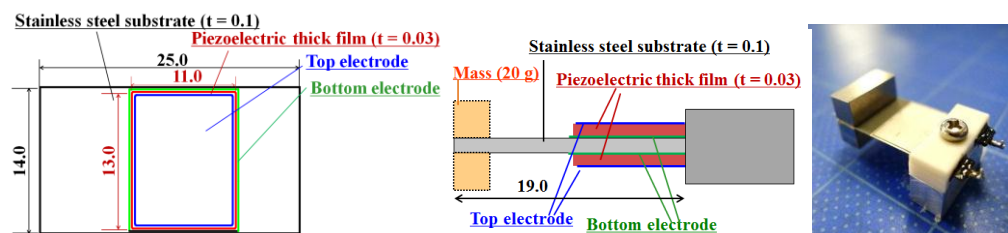


Figure 1. Appearance and structure of vibration power generation device.

3. Characteristics of PZT thick film

Table 1 shows the electric properties of the PZT thick films prepared using screen-printing and of the bulk PZT materials. The dielectric permittivity was determined using the capacity value (measured using an LCR meter), area, and thickness. The piezoelectric constant d_{31} of the thick films was measured on a cantilever device with the PZT thick film on only one surface. How much the tip of the beam was displaced when an alternating voltage was applied to the cantilever device was measured using a laser Doppler vibrometer (LDV), and the d_{31} and k_{31} value was calculated using the equation below [5]. Here, t_1 and t_2 denote the thickness of the PZT thick film and stainless steel, and s_1 and s_2 denote the elastic compliance of the PZT and stainless steel.

$$d_{31} = \frac{\delta(s_1^2 t_2^4 + 4s_1 s_2 t_1 t_2^3 + 6s_1 s_2 t_1^2 t_2^2 + 4s_1 s_2 t_1^3 t_2 + s_2^2 t_1^4)}{3(s_1 s_2 t_1 (t_1 + t_2) l 2V)}$$

$$k_{31} = d_{31} / (\epsilon_{33}^T s_{11}^E)^{1/2}$$

Table 1. Piezoelectric properties of PZT thick films and bulk ceramics

	Thick film	bulk
$\epsilon_{33}^T / \epsilon_0$	400	1400
d_{31}	-45 pm/V	-115 pm/V
k_{31}	0.20	0.30

Figures 2 and 3 (SEM images) show a surface view and a cross-sectional view of the piezoelectric thick film. The images show that the piezoelectric thick film has been sintered to sufficient density, indicating that the decline in relative permittivity and piezoelectric constant was not caused by inadequate sintering.

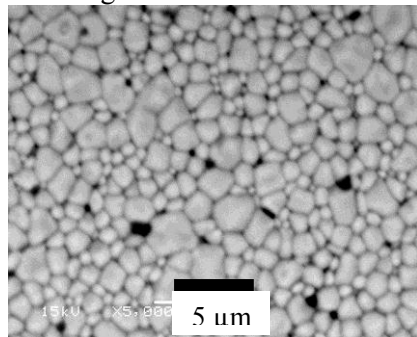


Figure 2. SEM image of the surface view of PZT thick film.

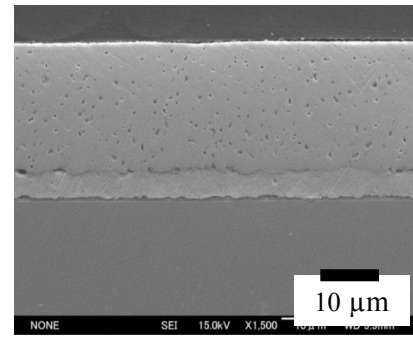


Figure 3. SEM image of the cross-section of PZT thick film.

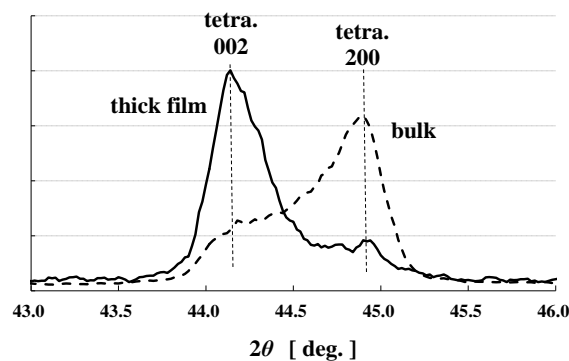


Figure 4. Comparison of PZT thick film and bulk PZT.

Figure 4 shows a comparison result between the XRD pattern of the bulk PZT and the piezoelectric thick-film device. Comparison between the (002) and (200) peak intensities indicates that the (002) peak intensity is higher in the piezoelectric thick film. This is likely due to the difference in thermal expansion coefficient between the stainless steel and piezoelectric materials, which produced high compression stress on the piezoelectric thick film during the temperature-lowering step of the sintering process. The large compression stress caused more PZT crystals to be oriented in the c-axis direction with respect to the film thickness direction, causing a lowering of dielectric permittivity and piezoelectric constant [6].

Measuring the residual stress of the piezoelectric film using x-ray diffractometry indicated a stress of approximately 500 MPa. Although causing a deterioration of electric characteristics, the large residual compression stress of the piezoelectric thick films is able to compensate for the fragility of the ceramic materials under tensile force.

4. Characteristics of vibration power generating device

Figure 5 shows the relationship between the output power and the frequency when sinusoidal wave vibration with acceleration of $0.1 G_{op}$ (0.98 ms^{-2}) was applied to the cantilever-type vibration power generation device. The output power was determined by connecting a load resistance of $100 \text{ k}\Omega$ between the top and bottom electrodes and measuring the voltage at both ends. A maximum output power of approximately 1.1 mW was recorded at the device's resonance frequency of 24 Hz .

Figure 6 shows the relationship between the vibration acceleration and the output power at the resonance frequency. The output power increased with a rise in vibration acceleration, reaching approximately 5 mW or higher at $0.3 G_{op}$ (2.9 ms^{-2}).

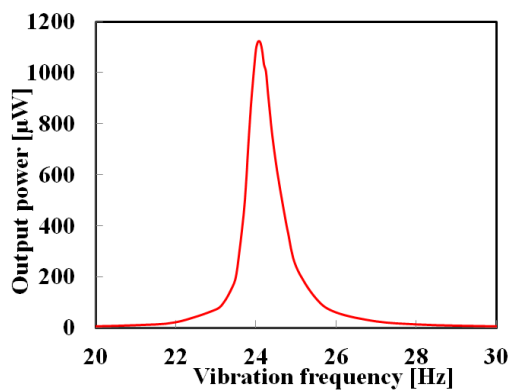


Figure 5. Frequency characteristics of vibration power generation device.

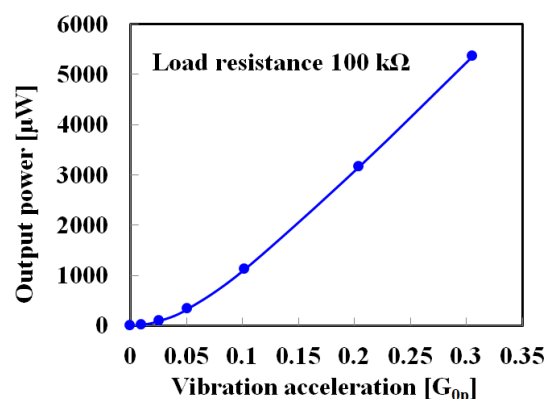


Figure 6. Relationship between vibration acceleration and output power at the resonance frequency.

Next, the durability of the vibration power generation device was evaluated. A 10 mm -wide and 17 mm -long vibration power generation device was prepared for the durability test as shown Figure 7. The device was fabricated from an element consisting of a 10 mm -wide, 0.2 mm -thick stainless steel substrate with a piezoelectric thick film measuring 9.4 mm wide, 10 mm long, and 0.03 mm thick, formed on both surfaces. The tip of the element was struck with a rotating bar to evaluate its durability based on how the power generation characteristics changed when damped resonant vibration was repeatedly applied to the device. Figure 8 shows the power generation characteristics under damped resonant vibration. At the striking instant, a maximum power of 100 mW or higher was generated, with approximately 0.9 mJ of power measured per single damped resonant vibration. Figure 9 shows

how the power generation characteristics changed over 10 million strikes. The stainless steel substrate and piezoelectric thick films remained intact, with no change in the power generation characteristics.

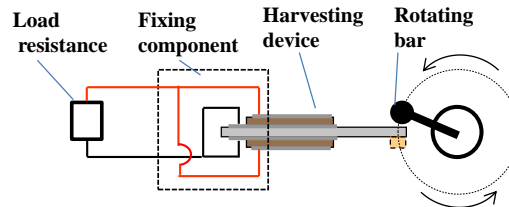


Figure 7. Appearance of the durability test by striking with rotating bar.

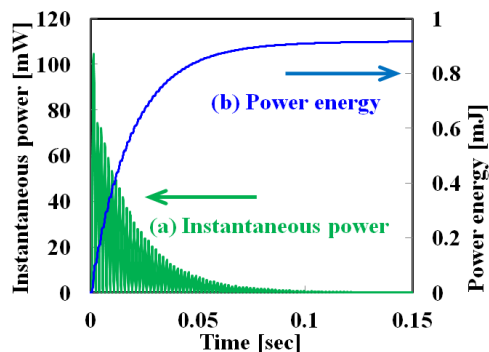


Figure 8. The behavior of instantaneous power and power energy with time.

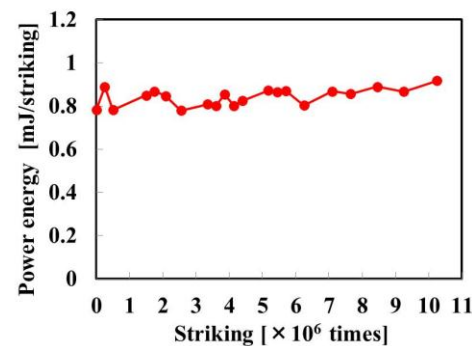


Figure 9. Power output with cumulative number of strikes.

The power obtained with the vibration power generation device was rectified, converted into 2.5 V direct voltage and used to successfully drive a temperature and acceleration sensor module. This indicates that continuous sensing and wireless transmission is possible over the 920 MHz radio band.

5. Conclusion

We prepared a simple and cheap cantilever-type vibration power generation device using PZT materials and screen-printing. The piezoelectric thick films obtained with screen-printing showed lower relative permittivity and piezoelectric constant than the bulk materials. These films are not prone to the fragility that is characteristic of conventional ceramic materials, and are inexpensive to prepare, and are thus likely to find applications in a wide range of fields as self-supporting power sources for sensor modules, for which there is expected to be a growing demand.

6. References

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