Output power of piezoelectric MEMS vibration energy harvesters under random oscillations

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Abstract. Environmental vibrations include random oscillations of different frequencies and amplitudes. Energy harvesters recover the energy associated with these vibrations. Properties of the vibrations and output power are characterized for cantilever-type piezoelectric vibration energy harvesters using (100)-orientated BiFeO₃ films subject to both ideal and random oscillations. The displacement and output power under random oscillations were smaller than those under ideal oscillations. This decrease originates with the decreasing acceleration of the fundamental wave with the spurious component having little influence on the resonance response.

1. Introduction

Recently, the concepts “Internet of Things” and the “trillion sensor universe” have attracted considerable attention. The underlying motivation is that energy harvesting from light, heat, microwaves, and vibrations has potential as power sources for sensor nodes. Among them, vibration energy harvesters (VEHs) are promising because they can provide relatively constant electric power.[1,2] Three energy transduction mechanisms for VEHs are available: electromagnetic induction, electrostatic, and piezoelectric effect. VEHs using the piezoelectric effect have advantages of high energy density and potential for miniaturization by micro-electro-mechanical systems (MEMS).[2–5] The figure of merit (FOM) of the piezoelectric thin films for VEHs is given by \( (e_{31,f})^2/\varepsilon_0\varepsilon_{33} \), where \( e_{31,f} \) is the effective transverse piezoelectric coefficient, \( \varepsilon_0 \) the permittivity in free space, and \( \varepsilon_{33} \) the relative permittivity.[6,7] FOM higher than 20 GPa have been reported for Pb-based ferroelectric films such as Pb(Zr,Ti)O₃, because of a high \( e_{31,f} \) (≈20 C/m²).[8,9] AlN thin films also have relatively large FOM (11 GPa) because of a low \( \varepsilon_0 \) (≈11).[9] We have focused on BiFeO₃ because it has high spontaneous polarization (≈100 μC/cm²) and low \( \varepsilon_{33} \) (≈100), which suggests that BiFeO₃ potentially has large FOM.[10,11] We have reported that (100)-epitaxial and (100)-orientated BiFeO₃ films have FOM of 11 and 14 GPa, respectively, and also demonstrated MEMS VEHs using BiFeO₃ films.[12–14] VEHs using (100)-orientated BiFeO₃ films have an output power of 10.5 μW·mm⁻³·G⁻² (G=9.8 m/s²), which is approximately four times larger than that using a polycrystalline film.[15,16] The output power is comparable to those of the best-performing VEHs using Pb(Zr,Ti)O₃ and AlN films.[2] The results described above were obtained using monochromatic vibrational waves. However, environmental vibrations have random oscillations comprising various frequencies and amplitudes. For instance, the power spectrum of an oil-sealed rotary pump (Fig. 1) shows spurious components:
the harmonic and sub-harmonic waves. In this study, to discuss the influence of the spurious components on VEH performance, the output power is characterized using vibrations composed the fundamental, harmonic, and sub-harmonic waves.

2. Experiment

LaNiO\textsubscript{3} films, which are used as bottom electrodes and seed layers for the (100)-oriented growth of BiFeO\textsubscript{3} films, was deposited on Pt/Ti/SiO\textsubscript{2} diaphragms using the rf-magnetron sputtering method. Sputtering was performed at an rf power of 50 W and a working pressure of 10\textsuperscript{-2} Torr. The 200-nm-thick films were deposited at 300 °C under a gas mixture of O\textsubscript{2} (30%) and Ar (70%) and then annealed at 600 °C under O\textsubscript{2} atmosphere by rapid thermal annealing (RTA) to reduce oxygen defects in the films. The resistivity of the films was around 5×10\textsuperscript{-4} Ω·cm. BiFeO\textsubscript{3} films were prepared on the LaNiO\textsubscript{3} film using the sol-gel method. The films were crystalized at 500 °C by RTA. The film thickness was 250 nm. The 2θ-ω XRD profile of the film (not shown here) indicated that the BiFeO\textsubscript{3} and LaNiO\textsubscript{3} have (100) preferential orientation and no secondary phase and misoriented grains.[13,14] The $e_{31/f}$ coefficient of the film before the MEMS process was $-2.8$ C/m\textsuperscript{2}. The unimorph-type cantilever (Fig. 2) was fabricated using a conventional MEMS process. The details are described in Ref. 16. The width, length, and thickness of the cantilever were 3.20, 0.400, and 0.006 mm, respectively. The top electrode was 0.380 × 1.00 mm × 3.50 μm. A 0.4-mg Cu mass of dimension 0.380 × 0.470 × 0.250 mm was attached to the free end of the cantilever to match the frequency of the environmental vibrations (60–200 Hz).

Vibrations were applied to the VEHs toward the vertical direction using a shaker. We applied several waves to the shaker to characterize the output power of the VEHs under ideal and random vibrations. Figure 3 depicts profiles of these vibrational waves, which have the following specifications: wave 1 (fundamental wave of 92.3 Hz), wave 2 (fundamental wave + sub-harmonic wave of 46.15 Hz), wave 3 (fundamental wave + harmonic wave of 184.6 Hz), and wave 4 (fundamental wave + harmonic wave + sub-harmonic wave). Each were prepared by a function generator (HP 33120A, Hewlett Packard). The amplitude of each vibration was the same. The applied acceleration was measured using an accelerometer (352A24, PCB Piezotronics, inc.). The displacement of the cantilever was determined using a laser head LK-020 and laser displacement sensor (LK-G5000, Keyence Corporation). To characterize the generated electrical power of the VEH, a load resistance was connected to the BiFeO\textsubscript{3} film. The output voltage across the load resistor was measured using a lock-in amplifier (LI5640, NF Corporation).
3. Results and discussion

3.1. Output power under ideal vibration

Figure 4 shows the open-circuit output voltage at different accelerations under wave 1, the ideal vibration. The accelerations of 0.009, 0.017, 0.035, and 0.052 G$_{\text{rms}}$ were applied. The output voltage is normalised by the acceleration because the induced charge via the piezoelectric effect of the BiFeO$_3$ thin film is proportional to the applied strain. The hysteresis behaviour, which is the difference of the power responses between the frequency sweep-up and sweep-down, was observed. With increasing acceleration, the curves of the output voltage near resonance frequency become asymmetric. Simultaneously, the resonance frequency gradually shifts to higher frequencies with increasing acceleration. This nonlinear resonance is caused by the increase in stiffness of the cantilever at large deformation. The resonance frequency, $Q$-factor, and maximum normalised output voltage are 92.3–93.9 Hz, 280, 2.8 V$ \cdot$G$^{-1}$, respectively. Figure 5 shows the normalised output power as a function of load resistance. The maximum output power is obtained at 1.0 M$\Omega$, which is consistent with the calculated resistance (8.6 k$\Omega$) to obtain impedance matching. The maximum output power is 2.6 $\mu$W$ \cdot$mm$^{-2} \cdot$G$^{-2}$. Static output power $P_{\text{Rmax}}$ and generalized electro-mechanical coupling coefficient $K^2$ are given by:

$$ P_{\text{Rmax}} = \frac{M Q^2 A^2}{\omega_r} \frac{9d}{4l^3 u} \left( \frac{1}{4} x^3 - lx^2 + l^2 x \right) K^2, \quad (1) $$

$$ K^2 = \frac{(1 - \nu)^2}{E} \frac{e_{31,eff}^2}{\varepsilon_0 \varepsilon_{33}}, \quad (2) $$

where $M$ is the mass of the proof mass, $Q$ the $Q$-factor, $A$ the acceleration of the applied vibration, $\omega_r$ the angular velocity at resonance frequency, and $d$, $x$, $\nu$, $E$, $l$, and $u$ are the thickness of the piezoelectric film, length of the top electrode, Poisson’s ratio, Young’s modulus, length, and thickness of the cantilever, respectively. Using values for the $e_{31,eff}$ coefficient and $\varepsilon_0$ of the (100)-orientated BiFeO$_3$ thin film on (100) LaNiO$_3$/Pt/Ti/SiO$_2$/Si, which are $-2.8$ C/m$^2$ and 123, respectively, $K^2$ expected from Eq. (2) is 2.3%, which is approximately five times larger than that of a polycrystalline film.[15] The $e_{31,eff}$ coefficient and $K^2$ calculated using Eqs. (1) and (2) are $-3.0$ C/m$^2$ and 2.5 %, which are consistent with those of the film before the MEMS process.

*Figure 4.* Frequency dependence of the normalised voltage at (a) 0.009, (b) 0.017, (c) 0.035 G$_{\text{rms}}$, and (d) 0.052G$_{\text{rms}}$.

*Figure 5.* Normalised output power as a function of load resistance at (a) 0.009, (b) 0.017, (c) 0.035 G$_{\text{rms}}$, and (d) 0.052 G$_{\text{rms}}$. 
3-2. Vibration and output power under random vibration

The relative displacement and output power of the VEH under random vibrations were characterized. Figure 6 shows the waveforms of the input vibrational acceleration and displacement of the tip of the cantilever under waves 1–4. Each displacement waveform is different from that for acceleration under random vibrations and all the waveforms look roughly sinusoidal. This indicates that only a single frequency component is included in each wave. The results of fast Fourier transform analysis indicate that the VEH responds only to the resonance vibration of 92.3 Hz, which is the resonant frequency of the VEHs. Nevertheless, the displacement amplitude under random vibrations is smaller than that under an ideal vibration of the fundamental; the maximum accelerations of waves 1–4 are similar.

The waveforms of acceleration were also Fourier analysed. Figure 7 shows that the ratios of the maximum acceleration of waves 2–4 with respect to wave 1. The displacement calculated using the acceleration ratio and the maximum displacement at wave 1 (0.232 mm) are 0.148, 0.167, and 0.128 mm for waves 2, 3, and 4, respectively, which are smaller than the experimental results (0.188, 0.192, and 0.172 mm, respectively). Similarly, the output power of each of the waves 1–4 also depends on the acceleration ratio. The maximum output power normalised by the area of the cantilever was 1.2, 0.73, 0.77, and 0.62 nW·mm⁻² for waves 1, 2, 3, and 4, respectively. The ratios of the output power for waves 2–4 do not correspond to the acceleration ratio as shown in Fig. 7.

To investigate the effect of spurious component on output power in detail, the component of the output power at 92.3 Hz under wave 1–4 were characterized by the lock in amplifier. The results are shown in Fig. 8. The output power is independent of the wave. This indicates that the spurious component has no influence on the resonance response. The curves shown Fig. 8 have two regimes. For lower accelerations, the output power is proportional to the square of the acceleration. For higher accelerations, above 0.01 G, the output power is saturated because of nonlinear resonance. The incline of the curve at saturation gradually decreases with increasing...
acceleration. It appears that this nonlinearity causes a difference in the acceleration and power or displacement ratio shown in Fig. 7.

4. Conclusion

A piezoelectric MEMS VEH using (100)-orientated BiFeO$_3$ film was fabricated and the output power of a cantilever-type VEH under ideal and random vibrations were characterized. The maximum output voltage and power at the ideal resonance vibration were $2.8 \text{ V} \cdot \text{G}^{-1}$ and $2.6 \mu \text{W} \cdot \text{mm}^{-2} \cdot \text{G}^{-2}$, which is comparable to the best-performing VEHs using Pb(Zr,Ti)O$_3$ and AlN. The $K^2$ of the VEH using (100)-orientated BiFeO$_3$ film is 2.3 %, which is approximately five times larger than that using a polycrystalline film. To characterize the vibration and output power properties of the VEH, several waves composed of the fundamental (92.3 Hz), harmonic (184.6 Hz), and sub-harmonic (46.15 Hz) were applied to the VEH. The waveforms of displacement of the mass were independent of those of acceleration under ideal and random vibration and were only composed of a single frequency component corresponding to the resonance fundamental. In contrast, the displacement under random vibrations was smaller than that under ideal vibrations. To uncover its origin, the output power properties as a function of acceleration of the resonance frequency under ideal and random vibrations were characterized. The results were independent of the form of the vibration. This indicated that the decrease in displacement stems from the nonlinear resonance of the VEH and that the resonance response depends only on the fundamental component of the wave.

Acknowledgement

This work was supported by the Industrial Technology Research Grant Program in 2011 from the New Energy and Industrial Technology Development Organization (NEDO) of Japan.

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