

# Development of Piezoelectric MEMS Vibration Energy Harvester Using (100) Oriented BiFeO<sub>3</sub> Ferroelectric Film

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**Abstract.** Piezoelectric vibration energy harvesters (VEHs) with unimorph structure have been developed using Si micro-electrical mechanical systems (MEMS) technology. Since we revealed that (100) epitaxial BiFeO<sub>3</sub> (BFO) piezoelectric films have high figure-of-merit on energy conversion, (100)-oriented BFO films have been prepared on (100)-oriented LaNiO<sub>3</sub> bottom electrodes by the sol-gel method. We fabricated the piezoelectric VEHs using BFO films with resonance frequencies of ~100 Hz. The maximum output power density of these VEHs was determined to be 10.5  $\mu\text{Wmm}^{-3}\text{G}^{-2}$  ( $G=9.8 \text{ ms}^{-2}$ ) at a load resistance of 1 M $\Omega$ , which exceeds or is comparable to those of the best-performing VEHs using other piezoelectric films.

## 1. Introduction

Recently, considerable attention has been directed toward vibration energy harvesters (VEHs). This arises from the fact that wasted mechanical energy from vibrations is present in various environments and can be converted into electrical power for microelectronic systems, such as wireless sensor remote systems. Several methods to date have been reported to be useful in obtaining electrical energy from vibrational energy including electromagnetic induction, electrostatic generation, and piezoelectric effect. Although each of methods seems to provide a useful amount of energy, the piezoelectric effect has advantages of high energy density and miniaturization potential [1–5]. Therefore, we have focused on piezoelectric VEHs using micro-electrical mechanical systems (MEMS) technology [6,7]. We have already demonstrated that VEHs using polycrystalline BiFeO<sub>3</sub> (BFO) piezoelectric film can produce output voltages of 1.5 V G<sup>-1</sup> ( $G=9.8 \text{ m/s}^2$ ) and electrical power of 2.8  $\mu\text{Wmm}^{-3}\text{G}^{-2}$  at a load resistance of 1 M $\Omega$  with a resonance frequency of ~98 Hz [8]. The characteristics are comparable to those of MEMS VEHs using other piezoelectric film materials such as Pb(Zr,Ti)O<sub>3</sub> (PZT) AlN and (K,Na)NbO<sub>3</sub> (KNN) [5].

In this study, we fabricated MEMS VEHs using (100)-oriented BFO films on (100)-oriented LaNiO<sub>3</sub> bottom electrodes, which have larger piezoelectric responses than polycrystalline BFO films [8]. The energy harvesting performance of MEMS VEHs was characterized at resonance frequencies of ~100 Hz. These VEHs showed higher performance than the VEHs using polycrystalline BFO films.



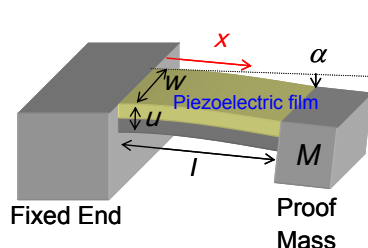
## 2. Fabrication process and experiment

The structure of the fabricated piezoelectric MEMS VEHs of the present study is shown schematically in figure 1. It consists of a single cantilever structure, which is composed of a supporting silicon membrane, LaNiO<sub>3</sub>/Pt/Ti bottom electrode, BFO piezoelectric film, Pt upper electrode, and Cu proof mass. A schematic of the MEMS fabrication process of VEHs is shown in figure 2. The starting material was a silicon-on-insulator (SOI) wafer with 5- $\mu\text{m}$ -thick Si, 1- $\mu\text{m}$ -thick SiO<sub>2</sub> (insulating layer), and 650- $\mu\text{m}$ -thick Si-bulk. The structures of the VEHs were fabricated as follows;

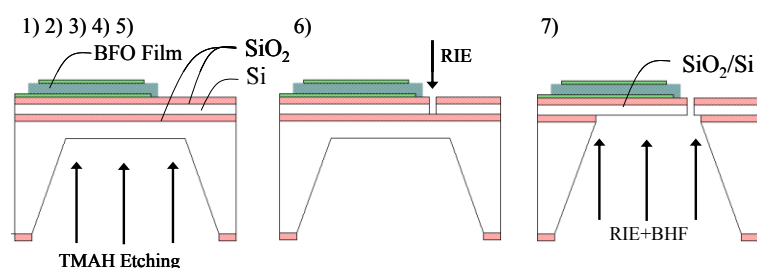
- 1) An SOI wafer was oxidized on both sides with a thickness of 0.5  $\mu\text{m}$ .
- 2) Thin diaphragm structures were formed using the anisotropic etching technique with TMAH (25 wt%, 90 °C) etchant. An important point here is to stop etching, saving a final diaphragm with about 100- $\mu\text{m}$ -thick Si-bulk, so as to take care of process-handling in the post-process flow.
- 3) We used LaNiO<sub>3</sub>/Pt/Ti films as bottom electrodes. The thicknesses of LaNiO<sub>3</sub>, Pt, and Ti were 150, 200, and 20 nm, respectively. The Pt/Ti film was deposited on the front surface by sputtering, and patterned using a lift-off technique to form the bottom electrode. The LaNiO<sub>3</sub> film was deposited by sputtering, and patterned by wet-etching with HF and HNO<sub>3</sub> etchant.
- 4) A piezoelectric BFO thin film was prepared by the sol-gel method. The film was crystallized by annealing at 500 °C for 10 min in a rapid thermal annealing furnace. The thickness of the film was 250 nm. The BFO film was patterned by etching with HF and HNO<sub>3</sub> etchant.
- 5) The Pt upper electrode with a thickness of 200 nm was formed by sputtering and a lift-off technique.
- 6) To form the cantilevers, the SiO<sub>2</sub> and Si layers on the front surface around the cantilevers were removed completely by BHF etchant and by reactive ion etching (RIE) with SF<sub>6</sub> reactive gas, respectively.
- 7) The Si-bulk and insulator layer below the cantilever were all etched out by RIE with SF<sub>6</sub> reactive gas and by BHF etchant, respectively.
- 8) A proof mass made of Cu was attached at the free end of the cantilever. The proof mass was about 0.4 mg and had dimensions of 0.40×0.45×0.25 mm<sup>3</sup>.

We could finally fabricate the piezoelectric VEHs with unimorph structure, as shown in figure 3. The width, length, and thickness of the cantilever were 0.4 mm, 3 mm, and 6  $\mu\text{m}$ , respectively. Therefore, the effective volume of the fabricated VEH was 0.40×3.0×0.256 mm<sup>3</sup>.

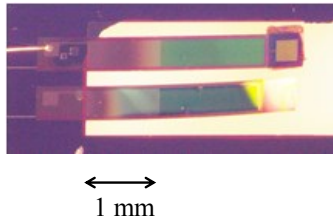
The experimental setup with a vibrator for measuring the output voltage and electrical power of the fabricated piezoelectric MEMS VEHs is shown in figure 4. Vibrations were applied to the VEH in the perpendicular direction using a vibrator. A load resistance was connected to the bottom and upper electrodes. Output electrical power was determined by measuring the voltage of the load resistance with a lock-in amplifier.



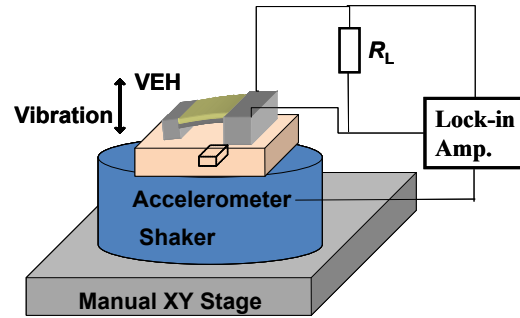
**Figure 1.** Structure of vibration energy harvester using a piezoelectric film.



**Figure 2.** Fabrication of a piezoelectric vibration energy harvester using the MEMS technique.



**Figure 3.** Photo of a piezoelectric energy harvesting device with a BiFeO<sub>3</sub> films.



**Figure 4.** Experimental setup with a shaker for measuring the output voltage and electrical power of the fabricated piezoelectric vibration energy harvester.

### 3. Piezoelectric thin films for vibration energy harvester

When the VEH device is accelerated in the perpendicular direction, the proof mass receives an inertial force, which bends the cantilever, thereby inducing a strain. Consequently, the piezoelectric film converts the strain to electrical power in the  $d_{31}$  mode. The charge density  $D_3$  induced by the piezoelectric effect is given by

$$D_3 = e_{31,f}(x_1 + x_2), \quad (1)$$

where  $e_{31,f}$  is the effective transverse piezoelectric coefficient and  $x_i$  the in-plane strain.  $e_{31,f}$  is defined as [9]

$$e_{31,f} = \frac{d_{31}}{s_{11}^E + s_{12}^E}, \quad (2)$$

where  $d_{31}$  is the transverse piezoelectric coefficient and  $s_{ij}^E$  the elastic compliance coefficient.

$e_{31,f}$  is a useful parameter rather than  $d_{31}$  to discuss the piezoelectric property of the piezoelectric film for the VEHs, because  $e_{31,f}$  can be determined directly by the method based on substrate bending and collecting accumulating charges [6,9]. The output power of the VEHs is also proportional to  $e_{31,f}^2$ , as described below. Although  $d_{31}$  might be more familiar than  $e_{31,f}$  for the characterization of the piezoelectricity, using  $d_{31}$  is not practical in modelling MEMS devices using piezoelectric films. This is because  $s_{ij}^E$  of the films are different from those of the bulk, and depend significantly on preparation conditions of the films.

Accounting for the distribution of strain along the longitudinal direction of the cantilever, the maximum electrical power dissipated in the load resistor,  $R_L$ , which is connected to the piezoelectric film on the cantilever at the impedance matching point, is given by the following equation: [8]

$$P_{R_{\max}} = \frac{MQ^2 A^2}{\omega_r} \frac{9d}{4l^3 u} \left( \frac{1}{4}x^3 - lx^2 + l^2x \right) \frac{(1-\nu)^2}{E} \frac{e_{31,f}^2}{\epsilon_0 \epsilon_r}, \quad (3)$$

where  $M$  is the mass of the proof mass;  $Q$  mechanical quality factor of the cantilever;  $A$  acceleration of the applied vibration;  $\omega_r$  angular velocity;  $d$  thickness of the piezoelectric film;  $l$  and  $u$  length and thickness of the cantilever, respectively;  $\nu$  Poisson's ratio;  $E$  Young's modulus of the cantilever; and  $\epsilon_0$  and  $\epsilon_r$  are the permittivity of the vacuum and the relative permittivity of the piezoelectric film, respectively. As can be seen in Eq. (3), the maximum electrical power,  $P_{R_{\max}}$ , is proportional to  $M$ ,  $Q^2$ ,  $A^2$ , and  $1/\omega_r$ . In addition, from the last term of Eq. (3),

$$FOM = \frac{e_{31,f}^2}{\varepsilon_0 \varepsilon_r} \quad (4)$$

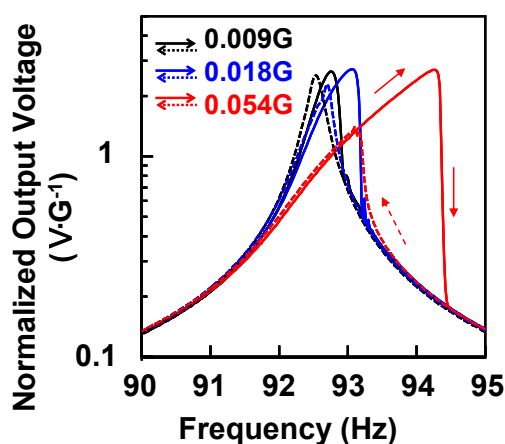
can be regarded as the figure-of-merit (FOM) of the piezoelectric film for vibrational energy harvesting. Thus, the development of piezoelectric films with large  $e_{31,f}$  and low  $\varepsilon_r$  is important to increase the output energy of the VEHS.

In general,  $\text{Pb}(\text{Zr,Ti})\text{O}_3$  (PZT) films are often used as piezoelectric films in energy harvesting. Because  $\varepsilon_r$  of the BFO films is an order of magnitude lower than that of the PZT films, BFO films are expected to have high FOM. Therefore, we have so far demonstrated the piezoelectric VEHS with polycrystalline BFO films that were prepared on the Pt/Ti bottom electrodes. The VEHS, fabricated using the MEMS process, produced output energies comparable to those of VEHS using other piezoelectric films, as described above [8].

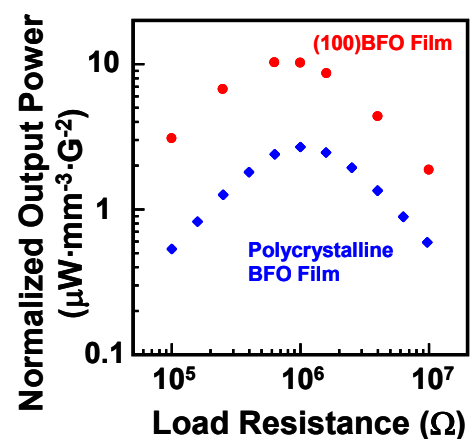
Growth of the (100)-oriented BFO films is one of the most important factors to obtain larger  $e_{31,f}$  and consequently higher FOM [6,7,10]. In the present study, the BFO films, which were prepared by the sol-gel method on the (100)-oriented  $\text{LaNiO}_3$  bottom electrodes, showed (100) orientation, and exhibited high  $e_{31,f}$  of  $-2.8 \text{ C/m}^2$ , which is close to that of the (100) epitaxial BFO film [7]. The FOMs of the (100)-oriented BFO film and the polycrystalline BFO film were determined to be 8.5 and 1.1 GPa, respectively. Therefore, VEHS using the (100)-oriented BFO film can be expected to show higher performance than those using the polycrystalline BFO film.

#### 4. Characteristics of the vibration energy harvester using (100) BFO films

The vibration frequency dependence of the normalized output voltage of the VEHS using the (100)-oriented BFO film is shown in figure 5. The accelerations of the applied vibrations were 0.009, 0.018 and 0.054  $G_{\text{rms}}$ . It can be seen that the VEHS has a resonance frequency around 92–95 Hz and that the normalized maximum output voltage at the resonance frequency is independent of the acceleration. In contrast, hysteresis behaviours were observed near the resonance frequency and the non-linear resonance increased with increasing acceleration. These behaviours were observed also with the VEHS using the polycrystalline BFO films. It appears that the nonlinear resonance of the VEHS mainly originates from the dumping effect of air and the nonlinear elasticity of the cantilever [8].



**Figure 5.** Normalized output voltage as a function of vibration frequency of the harvester using the (100)-oriented  $\text{BiFeO}_3$  film.



**Figure 6.** Load resistance dependences of the normalized output power of the harvesters with (100)-oriented or polycrystalline  $\text{BiFeO}_3$  films.

The load resistance dependence of the output power density of the VEH with the (100)-oriented BFO film was characterized at the acceleration of  $0.018\text{ G}_{\text{rms}}$  and the resonance frequency of 93 Hz as shown in figure 6. The output power is the electrical power that is dissipated in the load resistance, and normalized using  $G^2$  and the effective volume of the VEH. The output power density of the VEH using the polycrystalline BFO film [8] is also shown in figure 6. The maximum normalized output power of the VEH using the (100)-oriented BFO films is  $10.5\text{ }\mu\text{Wmm}^{-3}\text{G}^{-2}$  at a load resistance of  $1\text{ M}\Omega$ , which is about three times larger than that of the VEH using the polycrystalline BFO films. This result is comparable to or larger than those of the best-performing VEHs using other piezoelectric films.

## 5. Conclusions

We fabricated piezoelectric VEHs using MEMS technology. To obtain better performance, we prepared (100)-oriented BFO films on the (100)-oriented  $\text{LaNiO}_3$  bottom electrode by the sol-gel method. The VEH with the low resonance frequency of  $\sim 100\text{ Hz}$  showed a high output power density of  $10.5\text{ }\mu\text{Wmm}^{-3}\text{G}^{-2}$  at a  $1\text{-M}\Omega$  load resistance. It exceeded or was comparable to those of the best-performing VEHs using other piezoelectric films. These results indicated that the (100)-oriented BFO film is a good candidate material for piezoelectric VEHs.

## Acknowledgments

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

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