Temperature effects on output power of piezoelectric vibration energy harvesters

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The performance of piezoelectric vibration energy harvesters was studied as a function of environment temperature. The devices fabricated by soft or hard PZTs were used to investigate the effect of material parameters on the thermal degradation of the devices. PZT MEMS device was also prepared and compared with the bulk devices to investigate scaling effect on the thermal degradation. All devices were heated up to 150°C in an insulating chamber. Output power was estimated by Roundy’s equivalent circuit model and compared with experimental data. The output power of all devices decreased with the increase of the temperature. The output power as a function of temperature can be predicted by the change of piezoelectric coupling coefficient that is proportional to piezoelectric constant and inverse of square root of dielectric constant. Such combined influence on the output power leads to a lower thermal degradation rate of the soft PZT-based device at a lower temperature. For MEMS scale device based on PZT films, temperature dependence of the output power was reduced. This result can be attributed to decreased temperature dependence of dielectric and piezoelectric constants mainly due to constrained domain motions.

1. Introduction

A piezoelectric energy harvester can be one of the potential subsidiary energy sources in lieu of batteries in mobile devices and microelectromechanical system (MEMS) devices such as wireless sensor network and structural health monitoring systems [1]. Numerous research on piezoelectric vibration energy harvesters has been focused on the maximum power generation through structural modification [2–4], resonance frequency tuning [5,6], or electric circuit adaptation [7]. In practical applications, these piezoelectric devices can be operated at various environmental temperatures, but the characterization of the devices was mostly performed at room temperature. Since material constants of a piezoelectric material strongly depend on temperature, the performance of the piezoelectric device may vary significantly. In addition, investigation of a piezoelectric material that can work robustly at a higher temperature is required to maximize the potential for applications. Shen et al. investigated the most popular piezoelectric materials such as soft PZT, polyvinylidene fluoride (PVDF), and macro fiber composite [8]. The comparison of the piezoelectric materials was investigated only at room temperature. Bedekar et al. also conducted a comparative study of single crystals for high temperature applications of piezoelectric devices [9]. Results suggest that only YCa4O(BO3)3 (YCBO) and La3Ga5SiO4 (LGS) will operate at temperatures higher than 500°C, although PZT performs best at room temperature. Although significant progress has been made in piezoelectric vibration energy harvesters, the temperature effects on the device performance and the consideration of the material selection are rarely addressed.

In the present study the behavior of the piezoelectric vibration energy harvesters was characterized at different environmental temperatures and compared with a model. In order to investigate the effects of material constants and provide guidance of material selection, PZT is selected as a piezoelectric material. Two sets of devices constructed by soft or hard PZTs distinguished by doping elements were examined. Soft and hard PZTs are modified from PZT by doping higher and lower valent elements, respectively. Soft PZT exhibits lower coercive field and higher dielectric constant than hard PZT. Furthermore piezoelectric MEMS energy harvesting device was characterized to compare temperature dependence with bulk scale devices.

2. Experimental method

Commercial PZT bimorphs (Piezo Systems, Cambridge, MA) were used to construct cantilevers, whose dimensions are 24.7 × 3.2 × 0.38 (mm³) (length × width × thickness). The bimorphs consist
of two layers of soft (T215-H4-103X) and hard (T215-A4-103X) PZT on both top and bottom with brass between them. A 0.09g of proof mass was attached at the end of a cantilever beam. The cantilever with a proof mass was fixed between electrically insulated metal holders for minimum thermal gradient. The resonance frequency of the device was designed to be approximately 200 Hz because the frequency of commonly occurring vibrations is in the range 50–400 Hz [10,11]. MEMS scale PZT unimorph was made by microfabrication process and dimensions are 7000 × 2000 × 21 (μm³) with resonance frequency at 125 Hz. Detailed information on fabrication process was reported elsewhere [12]. The experimental setup designed to evaluate the device at various temperatures is shown in Fig. 1. A function generator and an amplifier were used to provide vibration signals to the shaker where the device was located. A heater was located in an insulated temperature chamber to change environmental temperatures ranging from room temperature to 150 °C. The device characterization was performed at different temperatures after obtaining thermal equilibrium by heating it for 10 min. Maximum power was obtained from the measurement under various loaded conditions when the device was vibrated at resonance by tuning load and vibration frequency. The acceleration value was fixed at 0.5g (1g = 9.8 m/s²).

3. Result and discussion

Experimentally determined output power values from two types of devices constructed using soft and hard PZTs are shown in Fig. 2. The generated output power decreased with the temperature for both devices. Since the device dimensions of soft and hard PZTs are identical, the difference between the two devices can originate from the difference in the electromechanical properties of soft and hard PZTs. Hard PZT-based device generates slightly higher power at room temperature, but the power values become lower than that of soft PZT-based devices with the increase of temperature, i.e. the hard PZT-based device has a larger decreasing rate compared to the soft PZT-based device. The increased power of the soft PZT-based device was often observed at temperatures higher than 120 °C, and this is thought to occur primarily due to the failure of the bonding layers between the brass center layer and the PZT layers. Weaker bonding between PZT and the center layer driven by a higher temperature may induce slip between the two layers. This most likely promotes a higher strain to the horizontal direction, i.e. higher output power.

For modeling, temperature dependence of the devices was analyzed using Eq. (1) based on an equivalent circuit model [13].

\[ P = \frac{1}{\omega^2 (4C_k^2 + k^2RC_p \omega^2 + 4\zeta^2k^2RC_p \omega + 2\zeta^2)} \]

The calculated power is shown in Fig. 3(a). Compared with experimental values, the calculated values have the same decreasing tendency, which is a larger decreasing rate in hard PZT-based device below 100 °C. However, the measured values are approximately 30% of calculated values. The difference can be attributed to a mismatch in the damping and nonlinear effect that was ignored for simplification [17]. In addition, the ignored adhesion layer between the PZT and brass could cause a discrepancy [18]. Since experimental result above 120 °C is not reliable due to the failure of bonding layer, the calculated power graph is extended to observe deterioration trend to 150 °C as in the graph. In case of soft PZT-based device, power degeneration rate increases as temperature increases. In order to understand why the experiment and modeling results show faster degradation at low temperature range in hard PZT, the thermal degradation of output power in PZT devices was analyzed by modifying Eq. (1) so that the temperature dependent parameters can be isolated. Temperature independent terms such as the thickness and length in Eq. (1) are simplified to C₀ as shown in Eq. (2). Only the coupling coefficient is different depending on whether the device is a soft or hard PZT-based device. The value of the coupling coefficient decreases with increasing temperature as shown in Fig. 3(b). By comparing Fig. 3(a) and (b), power degradation tendency of each device can be attributed to coupling coefficient because of quadratic and linear variation in soft and hard PZT-based devices, respectively. Piezoelectric coupling coefficient is proportional to the piezoelectric constant and inverse square root of dielectric constant as described...
in Eq. (3). The change of piezoelectric and dielectric constants is shown in Fig. 4. All of them increase linearly with temperature except for dielectric constant of soft PZT. Therefore, the most influential factor for the difference between soft and hard PZT-based device can result from a drastic increase of dielectric constant. The dielectric constant of soft PZT increases linearly at a low temperature range (25–100°C) and exponentially at a high temperature range (100–150°C). Therefore, the output power of a soft PZT-based device decreases slowly to 100°C and rapidly above 100°C.

\[ P = C_0 \frac{d_31}{Y_c \sqrt{(2 + k^2)^2 + k^2}} \]

\[ k \propto \frac{d}{\sqrt{\varepsilon}} \]  

The material parameters of soft PZT have a large variation as the temperature changes, but the decreasing rate of the output power was not steep or similar to hard PZT-based device. This is due to the compromise between the increase in the piezoelectric strain coefficient and the decrease in the inverse dielectric constant. On the other hand, hard PZT undergoes less change due to slow degradation of material parameters. Such a difference is originated from defect dipoles formed by doping, which are highly mobile in hard PZT and reoriented by polarization. There is higher free energy increase with domain switching in hard PZT. Therefore, domain walls are strongly pinned and external contribution is weak in hard PZT [19]. Domain motion in soft PZT can be pinned by Pb vacancies that are faster and more sensitive to temperature than oxygen vacancies in hard PZT [20]. Fundamentally, to minimize degradation of the output power from a piezoelectric energy harvester with environment temperature, the coupling coefficient should be maximized by choosing the largest piezoelectric strain coefficient and the smallest dielectric constant. This could be achieved theoretically by promoting depinning of non-180° domains and preventing 180° depinning because dielectric properties are attributed to 180° and non-180° domain walls while piezoelectric properties are ascribed to only non-180° domain walls [20,21].

It is known that extrinsic contribution such as domain wall motion to piezoelectric response in PZTs becomes smaller as the grain size of PZT decreases [19,22]. Degradation of the MEMS scale device is shown in Fig. 5(a) and compared with hard and soft PZT-based devices in Fig. 5(b), where normalized power represents the power at a certain temperature divided by the power at room temperature. MEMS scale device presents slower thermal degradation rate than bulk scale devices. Such a different degradation can result from the differences between thin films and
bulk PZTs such as grain size, orientation, and constraint by substrate. Since higher internal strain is induced in smaller grain, 180° domain wall motion may be inhibited [19]. Reduced temperature dependence of the dielectric constant can be the possible cause for the lower thermal degradation rate. This finding can imply that the adoption of PZT films with Ti rich composition or high Tc ferroelectrics potentially leads to lower temperature dependence of the output power from vibration energy [22,23].

4. Conclusion

The performance of piezoelectric vibration energy harvesters was investigated as a function of temperature by comparing experimental results and modeling of soft and hard PZT. Degradation of the output power from hard PZT-based device was slightly higher than that of soft PZT-based device at temperature lower than 100 °C in environmental temperature. Modeling results present that the difference in the device from soft and hard PZT can be mainly due to the dielectric constant, and, therefore, such degradation could be minimized by controlling domain wall motions. MEMS scale device based on PZT thin film showed reduced temperature degradation, and the part of results could be influenced by less dependence of temperature on the dielectric constant due to constraint of 180° domain wall motion in smaller grain sized PZT films and substrate clamping condition in a MEMS device.

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References


Fig. 5. (a) Output power from MEMS scale device as a function of temperature, and (b) the comparison of degradation ratio of the output power from bulk PZTs and thin film PZT for energy harvesting devices.