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MULTILAYER PIEZOELECTRIC MEMS ENERGY HARVESTER BASED ON LONGITUDINAL EFFECT

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Abstract. Piezoelectric MEMS energy harvesters based on multilayer (ML) $Pb(Zr,Ti)O_3$ (PZT) thin films with interdigitated electrodes (IDE) as their internal and top electrodes are proposed and designed. Thick PZT thin films with good piezoelectric characteristics can be deposited by using multilayer deposition technique. Furthermore, IDE is adopted to the harvester design in order to take advantage of the longitudinal piezoelectric effect, which typically has twice piezoelectric constant as large as transverse effect. The energy harvesters with two electrode configurations, parallel plate electrodes (PPE) and IDE, are designed and estimate these output power. According to the result of finite element analysis, the output power per gravitational acceleration for the IDE configuration. On the other hand, the output power per gravitational acceleration for the IDE configuration is about three times as large as that for PPE. Moreover, the influence of IDE patterns and the number of PZT layers were investigated. The larger number of layers results in the larger output power.

1. Introduction

Along with the development of the Internet of Things (IoT) society, vast amount of sensors have been used. The sensors should be self-powered in order to avoid troublesome power wiring and exchange cost of butteries. Therefore, energy harvesting devices are important as the alternatives of the sensor butteries. In particular, vibration-type energy harvesting devices have been attracted attention because vibration presents everywhere. For the self-powered sensors, the harvesters and sensors should be integrated as a MEMS device. In addition, piezoelectric harvesters have been the most popular manner because piezoelectric MEMS have features such as simple structures and moderate output impedance.

The typical structure of piezoelectric MEMS energy harvesters are simple beam with a proof mass. The beam is the lamination of piezoelectric thin films and Si supporting layer. The external vibration deforms the beam and provides piezoelectric films with in-plane stress. For the material of the piezoelectric MEMS harvesters, PZT is a promising candidate because of its large electromechanical coupling factor. One of the most important problems is the thickness of PZT for the MEMS energy harvesters. Although thick PZT is preferable to obtain large output power and structural strength, it is difficult to achieve both thick and good piezoelectric characteristics. The typical thickness of PZT for MEMS is 3 µm or less [1]. Multilayer PZT (ML-PZT) thin films with internal electrode layers can

achieve 10 µm-thick PZT with good piezoelectric characteristics [2]. In this study, ML-PZT is used for the design of the energy harvesters.

On the other hand, conventional electrode configurations for the piezoelectric MEMS energy harvesters are shown in Figure 1. The most common electrode configuration is parallel plate electrodes (PPE). For PPE, the electric power is generated based on transverse piezoelectric effect. For IDE, the poling direction becomes longitudinal in-plane direction. The longitudinal piezoelectric effect (directions of the stress and poling are same) has about twice piezoelectric constant as large as transverse one. Therefore the output power from the piezoelectric energy harvesters based on the longitudinal effect can be quadruple because that is proportional to the square of piezoelectric constant. However, IDE has several difficulties; (1) the piezoelectric material beneath the electrodes cannot contribute the electric charge generation, (2) the best ratio of IDE gap to width is 2 for optimal poling treatment [3], and (3) the optimum ratio of electrode width to thickness of piezoelectric layer is 0.8 because the pole is not along to longitudinal direction [4]. To lighten these problems, ML-PZT with internal IDE is proposed in this study.



Figure 1. Illustration of ML-PZT with internal IDE.

2. Fundamental design for piezoelectric MEMS harvesters

As a fundamental design, an energy harvester with PPE and single-layer PZT was designed. The harvester has a supporting beam and a proof mass as depicted in Fig. 1. Assuming alternatives to button batteries, device size is configured to 10×10 mm². Thickness of the mass is configured 525 µm based on the thickness of a 4-inch wafer. Thickness of the PZT is configured to 10 µm based on our conventional study [2]. The length ratio of the beam and mass and substrate thickness is determined to have large output power and sufficient structural strength. The average longitudinal in-plane stress σ in the piezoelectric layer when gravitational acceleration g is applied is expressed as

$$\sigma = \frac{3Y_s Y_p t_s (t_s + t_p) \rho_m g l_m (t_m + t_s) (l_b + l_m)}{Y_s^2 t_s^4 + Y_p^2 t_p^4 + 4Y_s Y_p t_s^3 t_p + 4Y_s Y_p t_s t_p^3 + 6Y_s Y_p t_s^2 t_p^2},$$
(1)

where, *Y*, *t*, ρ , and *l* are Young's modulus, thickness, density, and length, respectively. The subscript "*s*", "*p*", "*b*" and "*m*" denote Si, PZT, beam, and mass, respectively. The optimum load *R* is given as

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$$R = \frac{t_p}{\omega \varepsilon_p l_e w}$$
, (2)

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where, ω , w, and ε_p are resonant angular frequency, width, and dielectric constant of piezoelectric layer, respectively. By using *R*, the output power is given as

$$P_{\rm R_fr} = \frac{Q_{\rm m}^2}{2R} \left(\frac{l_{\rm e}wd_{31}\sigma}{C}\right)^2,\tag{3}$$

where, d_{31} , C, and Q_m are piezoelectric constant, capacitance, and quality factor, respectively. The dimensions were optimized to have maximal output power below the yield strength of the materials under application of 10G (=98 m/s²) acceleration (Fig. 2), assuming $Q_m = 100$. The dimensions are shown in Table 1. The output power per gravitational acceleration is about 124 μ W for the PPE configuration.



Figure 2. Estimation of output power for designed piezoelectric energy harvester with PPE configuration.(single layer PZT with thickness of 10 µm)

Dimensions	Value
Length of beam (mm)	3.33
Thickness of Si on beam (µm)	80
Thickness of PZT on beam (μm)	10
Width of beam (mm)	10
Thickness of Si mass (µm)	525

Table 1. Dimensions of designed energy harvester.

3. Analysis for IDE configuration

The energy harvester with ML-PZT and internal IDE was designed. For the design, the basic dimensions are same as mentioned in chapter 2. The ML-PZT is composed of four layers of PZT with internal IDE. The thickness of the each PZT layer is $2.5 \,\mu$ m. For actual case with taking the fabrication process into account, the electrodes and Si sandwiching insulation SiO₂ and buffer layers makes stray capacitance because Si substrate is modelled as conductive material. Therefore the influence of these layers (SiO₂ with thickness of 1 μ m and TiO₂ buffer layer with the thickness of 75nm) are also modelled. The line

width of the IDE is decided to be 5 µm because of convenience in fabrication process. The rest parameter of the dimensions is IDE gap. The poling direction of PZT is assumed as in-plane direction except for the PZT regions underneath the electrode (the underneath regions have out-of-plane poling direction). The output power for the harvester with IDE gap as the parameter was calculated from the results of piezoelectric structure analysis and electromagnetic analysis. The calculation results are shown in Fig. 3. The output power increase with an increase of the IDE gap, because the capacitance between the electrodes pair decrease with the increase of the IDE gap in despite of same generative electric charge. The output power reaches about three times as large as that with PPE. Figure 4 shows the influence of the layer number. The larger number of layers generates larger output power. The out-of-plane poling region underneath the electrodes would influence.



Figure 4. Effect of multilayer

Figure 3. Calculation results for ML-PZT harvester with internal IDE.

4. Conclusions

This paper proposed and designed piezoelectric MEMS energy harvesters based on multilayer PZT thin films with internal IDE. The output power of the harvester device is estimated about 0.3 mW per gravitational acceleration. This value is about three times larger than that of the conventional harvester with PPE. In addition, it was found that the larger number of layers generates larger output power.

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