Soft X-ray Charged Piezoelectret for Kinetic Energy Harvesting

Jia Lu¹, Hangjun Cho¹, and Yuji Suzuki¹

¹Dept. of Mechanical Engineering, The University of Tokyo, Tokyo, Japan

Email: jlu@mesl.t.u-tokyo.ac.jp

Abstract. Piezoelectret polymer attracts much attention for its high piezoelectric coefficient. Multilayered piezoelectret structures are often charged with corona discharge, but it is difficult to get high surface charge density. To address this issue, a multilayered piezoelectret structure with embedded electrode is proposed, which can be efficiently poled with soft X-ray charging. With the aid of embedded electrodes, the bias voltage is directly applied to each unit cell, rather than divided and distributed to multiple layers. With an early PTFE-based prototype, output power of 0.5 µJ has been obtained for 0.3 mm displacement in 0.2 s.

1. Introduction

Piezoelectrets are space-charged porous polymers, in which change of the macro dipole moment under structure deformation leads to piezoelectricity. They are gaining much attention in energy harvesting due to their softness and high piezoelectric coefficient [1]. Porous polypropylene is formed by gas expansion or stretching methods and then charged with contact or corona charging [2]. However, random pore dimensions and distributions would result in non-uniform polarization in those piezoelectrets and deteriorate the charge stability [3]. Alternatively, multilayered piezoelectret structures are often prototyped [4] as shown in figure 1a, where pores are charged with corona discharge.

Because the conventional charging method relies on the electrical breakdown in each void, the effective bias voltage per layer for the multilayered structure is much lower than the grid voltage. To address this issue, we propose a multilayered structure with embedded electrode that can be efficiently poled with the soft X-ray charging [5]. Figure 1b shows our concept for the improved piezoelectric structure. With the aid of the embedded electrode, the bias voltage is directly applied to each layer rather than divided and distributed to multiple layers. With the soft X-ray irradiation, positive and negative ions are generated in-situ through photo-ionization of gas molecules, and separated to the opposite sides by the bias voltage $V_{\text{bias}}$. With this approach, the surface charge density on pores could be much higher than that with the corona charging, therefore greatly increasing the output power.

2. Electromechanical Modelling

In order to study the output power of a multilayered piezoelectret under deformation, an electromechanical model shown in figure 2 is used. The electrostatic model [1] is employed with the assumption of 1-D electrostatic field, and the Euler-Bernoulli beam is used for estimating the deformation. Illustration of electric and mechanical models is shown in figures 2a and 2b.
Figure 2. Simulation models of the multilayered structure. (a) Electrostatic model [1], (b) Mechanical model based on the beam theory, (c) Electromechanical model of the multi-layered piezoelectret.

In figure 2a, $E$ is the electric field, with subscripts $p$ and $g$ standing for polymer electret and gas layers, respectively. $\sigma_s$ and $\sigma_i$ are the surface charge density on electret and induced charge density on electrode, respectively. According to the electrostatic model by Sessler [1], we have

$$\sigma_i = -e_0 \varepsilon_a E_p$$
$$\sigma_s = -e_0 \varepsilon_p E_g$$

$$E_p = E_g + E_{ph} + E_{tg} + U(t) = 0 \quad (1)$$

where $e_0\ \varepsilon_a$ (equal to 1) and $\varepsilon_p\ \varepsilon_a$ represent the vacuum permittivity, the relative permittivity of air and polymer electret, respectively. $h$ is the thickness of electret and $g(t)$ is the time-dependent gap. $U(t)$ is the voltage across the external load $R_{load}$. Using the Ohm’s law and the conservation of charge, we get

$$I(t) = U(t)/R_{load}, \quad Ad\sigma_s(t)/dt + I(t) = 0 \quad (2)$$

where $A$ is effective surface area of electrode overlapped with electret coating. With an initial condition of $U(t)$ and prescribed temporal gap $g(t)$, the output voltage and thus power is obtained.

For the mechanical model, an Euler-Bernoulli beam with two fixed ends and concentrated load at any place of the beam is assumed. Beam deflection at $x$ can be written as

$$\delta(x) = F_{load} x^2 (p-a)^2 [2a(p-x) + p(a-x)]/(6p'^3 E'I)$$

$$x \in [0, a] \quad (3)$$

where $p$ is the pitch between two fixed ends, and $EI$ is the flexural rigidity of beam. $F_{load}$ is the concentrated force applied at $x_f = a$ from the origin, and consists of the mechanical force $F_m$ applied at the top plate with the external force and the electrostatic force $F_e$ between oppositely-charged electrets. The electrostatic force is obtained through integration of local electrostatic forces $\Delta F_e(x)$ as

$$Fe(t) = \int \Delta F_e(x,t) dx = \int (1/2)\varepsilon_0 \varepsilon_a E_g(x,t)^2 wdx \quad (4)$$

where $w$ is the depth of the beam (in y axis direction).

3. Fabrication Process, Mechanical and Charge Stability Test

Based on the present model, we design an early prototype using PTFE for proof of concept. The fabrication process is shown in figure 3. Firstly, an aluminum electrode is sputtered onto a 0.2 mm-thick PTFE film. Each film is bonded to a 0.4 mm-thick PTFE plate, in which pillar structures are
formed by machining. This is followed by stacking and adhering five layers to form the multilayered structure with embedded electrodes. The as-fabricated prototype is shown in figure 3e, with dimensions of 30 mm × 30 mm × 2.8 mm.

Figure 4a shows the set-up for measuring the structure stiffness. The effective Young’s modulus is as low as 0.26 MPa even with the PTFE plates, which is lower than the estimates as shown in figure 4b.

The surface potential of the PTFE film is measured after the soft X-ray charging. Initial voltage is 1 kV, which is the same as the bias voltage. It decreases with time, and reaches its stable value of 350 V after 10 days. The present result with the stable voltage at 35 % of the initial voltage is in accordance with the previous result [6].

4. Power Generation Experiment

Power generation experiment is conducted using a set-up shown in figure 6. The multilayered structure is poled using soft X-ray (peak photon energy: 58.9 keV) with the bias voltage of 3 kV for 3 min. By using a linear motor, prescribed total deformation of 0.1~0.3 mm in 0.2 s is applied to the multilayered structure, and the output voltage is recorded.

Figure 7 shows the temporal profiles of the output voltage for 1.1 GΩ load. The maximum voltage for the 0.3 mm deformation reaches 100 V, which corresponds to the output power of 0.52 µJ; 0.52 µJ.

Figure 3. Fabrication process of the multilayered piezoelectret.

Figure 4. (a) Set-up for measuring the structure stiffness, (b) Applied stress versus strain.

Figure 5. (a) Surface potential measurement set up. (b) Surface potential of PTFE versus the elapsed time.
corresponds to the piezoelectric coefficient of 155 pC/N. This is somewhat lower than the model prediction of 0.77 µJ, but the trend is in accordance with the simulation results. Output power for 0.1 mm and 0.2 mm deformation is also shown in table 1.

With multilayered structures using softer materials than PTFE, and with higher-performance electret material such as CYTOP EGG [7], piezoelectric coefficient $d_{33} = 3000$ pC/N could be realized, which corresponds to the output power of 200 µJ under the same condition.

5. Conclusions

We have proposed a soft-X-ray-charged multilayered piezoelectret energy harvester with embedded electrodes for the first time. An electromechanical model based on the electrostatic model [1] and the beam deflection theory is developed. With the aid of the embedded electrodes, the bias voltage is directly applied to each unit cell, which greatly enhances applied voltage per layer and results in much higher output power. Even with our early prototype using PTFE, where PTFE surface charge density is merely 0.05 mC/m², output power of 0.5 µJ has been obtained for 0.3 mm displacement in 0.2 s.

The authors would like to thank Dr. K. Hagiwara in Japan Broadcasting Corporation (NHK) for his cooperation and fruitful discussion in the course of this work.

Table 1. Output power for different total deformation of the prototype.

| Deformation amplitude | Experiment   | Simulation  |
|-----------------------|--------------|-------------|
| 0.1 mm                | 0.018 µJ     | 0.059 µJ    |
| 0.2 mm                | 0.22 µJ      | 0.28 µJ     |
| 0.3 mm                | 0.52 µJ      | 0.77 µJ     |

5. Conclusions

We have proposed a soft-X-ray-charged multilayered piezoelectret energy harvester with embedded electrodes for the first time. An electromechanical model based on the electrostatic model [1] and the beam deflection theory is developed. With the aid of the embedded electrodes, the bias voltage is directly applied to each unit cell, which greatly enhances applied voltage per layer and results in much higher output power. Even with our early prototype using PTFE, where PTFE surface charge density is merely 0.05 mC/m², output power of 0.5 µJ has been obtained for 0.3 mm displacement in 0.2 s.

The authors would like to thank Dr. K. Hagiwara in Japan Broadcasting Corporation (NHK) for his cooperation and fruitful discussion in the course of this work.

References

[1] G.M. Sessler, and J. Hillenbrand 1999 Appl. Phys. Lett. 75 3405-07
[2] M. Paajanen, H. Valimikki and J. Lekkala 1999 10th Int. Symp. on Electrets
[3] X. Qiu, R. Gerhard and A. Mellinger 2011 IEEE Trans. Dielectr. Electr. Insul. 18 34
[4] J.-J. Wang, et al. 2012 J. Micromech. Microeng. 22 015013
[5] K. Hagiwara, et al. 2012 IEEE Trans. Dielectr. Electr. Insul. 19 1291-98
[6] Z. Xia, et al. 1999 J. Phys. D: Appl. Phys. 32 L83–L85
[7] K. Kashiwagi, et al. 2011 J. Micromech. Microeng. 21 125016