Push-button Kinetic Energy Harvester with Soft-X-ray-charged Folded Multilayer Piezoelectret

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Abstract. Piezoelectret using space-charged porous polymer attracts much attention recently for its softness and high piezoelectric coefficient. It has already been applied to tactile or pressure sensing as well as to kinetic/vibrational energy harvesting. In the present study, a push-button energy harvester based on soft-X-ray charged folded multilayer piezoelectret is proposed. The folded structure with CYTOP-coated parylene-C membranes yields an extremely low stiffness with effective Young’s modulus as low as 14 kPa. With the early prototype, 15.5 μJ/push has been obtained with a maximum force of only 1 N, which corresponds to the record-high piezoelectric coefficient $d_{33}$ of 30000 pC/N. In addition, LED light-up is also demonstrated upon finger press.

1. Introduction

Piezoelectrets or ferroelectrets are space-charged porous polymers, of which piezoelectricity is attributed to the change of macro dipole moment under structure deformation. Recently, they are gaining much attention in kinetic and vibrational energy harvesting due to their softness and high piezoelectric coefficient [1]. Porous polypropylene is the first piezoelectret formed by gas expansion and double stretching, and charged with contact or corona charging [2]. It has voids of different sizes, leading to ineffective charging. Later, multilayer piezoelectret structures with uniform voids are prototyped in order to enhance piezoelectric performance [3, 4]. Corona charging is used for poling, and their quasi-static piezoelectric coefficient $d_{33}$ are from 1000 to 3000 pC/N.

However, because conventional corona charging relies on the electrical breakdown in each gas void, the effective bias voltage per layer for the multilayer structure is much lower than the grid voltage. To address this issue, we previously proposed a multilayer piezoelectret with embedded electrodes to enhance the surface charge density of piezoelectrets as illustrated in Figure 1 [5]. SU-8 pillars were used to define the initial air gap. Although $d_{33}$ of 14000 pC/N has been obtained, the structure was much more rigid than expected, which required a large force (4 N) for power generation. In the present study, a softer piezoelectret using a folded multilayer structure is proposed, aiming to reduce the stiffness while still increase the output energy.

2. Structure Design and MEMS-based Fabrication Flow

Figure 2 shows the present design. Two CYTOP-coated parylene-C sheets, with embedded electrodes and with “protrusions” and “trenches” for keeping the initial air gap after assembly, are placed at a right angle and folded alternatively to form the positive and negative electrodes. After soft-
X-ray charging with a bias voltage, oppositely-charged ions generated by photoionization of nitrogen will be implanted to the CYTOP electrets to form macro dipoles. When the piezoelectret is deformed upon mechanical load, the dipole moment changes, yielding a change of induced charge in electrodes and thus an electric current in the external circuit.

The MEMS-based fabrication process starts with the growth of a 200 nm SiO$_2$ layer by thermal oxidization on a 4-inch (100) Si wafer (Figure 3a). By using standard photolithography, SiO$_2$ etch mask is patterned. In order to obtain a trapezoidal “protrusion” structure without overetching of Si at the edges, compensation mask pattern is needed as shown in Figure 3b. For the “trench” structure, no compensation is needed, as the etching profile is self-confined by the (111) plane. Then, Si wafer is anisotropically etched in 25% TMAH for 6 hours to obtain 100 μm-high “protrusion” and “trench” structures. After removing SiO$_2$, diluted micro-soap is spin coated on the patterned Si wafer. Next, 18 μm-thick parylene-C is deposited on the etched Si wafer using chemical vapor deposition (CVD), which is followed by sputtering the Cr/Au/Cr electrode and a second 18 μm-thick parylene-C deposition, thus achieving the embedded electrode design. Parylene-C is used as the structural layer due to its flexibility, good electrical insulation property and high X-ray transmittance. The wafer is
then blade diced. The thin parylene-C membranes are easily peeled off when washed in IPA solution.
Dip coating is used to coat 10 \( \mu \)m-thick CYTOP CTL-107MK (AGC Co.) electret on both sides. Finally, the piezoelectret is fabricated by assembling two folded sheets and charged by soft-X-ray with a bias voltage of 1 kV for 60 minutes. Figure 4 shows the as-fabricated prototype with dimensions 1.2 cm x 1.2 cm x 3.1 mm.

The stable surface potential of CYTOP after operation is limited by the Paschen’s air breakdown voltage, and about 500 V in the present prototype.

3. Power Generation Experimental Results

Power generation experiments were carried out with a setup shown in Figure 5. The initial capacitance of an undeformed piezoelectret is 160 pF. By pushing the piezoelectret with 2.7 mm deformation, a capacitance change of 156 pF is achieved at a maximum force as low as 1 N (Figure 6). The pillars made by “trenches” and “protrusions” in each air gap as well as the spring-like folding parts at the two ends help restore the piezoelectret to its original shape when the load is released.

Peak output voltage as high as 200 V has been obtained across a 500 M\( \Omega \) load, which corresponds to 15.5 \( \mu \)J electric energy in a whole pushing, holding and releasing operation cycle (Figure 7, 8). The present piezoelectret is quite soft with the effective Young’s modulus as low as 14 kPa. The circuit for \( d_{33} \) measurement is shown in Figure 9. Because the measurement capacitor \( C_M \) has much larger capacitance of 100 nF than the device capacitance \( C_{piezo} \) (160–320 pF), almost all the induced charges by the deformation of the piezoelectret will be accumulated in \( C_M \). Thus, the maximum voltage across \( C_M \) can represent the maximum transferred charge upon pushing. The quasi-static piezoelectric coefficient \( d_{33} \) thus measured is as high as 30000 pC/N, which is one order of magnitude higher than that of previous piezoelectrets and about double of our previous device using SU-8 pillars [5].

![Figure 4. As-fabricated (a) patterned sheets before assembly and (b) folded piezoelectret after assembly.](image)

![Figure 5. Experimental set-up for power generation experiments. A linear motor with prescribed motion pushes the piezoelectret, while the load cell underneath measures the force applied. Output current through resistors is collected via an I/V converter.](image)

![Figure 6. Force and capacitance change versus deformation.](image)

![Figure 7. Experimental results of output voltage across different load resistors.](image)
4. Demonstration of LED light-up by finger pushing

In Figure 10, a folded 10-layer piezoelectret is secured inside a 3D-printed push-button case and demonstrate LED light-up. The set-up consists of the push-button, a full-bridge diode rectifier, a small storage capacitor, a DC/DC converter and a LED. The LED has been successfully lit up when gently pushing the button once with finger.

5. Conclusions

In summary, we propose a soft-X-ray-charged folded multilayer piezoelectret with embedded electrode for push-button kinetic energy harvesting. It can generate 15.5 μJ with 2.7 mm deformation at a maximum pushing force only 1 N. It has an effective Young’s modulus as low as 14 kPa, and its record-high piezoelectric coefficient $d_{33}$ is 30000 pC/N. In addition, we have demonstrated the light-up of a LED bulb by finger pushing. Such push-button energy harvester could be applied to on-demand self-powered electronics in the future.

References

[1] Sessler G M and Hillenbrand J 1999 Appl. Phys. Lett. 75 3405-07
[2] Paajanen M, Valimiiki H and Lekkala J 1999 10th Int. Symp. on Electrets
[3] Wang J-J, Hsu T-H, Yeh C-N, Tsai J-W and Su Y-C 2012 J. Micromech. Microeng. 22 015013
[4] Zhang X, Hillenbrand J, Sessler G M, Haberzettl S and Lou K 2012 Appl. Phys. A 107 Issue 3 pp 621-629
[5] Lu J and Suzuki Y 2017 IEEE 16th Int. Symp. Electrets (ISE16), Leuven, p 105