Development of a pre-packaged MEMS electret energy harvester before charging

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Abstract. A novel MEMS electret vibration energy harvester sealed in a package before charging is developed, which should improve the package reliability and long-term stability of the charges. With an early prototype in package, vertical electret on the comb drives has been successfully charged with soft X-ray photoionization, and up to 3.58 μW has been obtained at 570 Hz and 2.2 g oscillation, which corresponds to the effectiveness as high as 42%.

1. Introduction

Rapid progress of low-power-consumption electronics opens up the possibility of powering wireless sensor nodes by harvesting ambient energy from the environment, which will make significant contribution to the vision of Internet of Things (IoT) [1, 2, 3]. Especially, structural vibration is one of the most promising energy sources [2]. Among various energy conversion principles from kinetic energy to electricity, electrostatic/electret energy harvesters have advantage in efficient use of ambient vibration energy at low frequency vibration [3,4].

Hoffmann et al. [5] developed an in-plane electrostatic energy harvester with overlapping-area-change comb drives and achieved output power of 1.26 μW (RMS value) with 6.5 g acceleration at the resonant frequency of 1460 Hz. Guillemet et al [6] prototyped an electrostatic vibration energy harvester with gap-closing combs and obtained output power of 2.2 μW with acceleration of 1 g at 150 Hz. Whereas these electrostatic generators with comb drives can realize relatively-high effectiveness (the ratio of the electrical power output and the VDRG limit [7]), external power source is inevitable for the priming voltage.

In our previous studies, we developed in-plane electret MEMS energy harvesters [8, 9]. Fu & Suzuki [9] prototyped an electret energy harvester with vertical electrets on the comb drives, which are charged with soft X-ray irradiation [10]. By combining the overlapping-area-change and the gap-closing mechanisms, they achieved 1.6 μW with 2 g acceleration at 266 Hz. The effectiveness is as high as 57%.

For long-term stability of electret, energy harvesters should be packaged to avoid unwanted effect of dust and moisture. However, in previous electret energy harvesters, electret is always charged before packaging, which limits the use of thermal packaging methods due to the charge decay of electret during the thermal cycle.
In the present study, an in-plane MEMS electret energy harvester with comb drives packaged before charging is developed, and the soft X-ray irradiation is used for charging vertical electrets on the comb drives.

2. MEMS electret vibration energy harvester with comb drives

Figure 1 shows fabrication process for an in-plane MEMS electret energy harvester with comb drives [9]. The Silicon-on-Insulator (SOI) MEMS technology is used to microfabricate the device. Process starts with standard lithography on a 4-inch SOI wafer with a 70 µm-thick device layer (Fig. 1a). The device layer is etched with DRIE for comb drives, springs, and etching holes (Fig. 1b). Then, vapor HF is used to remove the buried oxide layer through etching holes and release the structures (Fig. 1c). The device is bonded to a plastic package and the electrical connections are made with wire bonding (Fig. 1d). This is followed by parylene-C deposition on the whole structure, forming a 1.06 µm-thick electret layer on both sides of the interdigitated combs (Fig. 1f). Finally, the lid is bonded on the package in dry air (Fig. 1g), and the electret layer is charged with soft X-ray irradiation of 9.5 keV acceleration voltage (L9490, Hamamatsu) through the lid (Fig. 1h). The bias voltage is 100V.

Figure 2 shows the MEMS electret energy harvester thus fabricated. The seismic mass is 4.893 mg supported with four tilted folded-beam springs, which enable the maximum allowable traveling distance as large as 45 μm. The maximum capacitance change ΔC is 14.7 pF in the harvester with 600 finger pairs for the overlapping-area-change (OV) type and 452 finger pairs for the gap-closing (GC) one. The gap for OV is 8 μm, while the initial/minimum gaps for GC are 33/2 μm.

Figure 3 shows the frequency response before and after the parylene-C deposition measured with a stroboscopic video microscopy (MSA-500, Polytec). The resonant frequency is decreased from 755
Hz to 735 Hz due to the added mass with the parylene-C deposition. The quality factor remains higher than 70 even after the deposition.

3. Charging experiment

In Fu and Suzuki [9], the charging time for 150 s is enough to get uniform surface potential in open air. In the present study, the penetration rates for different lid materials are measured to estimate proper charging time for devices in package. Figure 5 shows the setup to measure the penetration rate of the soft X-ray with 9.5 kV acceleration voltage. During charging, movable fingers of the comb drives are grounded, and fixed fingers are connected to a source measure unit (2600, Keithley) for applying the bias voltage and for measuring the ion current. The distance between the soft X-ray bulb to the surface of device is 5 mm, while the distance between the surface and the lid is 2.5 mm. The penetration rates of 500 μm-thick polycarbonate (PC), 300 μm-thick glass, and 100/200 μm-thick aluminum lids are measured. Table 1 summarizes the measured ion current and the penetration rate of different lid materials. The penetration rate for 500 μm-thick PC is 13 %, while 100 μm-thick aluminum is 7 %. The penetration rate can be increased when an X-rays source of higher energy is employed.

In order to confirm the charging performance of the pre-packaged device, a Kelvin force microscopy (KFM, SPM-9600, Shimadzu) is used to measure the surface potential of the vertical

![Figure 3](image1.png) **Figure 3.** Frequency response before and after parylene-C deposition.

![Figure 4](image2.png) **Figure 4.** Prototype of a packaged MEMS electret vibration energy harvester with 0.5 mm-thick polycarbonate lid.

![Figure 5](image3.png) **Figure 5.** Setup for soft X-ray charging.

![Figure 6](image4.png) **Figure 6.** KFM measurement of surface potential for the vertical electrets.
Table 1. Ion current and penetration rate of different lid materials.

|                | w/o lid | PC 500 µm | Al 100 µm | Al 200 µm | Glass 300 µm |
|----------------|---------|-----------|-----------|-----------|--------------|
| Ion Current [nA] | 22.2    | 3.74      | 1.56      | 0.98      | 0.71         |
| Penetration Rate [%] | -       | 13        | 7.0       | 4.4       | 1.2          |

Figure 7. Surface potential distribution of the vertical electrets. (a) Surface potential in the depth direction, (b) Surface potential in the longitudinal direction.

Figure 8. Temporal change of the ion current after the onset of soft X-ray irradiation.

electrets. After charging through a 100 µm-thick aluminum lid for 2143 seconds, the device is intentionally broken, and one of the comb fingers is fixed onto the KFM stage. Figure 5 shows the measured points.

Figure 6 shows the surface potential distribution of the vertical electrets. The result shows uniform surface potential distribution with ±32 V (surface potential difference of 64 V), which is somewhat lower than the applied bias voltage of 100 V. Longer charging time than estimates with the penetration rate seems necessary to fully charge the device.

4. Power generation experiment

A device in a plastic package with 500 µm-thick polycarbonate lid is charged in a setup shown in Fig. 5. The device is exposed to soft X-rays for 30 minutes with 100V bias voltage to ensure complete charging. Figure 8 shows the ion current during the charging process.

The device is fixed onto an electromagnetic shaker (ET-126B-1, Labworks), and in-plane oscillation is applied. The amplitude is measured with a laser displacement meter (LC-2430, Keyence).
Figures 9 and 10 show the output power of the present device for external sinusoidal acceleration. The external load is chosen as 2.03 MΩ. At 1 g, 0.683 μW is obtained at 680 Hz with minimal hysteresis. At 2.2 g, up to 3.58 μW is obtained at 570 Hz. The effectiveness (the power output divided by the VDRG limit [9]) at 2.2 g is as high as 42%. With increasing acceleration, the power output exhibits a marked hysteresis. The nonlinear behavior becomes significant due to the softening mechanical springs at high acceleration.

5. Conclusion

We have developed a novel pre-packaged MEMS electret energy harvester and successfully charged with soft X-rays irradiation for the first time. The maximum output power of 3.58 μW has been obtained at 570 Hz and 2.2 g. The effectiveness at 2.2 g is as high as 42%. Note that, with the present charging method after packaging, thermal packaging process operated at 300°C (450°C for parylene HT electret) can be used. Although plastic package and lid are used in the present early prototype, metal/ceramic package/lid can be used as far as sufficiently-large transmission rate of the soft X-ray is obtained.

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