Photoelectric-Charging-Enhanced MEMS Electret Energy Harvester with Vacuum Packaging

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Abstract. A novel MEMS electret energy harvester charged with UV light after sealed in a vacuum package is proposed. By 265 nm UV irradiation, electrons are generated inside the package through the photoelectric effect. Uniform surface potential on sidewalls of the comb drives has been obtained. With a MEMS electret generator in a 60 Pa package, 2.28 µW has been obtained at 1 g and 740 Hz, which is 10 times higher than the output power at the atmospheric pressure.

1. Introduction
Electret energy harvester attracts much attention as a promising power supply for low-power-consumption electronics, because of its potential for effective use of ambient low-frequency vibration [1]. Although the charge trapped in electret can be stabilized for tens of years [2], unwanted external influence such as moisture-induced discharge, structure jamming caused from dusts should be avoided. Therefore, to guarantee its stable operation in long term, the harvester needs to be packaged. In case of previous electret energy harvesters, electret is charged before packaging, so that the use of reliable thermal packaging methods were limited due to charge decay of electret under the thermal cycle. To address this issue, we previously proposed soft X-ray charging after packaging, in which vertical electret on comb drives can be charged through photoionization of gas in the package [3].

Improvement of effectiveness (the ratio of the electrical power output and VDRG limit [4]) also has been one of the most spotlighted issues for energy harvesters. We have shown that the comb-drive MEMS electret energy harvester can acquire effectiveness up to 57 % [5, 6]. By decreasing the viscous damping of the device, the output power at the resonant frequency and the effectiveness can be further improved. This should be realized with a vacuum package, but the soft X-ray charging cannot be used, because the soft X-ray charging is based on photoionization of gases; when a low-pressure package is used to reduce the viscous damping, even longer charging time should be required.

On the other hand, UV charging [7, 8] employs the photoelectric effect as well as photoionization to generate ions and electrons. In the present study, for the first time, we propose UV charging as the electret charging method for packaged devices in the vacuum/low-pressure environment.

2. Post-packaging UV Charging
Figure 1 shows the charging setup in a vacuum chamber using UV LED (VPC131, Nikkiso) as the light source. The intensity of UV-LED is 12 mW and the wavelength of light is 265 nm. The UV light penetrates the glass lid and absorbed to the metal film on the backside of the glass lid, generating electrons through the photoelectric effect. Photoemitted electrons are accelerated downward by the
bias voltage. Then, more electrons and positive ions are generated in between the glass lid and the device electrodes through the Townsend avalanche, and collected to the electrodes.

As the photocathode, aluminum (Al) film is deposited on the backside of 1 mm-thick glass lid (Labo-USQ, Daico) by arc plasma gun (ARL-300, ULVAC). Work function of Al is 4.06-4.26 eV [8], which is lower than the energy of the UV light (4.67 eV). The transmission rate of the UV light is 91 % for the glass lid. The optical skin depth of Al is 11 nm [9], so that the Al film thickness is chosen in between 5-17 nm. The electrode for applying the bias voltage is covered with a 2 µm-thick nickel film (work function = 5.04-5.35 eV) to avoid unwanted photoelectric effect [8].

Figure 2a shows the ion current measured with different Al thicknesses at $2 \times 10^{-2}$ Pa. The electrons purely generated from the photoelectric effect are collected with the bias voltage of 200 V. The peak value of 2.12 nA is observed with the lid with 8 nm-thick Al. Figure 2b shows the ion current versus the chamber pressure with 6N (99.99995%) N$_2$ gas. The ion current is increased with the pressure, and reaches its peak at 60 Pa. At this pressure, 12 folds amplification has been obtained by the amplification through the Townsend avalanche. With higher pressures, the ion current is decreased.

3. MEMS Electret Harvester with Comb Drives

Figure 3 displays fabrication process of the MEMS electret energy harvester [3, 5, 6]. Photolithography and DRIE processes are used to pattern pairs of comb drives, etching holes, and folded-beam suspensions (Fig. 3a). Then, the structure on the 8 µm-thick buried oxide layer is released with vapor HF process (Fig. 3b). After bonded to a package, 1.1 µm-thick parylene-C is deposited as the electret (Fig. 3cd). Finally, the lid is bonded to seal the device in vacuum condition (Fig. 3e) and UV light is irradiated for charging (Fig. 3f). Figure 4 shows overview of the MEMS electret energy harvester with comb drives. The seismic mass of 4.29 mg is supported with four folded-tilted springs, which enable traveling distance of 45 µm. 448 pairs of gap-closing comb drives are prepared as electrodes. The maximum/minimum gap of the electrodes is 47/2 µm, designating maximum variation of capacitance $\Delta C$ to be 23.6 pF.

![Figure 1](image1.png)

**Figure 1.** (a) Schematic of the post-packaging UV charging. (b) Picture of the charging setup.

![Figure 2](image2.png)

**Figure 2.** (a) Ion current versus Al film thickness at $2 \times 10^{-2}$ Pa, (b) Ion current versus pressure for 8 nm thick Al.
Considering the shear flow and the squeezed film damping with the second-order slip flow model [11], viscous damping is found to be negligible below 500 Pa. As shown in Fig. 5, the Q factor is respectively 75 and 293 at 1 atm and 60 Pa, showing that the viscous damping has significant impact on the device performance.

4. Verification of Post-packaging UV Charging

The MEMS energy harvesters is exposed to 265 nm UV LED (B265SMDM1, Nikkiso, 4 mW) for 4 minutes with the bias voltage of 100V at the pressure of 70 Pa. Then, the sample is intentionally broken, and the surface potential on the sidewalls of the comb drives (Fig. 6a) is measured with Kelvin force microscopy (KFM, SPM-9600, Shimadzu). Figure 6b shows the surface potential distribution on the vertical/longitudinal direction. Although the charging condition is insufficient in this particular experiment, the surface potential is uniform at -22V in both directions, showing applicability of the present charging method for the comb drives.

Then, another device is exposed to UV LED (VPC131) for 10 min at the pressure of 60 Pa, and loaded into a vacuum container shown in Fig. 7a. Sinusoidal vibration is applied by an electromagnetic shaker (ET-126B-1, Labworks). The external load is 2.04 MΩ. Figure 7b shows the output power under 1 g acceleration with the requency sweeping rate of 0.25 Oct/min. At 60 Pa,
output power of 2.28 µW has been obtained at 740 Hz, which corresponds to the effectiveness as high as 52%. On the other hand, only 0.23 µW is obtained at 1 atm.

5. Conclusion
We have developed a novel post-packaging UV charging method using the photoelectric effect on the backside of the transparent package lid. Uniform surface potential is obtained for the vertical electret on comb drives. A UV-charged MEMS electret energy harvester is developed, and up to 10 times higher output power has been realized at 60 Pa than the atmospheric pressure.

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References.

Figure 6. (a) Surface potential measurement positions. (b) Surface potential distribution of the vertical electrets on the comb drive.

Figure 7. (a) Power generation setup, (b) Power output comparison at 1g acceleration.