Large-dynamic-range MEMS Electret Energy Harvester with Combined Gap-closing/Overlapping-area-change Electrodes

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Abstract: A novel in-plane MEMS electret energy harvester with combined electrodes of overlapping-area-change and gap-closing types is proposed for large output power both at low and high vibration accelerations. An early prototype has been successfully micro-fabricated with the single layer silicon-on-insulator process. Soft-X-ray charging is employed to establish uniform surface potential around 60 V on vertical electrets on the sidewall of the comb fingers. Up to 1.19 µW output power has been obtained at 552 Hz and 2.15 g acceleration oscillations, which corresponds to the effectiveness as high as 27.2%.

Keywords: Combined gap-closing/overlapping-area change electrodes, vertical electrets

1. INTRODUCTION

Vibration energy harvesting is a method to convert vibration energy in the environment to electricity for powering low-power electronics such as wireless sensor nodes. Among various energy conversion techniques, electrostatic/electret principle has attracted much attention for its high output power in small dimensions [1]. In our previous studies, we employ CYTOP as the electret material, and develop an in-plane MEMS energy harvester, in which overlapping area between the electret and the counter electrode is changed. Up to 6 µW output power has been obtained under 40 Hz and 1.4 g oscillation [1, 2]. Another configuration of in-plane electrostatic/electret energy harvesters is based on comb drives, which is micro-fabricated through one-mask SOI process without any assembling. Hoffmann et al. [3] and Nguyen et al. [4] separately developed MEMS electrostatic generators with overlapping-area-change comb drives and obtained output power up to 5 µW RMS and 3.4 µW, respectively. Guillemet et al. [5] developed an in-plane gap-closing electrostatic generator and obtained up to 2.3 µW at 250 Hz. However, external voltage source for the bias voltage is needed for those generators. Recently, Suzuki et al. [6] developed an electret generator with SiO₂ electret induced by highly-doped potassium ions. But, the maximum output power was limited to 50 nW at 58 Hz.

In the present study, an in-plane MEMS electret energy harvester with combined electrodes with overlap-area-change and gap-closing types is proposed for large dynamic range response. A novel charging method using soft X-ray irradiation [7] is employed to realize vertical electrets with high surface potential on the sidewall of comb drives.

2. PRINCIPLE AND DEVICE DESIGN

In electrostatic/electret energy harvesters, capacitance change per unit displacement should be max-
imized for large output power [1]. Capacitance of the gap-closing converters ((2) in inset of Fig. 1) is inversely proportional to the displacement, and thus the gap-closing converter is suitable for large vibration acceleration. However, at small acceleration, the capacitance change diminishes. On the other hand, capacitance of the overlapping-area-change converters with a constant gap ((1) in inset of Fig 1) is linearly changed with the displacement, and thus its change is higher than that of the gap-closing type at low acceleration (or small amplitude). Therefore, we propose a novel electrode configuration combined with in-plane overlapping-area-change and gap-closing converters that provide relatively-high output power both at low and high vibration accelerations.

Figure 1 shows a schematic of the proposed structure. The mechanical resonator has a seismic mass of 4.25 mg, which is suspended by four suspensions at the corners. Based on the VDRG (velocity-damped resonance generator) model [8], the output power of vibration energy harvester is proportional to the seismic mass amplitude. Thus, the spring structure should be designed in such a way that large amplitude is obtained without lateral instability. For that purpose, we employ tilted folded-beam springs having a width of 10 µm and a length of 970 µm, with a tilt angle of 2 degree. The capacitive electrodes comprise two types of interdigitated comb structures: gap-closing and overlapping-area-change. For the overlapping-area-change type, fixed and movable comb fingers are designed with a gap \( g \) of 10 µm and an initial overlap \( L \) of 40 µm. For the gap-closing type, \( g \) and \( L \) are 31 µm and 75 µm, respectively. Thickness of the device layer is 70 µm. The maximum variation of capacitance \( \Delta C \) is 10.2 pF in the harvester with 453 finger pairs for the overlapping-area-change type and 336 finger pairs for the gap-closing one. The oscillation amplitude \( X_{\text{max}} \) of the proof mass is limited to 25 µm by mechanical stoppers. The chip size is 1 cm by 1 cm.

### 3. MICROFABRICATION AND CHARACTERIZATION OF THE ELECTRET ENERGY HARVESTER

The device was fabricated through the silicon-on-insulator (SOI) MEMS technology. The process starts with a standard lithography on 4-inch SOI wafer using photoresist (Fig. 2a). 70 µm-thick device layer is etched with DRIE (Fig. 2b) to form springs, electrodes and etched holes. Then, the buried oxide layer is etched with vapor HF for releasing the structure through the etched holes on the seismic mass (Fig. 2c). This is followed by a 1.5-µm-thick parylene-C deposition as the electret material (Fig. 2d). Finally, soft X-ray charging using 9.5 keV acceleration voltages is applied with the bias voltage of 130V for 150 seconds (Fig. 2e).

Figure 3 shows the prototype device, which is then glued on a printed circuit board. After that wire bonding is employed for electrical connection. Figure 4 shows the mechanical response of the device, which indicates slight softening behavior. The resonant frequency is decreased from 668 Hz to 648 Hz after the parylene deposition, while the maximum amplitude is unchanged, which is as large as 23.6 µm. The quality factor is around 60.7.
We employ soft X-ray irradiation for electret charging as shown in Fig. 5. When the soft X-ray is irradiated onto comb drives, positive and negative ions are equally generated in the gap, which are dragged toward the electrets under an imposed electric field across the gap, so that the charges are transferred to the electrets. Since the soft X-ray can penetrate into narrow gaps, even the electrets on the sidewall of high-aspect-ratio structures can be charged [7]. The bias voltage and the charging time are 130 V and 150 s, respectively.

The surface potential of the vertical electrets is measured with Kelvin force microscope (KFM). After charging, the comb fingers are intentionally broken and one comb finger is fixed onto the KFM stage. Figure 6 shows the surface potential distribution in a 1 µm-square area of the vertical electrets. High surface potential of around 60 V is uniformly distributed in the depth direction down to 65 µm.
Figure 7a shows the output voltage waveform at the resonant frequency of 552 Hz and 2.15 g acceleration. Optimal load is 6.5 MΩ. Peak-to-peak voltage around 12 V is obtained without external bias voltage. Figure 7b shows the output power versus external acceleration at 552 Hz. Even at low acceleration of 0.6 g, 0.1 µW output power is obtained. Thanks to the gap-closing electrodes, the output power is rapidly increased with the external acceleration, and 1 µW is obtained at 2 g. Bi-stable behavior is found over 2 g acceleration, which is attributed to the mechanical response of the tilted folded-beam suspensions for large displacements, and the output power jumps from 1 µW to 1.17 µW. The maximum output power of 1.19 µW is achieved at 552 Hz and 2.15 g, which corresponds to the effectiveness defined by the output power divided by the VDRG limit [8, 9] as high as 27.2%.

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The output power at different vibration frequency is shown in Fig. 8. If compared with the frequency response shown in Fig. 4, the hysteresis becomes more significant, and broadened with increasing external acceleration. This is probably due to the electrical damping force, which increases for large oscillation amplitudes. By the combined effects of the electrical damping and the softening nonlinear spring of the tilted folded suspensions, the bandwidth is increased to 75 Hz at 1 g.

4. CONCLUSION
A novel in-plane electret energy harvester with combined electrodes of overlapping-area-change and gap-closing converters has been proposed in order to realize large dynamic range of the harvester. The proposed prototype is successfully microfabricated, and up to 1.19 µW output power has been obtained, which corresponds to the effectiveness as high as 27.2%.

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Figure 7. Power generation experiment results at 552 Hz. a) Output voltage waveform at 2.15 g external acceleration, b) Output power versus external acceleration.

Figure 8. Output power versus the vibration frequency for both up- and down-sweeps at the external acceleration of 2.15g.