A Design Method of In-plane MEMS Electret Energy Harvester with Comb Drives

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Abstract: In this report, a design method is proposed for in-plane MEMS electrostatic energy harvesters with comb drives. Dependent on the device layer thickness and the achievable aspect ratio of the DRIE process, either the overlapping-area-change or the gap-closing converter has higher output power than the other. Two prototypes of MEMS electret energy harvesters are developed to verify the present design method.

Keywords: Electrostatic generator, electret, comb drive, DRIE, aspect ratio

1. INTRODUCTION

The concept of vibration energy harvesting is to convert environmental vibration energy into electricity for powering low-power electronics such as wireless sensors. Among various energy conversion techniques, electrostatic/electret energy harvesters have attracted much attention for its high output power in small volumes [1]. In electrostatic energy harvesters, the capacitance change should be maximized for enhancing output power [1]. Comb drive is the most commonly used configuration for the MEMS variable capacitor. Hoffmann et al. [2] and Nguyen et al. [3] developed in-plane overlapping-area-change (OV) electrostatic energy harvesters using deep reactive-ion etching (DRIE) process to form the device layer, and obtained output power up to 5 μW (RMS value) and 3.4 μW, respectively. Tseng et al. [4] and Guilllemet et al. [5] developed gap-closing (GC) energy harvesters and achieved up to 1.2 μW at the resonance frequency of 1870 Hz and 2.3 μW at 250 Hz, respectively. However, at the authors’ best knowledge, appropriate choice of the overlapping-area-change or gap-closing converters for maximizing output power under given conditions remains unknown.

In the present study, a design method for electrostatic/electret generator with comb drives is proposed through comparison of the maximum capacitance change per unit area. We prototyped these two types of electret energy harvester and examined their performance.

2. MAXIMUM CAPACITANCE CHANGE RATIO PER UNIT AREA FOR OVERLAPPING-AREA-CHANGE AND GAP-CLOSING TYPE OF COMB DRIVES

Figure 1 shows the schematic of in-plane electrostatic converters, where \( l(t) \) and \( g(t) \) are the overlapping length and the gap opening between the movable and fixed fingers, respectively. The capacitance of each side of the electrodes can be expressed as:
\[ C = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot l(t) \cdot h}{g(t)}, \]

where \( h, \varepsilon_0 \) and \( \varepsilon_r \) represent the height of the comb fingers, the vacuum permittivity, and the relative permittivity of the dielectric surrounding the electrodes. The total capacitance for one pair of electrodes is computed by adding the capacitance on both sides of a finger.

For the OV type, the gap \( g_{ov} \) between the interdigitated combs is kept constant during oscillation. The maximum capacitance change \( \Delta C_{\text{max}} \) per one oscillation cycle of the mass can be given by

\[ \Delta C_{\text{OV, max}} = \frac{4 \cdot \varepsilon_0 \cdot h \cdot A}{g_{ov}}, \]

where \( A \) is the maximum travelling distance of the movable electrodes. Since \( g_{ov} \) is the minimum feature for the OV type, \( g_{ov} \) is defined by the device layer thickness \( h \) (same as the comb height) and the maximum achievable aspect ratio of the DRIE process \( AR = h/g_{ov} \).

On the other hand, for the GC type, the maximum capacitance change \( \Delta C_{\text{max}} \) per one oscillation cycle can be given by

\[ \Delta C_{\text{GC, max}} = \frac{4 \cdot \varepsilon_0 \cdot h \cdot l_{GC} \cdot g_{GC}}{(2g_{GC} - g_{GC,\text{min}})g_{GC,\text{min}}} - \frac{4 \cdot \varepsilon_0 \cdot h \cdot l_{GC}}{g_{GC}}, \]

where \( l_{GC} \) and \( g_{GC} \) are the overlapping length and the initial gap opening between the movable and fixed fingers. The minimum gap \( g_{GC,\text{min}} \), which is often defined by mechanical stoppers, is the key parameter for the GC type. Note that for GC type, double capacitance change occurs during one oscillation cycle.

Therefore, the capacitance change ratio per unit area, which is a measure of the power generation density, is given by

\[ \Delta C_r^* = \left( \frac{\Delta C_{\text{OV, max}}}{S_{\text{OV}}} \right) / \left( \frac{\Delta C_{\text{GC, max}}}{S_{\text{GC}}} \right). \]

The occupied area by the electrodes \( S_{\text{OV}} \) and \( S_{\text{GC}} \) are given by

\[ S_{\text{OV}} = a_{\text{OV}} \cdot b_{\text{OV}} = \left( 2w + 2g_{ov} \right) \cdot \left( 2A + 2d_{\text{min}} + l_{ov} \right), \]

\[ S_{\text{GC}} = a_{\text{GC}} \cdot b_{\text{GC}} = \left( 2w + 2A + 2g_{GC,\text{min}} \right) \cdot \left( 2d_{\text{min}} + l_{GC} \right). \]

Figure 2 shows \( \Delta C_r^* \) versus the maximum travelling distance \( A \) for different aspect ratios. As illustrated in Figure 2a, when \( AR=7 \), the OV type has higher capacitance change (and thus higher output power) than the GC type for \( h < 22 \mu m \). On the other hand, the GC type is superior to the OV type for larger \( h \).
Figure 2. Maximum capacitance change ratio per unit area versus the amplitude of movable electrode for different aspect ratios. a) AR=7, b) AR=15. When $\Delta C^*/C > 1$, the overlapping-area-change (OV) type has larger capacitance change than the gap-closing (GC) type, and vice versa.

Figure 3. Thresholds of the device layer thickness versus the aspect ratio. For thinner device layer, the overlapping-area-change (OV) type has higher performance, while the threshold increases with the aspect ratio of the DRIE process.
type for $h > 60 \mu m$. When $AR=15$, higher output power can be achieved with the OV type for $h < 45 \mu m$ (Fig. 2b), while the GC type is superior for $h > 128 \mu m$.

Figure 3 illustrates the mapping of the thresholds for different $AR$. With increasing $AR$, the region for the OV type is increased. As also shown in Fig. 3, some of the previous studies with the OV type are located in the region for the GC type. Figure 4 shows the mapping for the electret generator with the electret layer (thickness: $d$). With the electret layer, the effective aspect ratio is increased, and thus the region for the GC type is increased.

3. EXPERIMENTAL RESULTS

Figures 5 and 6 show the present prototypes of MEMS electret energy harvester [6] and their mechanical responses. The device layer thickness is 70 $\mu m$ and $AR=7$. 1.5 $\mu m$-thick parylene-C layer is used as the electret layer. For the present design of $\Delta C_r^* = 0.89$ (Eq. 4), the GC type has larger capacitance change than the OV type.

Figure 7 shows the output power versus the excitation frequency for the OV and GC types. At 3 g acceleration, maximum output power of 1.19 $\mu W$ and 1.71 $\mu W$ are obtained, respectively; the GC type has higher output power than the OV type even with its lower resonant frequency. Although more systematic comparison is necessary, the present experimental data are in accordance with the present analysis. Note that the GC type exhibits more significant nonlinear behavior than the OV type due to its inherent nonlinear behavior of the electrostatic force.

![Figure 4](image-url) **Figure 4.** Thresholds versus the aspect ratio for different thicknesses of electret film on comb drives.

![Figure 5](image-url) **Figure 5.** A prototype of MEMS electret energy harvester. Fabrication process can be found in [6].
Figure 6. Frequency response for the gap-closing/overlapping-area-change type of electret energy harvesters after the parylene-C deposition.

Figure 7. Output power of the present electret energy harvesters versus the excitation frequency at 3 g. a) overlapping-area-change type, b) gap-closing type. The thickness of device layer is 70 µm and AR=7. 1.5 µm-thick parylene-C layer is used as the electret layer, which corresponds to $\Delta C'_r = 0.89$.

4. CONCLUSION

A design method for in-plane MEMS electrostatic energy harvesters is proposed. Dependent on the device layer thickness and the aspect ratio of the DRIE process, either the overlapping-area-change or the gap-closing type has higher output power than the other. Two prototypes of MEMS electret energy harvesters are developed to verify the present design method.

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References
[1] Suzuki Y, 2011, *IEEE Trans. Electr. Electr. Eng.* 6 101-111
[2] Hoffmann D, Folkmer B, and Manoli Y 2009 *J. Micromech. Microeng.* 19, 094001
[3] Nguyen S D, Halvorsen E, and Paprotny I 2013 *Appl. Phys. Lett.* 102 023904
[4] Chiu Y, and Tseng V F G 2008 *J. Micromech. Microeng.* 18, 104004
[5] Guilllemet R, Basset P, Galayko D, Cottone F, Marty F, and Bourouina T 2013 *IEEE MEMS* 2013 817-820
[6] Fu Q Y, and Suzuki Y 2014 *IEEE MEMS 2014* 409-412