Electrostatic Energy Harvester Utilizing High Density of Electrode for Higher Output Power

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Abstract. In this study, we report an improvement of output power from an electret type vibration energy harvester. Typical crossing-area change harvester has a stripe-shaped electret and counter electrode for making the capacitance change. In order to improve space efficiency, the counter electrodes are divided and arranged with the same pitch of the electret. We investigate that adjoining the counter electrodes, the fringing effect is decreased and the capacitance change between the electrodes is larger than the conventional design from FEM analysis. The output power of 2.5 $\mu$W and 5.3 $\mu$W are obtained in each kind of counter electrode with the applied acceleration of 3 G at 350 Hz, which is about 2 or 4 times as high as our previous work.

1. Introduction
Wireless sensor networks (WSNs) are attractive for a tire pressure monitoring system (TPMS) or a human healthcare system. A power supply for the system needs long lifetime. Energy harvesters are expected as a power source for these systems [1][2]. Mechanical vibration sources are abundant in the environment and easy to use for conversion to electrical energy. We study an electrostatic vibration energy harvester, which transfers charge on the counter electrodes (CE) by capacitive induction from an electret material with electrical charge. Typical crossing-area change electrostatic energy harvester has a stripe-shape electret and the CE for making capacitance change. In order to obtain the larger capacitance change, the pitch of CE and the electret pitch are same in general (Fig. 1a) [3]. However, this design shows small capacitance change because of a large fringing effect. In this study, we demonstrate a new device with doubled number i.e. half pitch size of the CE for improving output power. The novel electrostatic energy harvester with high-density electrodes was fabricated by MEMS batch process. The preliminary measurement results are also described.

2. FEM analysis
In order to improve space efficiency and obtain the large capacitance change, the CE is divided to two parts, CE-N (negative) and CE-P (positive) with the same pitch of electret as shown in Fig. 1(b). The capacitance between the electrodes is calculated by FEM analysis (ANSYS 14.0) with considering fringing effect. The FEM analysis model for conventional and high-density (HD) CE model is same as Fig. 1. A 2.5 $\mu$m thick electret polymer CYTOP (CTL-809M, Asahi glass Corp.,) and 0.5 $\mu$m thick bottom electrodes (BGE-N, BGE-P; abbreviation of buried grid electrode-negative and positive) are fabricated on a 1 $\mu$m thick SiO$_2$ isolation layer on a 500 $\mu$m thick Si substrate. The all the dimensions are as same as our previous electrostatic energy harvester.
Figure 2 shows the vector plots of the electric field directions at half pitch displacement of CEs. The BGE-N and the BGE-P are set to the -200 V and GND (0 V), respectively. The vector arrow direction depicts an electric field direction, length and color shows intensity. From the results, the diffusion of electric field from the BGEs is smaller for the HD CE structure. Figure 3 shows the capacitance change between the CE-N and the BGE-N on conventional and HD CE design. Since the diffusion of electric field from the BGEs is reduced by adjoining CE, the fringing effect is decreased. Thus the capacitance change for the HD structure is twice as large as conventional design and the offset caused by the fringing effect was reduced.

![Figure 2. Vector plots of the electric field directions for (a) conventional design, and (b) high-density counter electrode.](image)

![Figure 3. The capacitance change between the CE-N and BGE-N for conventional and high-density structure](image)

3. Device design and fabric process
3.1 Device design
Figure 4 shows the cross-sectional schematic diagram of our electrostatic energy harvester. The harvester consists of a Si counter electrode, an electret with base electrodes placed on a mass-spring structure, and cover glass. The Si counter electrode functions harvesting counter electrode and charging grid. In order to prevent pull-in, the Si grid also has micro pillars for spacer. Figure 5 shows the fabrication process of the energy harvester. The shape comparison for conventional and HD CE is shown in Fig. 6. In the novel design, CE is divided into an interdigital shaped CE-N and CE-P.

![Figure 4](image1.png)

**Figure 4.** The concept of our electrostatic energy harvester [4].

![Figure 5](image2.png)

**Figure 5.** Fabrication process of the energy harvester.

**Figure 6.** The conceptual diagram of counter electrode for (a) conventional, and (b) slit high-density device.

3.2 Fabrication Process
An electret part, Cr was sputtered on a glass wafer (Pylex code 7740; Corning Inc., USA) and patterned. The glass wafer was etched by BHF with the Cr pattern as a mask. Then, the glass wafer was bonded to 500 μm thick Si wafer with 1 μm thick SiO₂ in anodic bonding (Fig. 5a). BGEs made of Al are sputtered on the Si substrate and patterned with the 85 μm width 15 μm intervals (Fig. 5b). Then, the SiO₂ film was patterned by CF₄ plasma etching (Fig. 5c). A 2.5 μm thick CYTOP was spun on and patterned by O₂ plasma etching. Then, the mass-spring structure was formed by DRIE.

The counter electrode is fabricated monolithically on a p-type Si wafer (<0.1 Ω·cm resistivity, 300 μm thick). The SiO₂ is patterned for the pillars and etch mask of 2nd-DRIE (Fig. 5f). The sputtered Al on Si surface is patterned (Fig. 5g). In order to improve the connectivity Al and Si are sintered at 460 °C for 30 min. Positive type photoresist (KMPR 1005; Microchem Corp., USA) is formed as the spacer for the air gap (Fig. 5h). The counter electrodes are fabricated in the shape of interdigital by 1st-DRIE (Fig. 5i). The air gap and the pillars are fabricated by 2nd-DRIE (Fig. 5j). Figure 7 shows the 4-inch wafer with CE-N and CE-P shape after 1st-DRIE process.

The electret wafer and counter electrodes were bonded by CYTOP heat Pressing method at 150 °C. An estimated output current is anti-phased for CE-N and CE-P. Therefore, the counter electrodes
should be divided to individual electrodes after a dicing process. Finally, the device was charged by corona discharging method. The dimension of the entire device is $13 \times 12 \times 1.2 \text{ mm}^3$. Figure 8 shows the fabricated harvester compared with coin battery (CR2032).

**Figure 7.** The structural of counter electrode after DRIE on 4-inch wafer.

**Figure 8.** The comparison of the electrostatic energy harvester and coin battery. (CR2032)

### 4. Harvesting experiment

Our electrostatic energy harvester was charged with the grid setup voltage of -200 V at the charge process. The device is attached on the shaker (ET-136; Labworks Inc., USA) and vibrated at 350 Hz. The acceleration of 3 G is sufficiently large to ignore the electrostatic force, which is caused by charged electret. Figure 9 shows the output waveform for CE-N and CE-P connected with 1 MΩ load resistance. The output waveform of individual CE-N and CE-P is anti-phase. Assuming the actual harvesting form the differential of CE-N and CE-P, the peak-to-peak voltage is twice as large as each one. The output frequency of our harvester is larger than the applied acceleration frequency because the amplitude of the vibration is larger than the electrode pitch. Utilizing HD CE, the output voltage is higher for improving the space efficiency.

Figure 10 shows the measurement output power for CE-N and CE-P; CE-N or CE-P is connected to a variable resistor with ultra high-impedance buffer (AD549; Analog Device Inc., USA) and the other is connected to GND. The simulated output power, which is calculated by the equivalent circuit model [5] that is shown in Fig. 10. The maximum output power for CE-N and CE-P are 2.5 μW and 5.3 μW at 5 kΩ and 7 kΩ load resistance, respectively. The measurement result of the harvester corresponds with the simulated one. Since the capacitance change between the electrodes is lager, the output power of the device is higher than conventional design. The output power will be 4 times as high as the result utilizing the bipolar electret, which charges not only negative but also positive charge in our previous work [6].

We evaluate a harvesting system by combing with a power management IC and our harvester on a SPICE circuit simulator (LTspice IV; Linear Technology Corp., USA). Figure 11 shows the harvesting system connected with LTC3588-1 and our novel harvester with HD CE and bipolar charged. The charged voltage of the harvester is ±200 V. From the result, the voltage after the power management of 1.8 V will be obtained after 35 s intervals. It is 5 times faster than our previous work.
5. Conclusion

In this study, an improvement of output power from an electrostatic energy harvester is investigated. Utilizing double number of counter electrode, the capacitance change between the electrodes is larger from FEM analysis. The electrostatic energy harvester was fabricated by MEMS batch process. The output power of the high-density device was 2.5 \( \mu \text{W} \) at CE-N and 5.3 \( \mu \text{W} \) at CE-P, which is 2 or 4 times as large as conventional design. The device connected with LTC3588-1 will output the management voltage of 1.8 V at 35 s intervals from the circuit simulator.

References

[1] Altena G, Renaud M, Elfrink R, Goedbloed M H, Nooijer C de and Schaijk R van 2013 Proc. of PowerMEMS2013 371-375
[2] Mitcheson PD, Yeatman EM, Kondala G Rao, Holmes AS, and Green TC 2008 Proc. of IEEE 96 14577-1486
[3] Marboutin C, Suzuki Y, and Kasagi N 2007 Proc. of PowerMEMS2007 141-144
[4] Fujita T, Fuji k K, Onishi T, Kanda K, Higuchi K, Maenaka K 2011 Proc. of Eurosensors 25 733-736
[5] Minami K, Fujita T, Sonoda K, Miwatani N, Kanda K, Maenala K 2014 Proc. of PowerMEMS2014 208-212
[6] Fujita T, Onishi K, Fujii K, Katsuma K, Kanda K, Higuchi, Maenaka K 2012 Proc. of PowerMEMS2012 436-439