DESIGN IMPROVEMENT FOR PREVENTING DISCHARGE DURING FABRICATION OF ELECTROSTATIC ENERGY HARVESTER

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Abstract. This paper reports an improvement of structure design of bipolar charged electret energy harvester to prevent an electrical discharge during a corona charging process on electret. We confirmed that differential output power of 33 μW is obtained with 8.8 g at 350 Hz sinusoidal vibration from the developed device. By using a commercially available power management IC, regulated voltage of 1.8 V is properly obtained and can drive a load resistance more than 500 kΩ.

1. Introduction
The vibration energy harvester is expected as a maintenance-free power supply for wireless sensors, such as tire pressure monitoring system (TPMS) [1]. In our electret type vibration energy harvester (VEH), the density of counter electrode (CE) was doubled for higher output power. we confirmed that the device can generate four times (above 40 μW) as large power as previous device in the same dimension [2]. However, the output power from the fabricated device was lower than expected because of the unintended discharge during the fabrication. In this paper, the device design is revised to overcome this problem. We also described the novel device's performance by measurement.

2. Harvester with double-density counter electrode
Figure 1(a) shows the cross-sectional schematic diagram of previous device with a normal-density counter electrode (CE) and a bipolar charged electret [3]. The buried grid electrodes (BGEs) beneath positive and negative charged electret are named the BGE-P (Positive) and the BGE-N (Negative) respectively. In this structure, CE is arranged in same pitch of a pair of BGE-P and BGE-N. Relative position and capacitance between CE and BGE are changed by a horizontal vibration. Unlike the ideal value, the capacitance change is smaller than theoretical calculation because of a large fringing effect.

Figure 1(b) shows the structure of our revised harvester with double-density CE. In this structure, the CE is electrically divided to two part i.e. the CE-P and CE-N, to induce reversed-polarity charges above the bipolar charged electret. In order to double the CE density, the electrode was arranged in half pitch size of previous one. The double-density CE structure can produce larger capacitance change compare to the previous one because an additional counter electrode acts as a guard-electrode to reduce the fringing effect. The half-pith CE also increase spatial efficiency, so the output will be improved.
Figure 2 shows top view diagrams of single and double-density counter electrode. The interdigital-shaped CE-P and CE-N which are fabricated by D-RIE process and electrically divided to individual electrode by removing conductive part after the dicing process.

![Figure 1](image1.png)

**Figure 1.** Cross-sectional schematic diagrams of energy harvester with bipolar charged electret for (a) normal-density CE and (b) double-density CE.

![Figure 2](image2.png)

**Figure 2.** Top view of structural schematics of CE (a) normal-density and (b) double-density. Red circle shows conductive part which is removed after dicing process to divide between CE-P and CE-N electrically.

### 3. Discharge prevention design

In our previous study, the harvester with double-density CE showed large difference between output powers from the CE-P and the CE-N. There was unintended parasitic resistance of few MΩ, $R_p$ that was generated between CE-N and BGE [2]. The $R_p$ brought an unbalance of output voltage from the harvester. We assumed that the $R_p$ was generated from the carbonization of polymer by discharging on the CE tip where an electric field was highly concentrated. During the bipolar charging process as shown in Fig. 3, the charging voltage is as twice as normal monopolar electret.

To avoid the discharge problem, we modified the counter electrode to be covered by polymer film (KMPR1005; Nihonkayaku Co., Ltd, Japan) for insulation as shown in Fig. 4. Electret charging voltage was reduced from ±200 V to ±150 V for considering a dielectric breakdown voltage, 9 kV/0.1 mm of electret material (CYTOP: CTL-809M, Asahi Glass Corp., Japan). Table 1 shows the $R_p$ and the parasitic capacitance $C_p$ for (a) before and (b) after the isolation measure. We confirmed that the unintended conduction between CE-N and BGE was drastically reduced from the previous device.

![Figure 3](image3.png)

**Figure 3.** Corona charging apparatus for bipolar-electret.

![Figure 4](image4.png)

**Figure 4.** Covered area of the CE tip insulation polymer film.
Table 1. Parasitic elements between each of electrodes by using a LCZ meter for (a)previous design and (b)improved design. The LCZ meter was configured with 0 V bias voltage and 1 kHz and 1 Vpp.

| Measured electrode | $C_p$ [pF] | $R_p$ [MΩ] |
|--------------------|------------|------------|
| CE-P and BGE       | 52.5       | -          |
| CE-N and BGE       | 60.0       | 3.1        |
| CE-N and CE-P      | 64.0       | 27.5       |

| Measured electrode | $C_p$ [pF] | $R_p$ [MΩ] |
|--------------------|------------|------------|
| CE-P and BGE       | 77.9       | -          |
| CE-N and BGE       | 80.4       | 28.7       |
| CE-N and CE-P      | 73.0       | -          |

4. Experiments

4.1. Waveform measurement

The novel harvester was mounted on a shaker and applied acceleration of 8.8 g ($g$: gravitational acceleration 9.81 m/s²) at a frequency of 350 Hz. Figure 5 shows the schematic of the measurement apparatus. The CE-P and CE-N are individually connected to load resistances. Measuring prove was connected through the ultra-high-impedance buffer (AD549; Analog Device Inc., USA).

Figure 6 shows output waveforms from the CE-P and CE-N with load resistance of 1 MΩ. The output anti-phased waveforms obtained from CE-P and CE-N were as expected. The differential output waveform from two CEs will be approximately as doubled as individual CEs (thin black line in Fig. 6).

4.2. Load characteristic

Figure 7 shows measurement and simulation results for maximum output power versus load resistance. The simulated output power was calculated by an equivalent circuit model of SPICE simulator in our previous work [4]. The maximum powers from CE-P and CE-N that connected with optimal load of 0.4 MΩ were 18 μW and 15 μW, respectively. The maximum differential output from both electrodes was reached 33 μW. We confirmed the maximum output power of novel device was 2.2 times as large as the simulation result. We assumed that wafer-level adhesive bonding process causes air-gap reduction, then the output was increased above the simulation.

Figure 7. Maximum output power versus load resistance from 10 × 10 mm² of active area. Novel device was charged at ±150 V and applied acceleration of 8.8 g at 350 Hz.
4.3. Connect to power management IC

Our novel VEH was connected to commercially available power management IC (LTC3588-1: Linear Technology Co., USA), which is designed for high impedance energy harvester. Figure 8 shows input ($V_{in}$) and output ($V_{out}$) voltage on LTC3588-1. The regulated output voltage was set to 1.8 V. Figures 8(a) to (c) show startup voltage of $V_{in}$, $V_{out}$ for load resistances of 1 MΩ, 500 kΩ and 100 kΩ, respectively. The specified voltage of 1.8 V was obtained after 37s case of 1 MΩ load. Due to a current from load resistance during charging, the IC never reaches specified voltage to connect under 100 kΩ.

![Figure 8](image.png)

**Figure 8.** Input and output waveform from LTC3588-1. (a)1 MΩ, (b)500 kΩ, and (c)100 kΩ load resistance. $V_{in}$ is charging terminal from differential output of harvester to connected capacitor. $V_{out}$ is output terminal to supply DC power for loads.

5. Conclusion

The energy harvester with double-density counter electrode was developed and improved by polymer-insulation film. We confirmed that conduction by $R_p$ was greatly reduced from discharge prevention device. The differential output power of 33 μW was obtained from novel energy harvester as the acceleration was 8.8 g at 350 Hz with 0.8 MΩ of optimum load resistance from 10 × 10 mm² of active area. Specified regulated voltage of 1.8 V is properly obtained with load resistance more than 500 kΩ by using a power management IC.

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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] Miwatani N, Minami K, Fujita T, Kanda K, and Maenaka K 2016 *Proc. of APCOT 2016*, 219-229

[3] Fujita T, Onishi T, Fujii K, Katsuma K, Kanda K, Higuchi K, and Maenaka K 2012 *Proc. of PowerMEMS2012* 436-439

[4] Minami K, Fujita T, Sonoda K, Miwatani N, Kanda K and Maenaka K 2014 *Proc. of PowerMEMS2014* 208-212