Evaluation of Electrostatic Force on Bipolar Charged Electret

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Abstract This paper presents an evaluation of an electrostatic vibration energy harvester with the bipolar charged electret. The energy harvester with the size of 13 × 12 × 1.2 mm³ was fabricated. The output power of the bipolar charged with ±250 V harvester was 9 µW when the acceleration was 1.4 g at 352 Hz with 0.9 MΩ load resistance. The effectiveness against the velocity-damped resonant-generator (VDRG) limit was 2.5%. The electrostatic forces of the actual device with DC bias, which simulates charged electret with monopolar and bipolar were experimentally and numerically verified. We estimated the electrostatic force by measuring the vibration amplitude versus applied acceleration of the electret mass. As a result, we investigated the bipolar charged device can reduce the effect of electrostatic force as low as no bias condition. The numerical model of the energy harvester considering the electrostatic force by FEM static analysis was also established. The comparison between the numerical model and the measurement results showed a similar inclination.

1. Introduction
We study an electrostatic energy harvester for an ambient vibration. Electrostatic energy harvester generally uses electret, which holds electric charges for a long year. Charging electret with high surface potential and decreasing a parasitic capacitance[1] is effective to improve output power, although surface charge density and potential are limited by thickness of the electret film[2]. High surface potential thick film electret is fabricated by multi-layer electret film[3]. However, surface potential also increases electrostatic force, which restrains mass movement[4]. In order to overcome this issue, a reduction method of the electrostatic force for horizontal direction with a dual-phase arrangement and for vertical direction by using a repulsive force, which electrets are charged with monopolar charge have been reported[5]. We proposed a bipolar charging method by selective charging method[6] in order to form an electret, which has not only negative charge but also positive charge. From the analytical and numerical estimation, we investigated the reduction for electrostatic force on our bipolar charged electret device.

In this paper, we demonstrate that the bipolar charged electret is effective to decrease the electrostatic force because the potential difference between the electrodes can be reduced in comparison with the monopolar charged electret for the same surface potential difference of the electret e.g. monopolar charged with -200 V, bipolar charged with ±100 V. From the generated power of the bipolar charged
device, we also confirmed the reduction of electrostatic force of bipolar biased electret by comparison between the measurement and the numerical analysis. In order to formulate a numerical model considering an effect of electrostatic force, the electrostatic force of static condition is estimated by FEM analysis.

2. Bipolar Charged Energy Harvester

The surface potential after charging the CYTOP (CTL-809M; Asahi glass Co., Ltd., Japan) with the thickness of 2.5 µm was examined. In conventional electrostatic energy harvesters, electrets are charged mainly with negative charge. The grid potential during the charging process was applied from 0 V to 1 kV with negative and positive potentials. The surface potential is measured by an electrostatic voltmeter (Model 279; Monroe Electronics Inc., USA) and it is shown in figure 1. The surface potential of the CYTOP is saturated around 600 V because of the material dielectric breakdown voltage for 2.5 µm thickness. The characteristic of the positive charging indicated as similar as the negative charging one.

The energy harvester with the size of 13 × 12 × 1.2 mm³ was fabricated and charged with ±250 V bipolar potential as shown in figure 2. The diagram of bipolar charged electret on the device are shown in figure 3. The actual device consists of 50 pieces of analysis model. We already reported that the test specimen of the bipolar charged electret, which is charged with the pitch of 1 mm[7]. The energy harvester, which consists of the electrode pitch of 100 µm, was charged with bipolar charge and the

![Figure 1](image_url1) ![Figure 2](image_url2) ![Figure 3](image_url3)

**Figure 1.** Characteristic of surface potential saturation for 2.5 µm thickness CYTOP film.  
**Figure 2.** Photo image of energy harvester and schematic diagram of device design.  
**Figure 3.** Device design of energy harvester and diagram of bipolar charged electret.
output power was investigated. The oscillation amplitude and the weight of the mass are 200 \mu m and 120 mg, respectively. Figure 4 shows the output power versus external load when applied acceleration is 7 g at 352 Hz. The maximum output power appeared at 0.9 M\Omega optimum load resistance. The optimum resistance for maximum output power also can be calculated by the following equation: 
\[ R_{OPT} = (2\pi f C)^{-1} \]
where \( f \) is the peak frequency of the output waveform by FFT analysis and \( C \) is the parasitic capacitance of the device. The optimum resistance is calculated as approximately 1.1 M\Omega load resistance. The parasitic capacitance of the device was approximately 80 pF. The output waveform is shown in figure 5. The peak frequency of the output waveform was 1756 Hz, which is 5 times of 352 Hz because it is an initial position of the actual device that the counter electrode has an offset of +50 \mu m due to a process error from arrangement in figure 3. The calculated optimum resistance was according to the measurement resistance at the maximum output power. The maximum effectiveness against the velocity-damped resonant-generator (VDRG) limit is 2.5% when the harvester outputs 9 \mu W by applying acceleration of 1.4 g at 352 Hz with 0.9 M\Omega load resistance.

3. Numerical Model of Energy Harvester

The electrostatic forces under static condition of the monopolar and bipolar charged harvester were obtained by FEM analysis. The electrostatic force versus the displacement of the proof mass changes sinusoidally. The electrostatic forces along to vertical and horizontal directions were respectively reduced to 15% and 20% from the same potential difference for monopolar charged electret[7]. The formula of the electrostatic force is calculated by curve fitting and applied to the numerical model. The numerical model from equation of motion of the energy harvester considering the electrostatic force as shown in figure 6 is given by

\[ m\ddot{x} + D\dot{x} + kx + F_e(x) = F(t), \]

where \( x, m, D, k, F_e, \) and \( F \) are the expression for the displacement of the proof mass, the weight of the proof mass, the damping coefficient, the spring constant, the electrostatic force of horizontal axis...
under static condition, and the applying force, respectively. The mechanical quality factor of the proof mass is approximately 150. The numerical model is evaluated by the comparison with the characteristics of actual device.

4. Evaluation of Electrostatic Force of Monopolar and Bipolar Charging

We investigated the electrostatic force of the device, which didn’t use fixed charged electret, by measuring the vibration amplitude of the proof mass versus applied acceleration as shown in figure 7. During the measurement and the simulation, the DC bias voltage is applied to the buried grid electrodes (BGEs) and the counter electrode (CE) is grounded as similar as actual harvesting operation. The DC bias voltage simulates charged electret. The applied bias voltage conditions and its resonant frequency were measured as shown in Table 1. Because the electrical spring stiffness is changed with different bias voltage, all measurement and simulation were carried out with different resonant frequency. The experiment results and the numerical analysis value are shown in figure 8. The mass movement of no bias condition showed only mechanical spring stiffness. When -200 V bias voltage is applied to the BGE-N (blue marker in figure 8), the mass movement showed smaller amplitude i.e. higher electrostatic force was occurred between the CE and the BGE-N. On the other hand, applying -200 V bias voltage to the BGE-P, the result showed lower electrostatic force because the CE was pulled laterally by BGE-P (green marker in figure 8). When ±100 V bipolar bias was applied, the mass movement showed as similar as the no bias condition. As a result, the bipolar charged electret was able to reduce the effect of electrostatic force as low as no bias condition. We confirmed that the numerical model with the electrostatic force from FEM static analysis accorded with the measurement results. In future, the evaluation of output power versus applied acceleration with load resistance for measurement and simulation is required to reproduce an actual harvesting operation.

Figure 7. Experiment setup for evaluating the electrostatic force with DC bias between CE and BGEs. Laser Doppler Vibrometer (LDV) measures the amplitude of mass during vibrating. Force measurement of fabricated device was performed with controlled bias voltage and variable acceleration on shaker.

Table 1. Experiment potential on BGEs and resonant frequency \( f_r \). Applied bias voltage conditions and its each resonant frequency were measured. CE is grounded under all conditions.

|            | BGE-N [V] | BGE-P [V] | \( f_r \) [Hz] |
|------------|-----------|-----------|----------------|
| No bias    | -         | -         | 433.0          |
| Monopolar  | -200      | 0         | 427.2          |
| Bipolar    | -100      | +100      | 434.7          |
5. Conclusion
The energy harvester with bipolar charged electret with the size of $13 \times 12 \times 1.2 \text{ mm}^3$ was fabricated. The output power of the bipolar charged with $\pm 250 \text{ V}$ harvester was $9 \mu\text{W}$ when the acceleration was $1.4 \text{ g}$ at $352 \text{ Hz}$ with $0.9 \text{ M}\Omega$ optimum load resistance. The effectiveness against the VDRG limit was 2.5%. The numerical model of the energy harvester considering the electrostatic force obtained by FEM static analysis was also established. The characteristic of vibration amplitude versus applied acceleration was investigated and the results indicated that the bipolar charged device can reduce the effect of electrostatic force as low as no bias condition. The comparison between the numerical model and the measurement results showed a similar inclination.

References
[1] Masaki T et al., *J. Micromech. Microeng.*, 21, 104004, pp.1-5 (2011)
[2] Suzuki Y, *IEEJ Trans*. 2011, 6, pp.101-111 (2011)
[3] Wada Y et al., *Proc. of The 4th Symposium on Micro-Nano Engineering*, OS4-1-4 (2012) (in Japanese)
[4] Altena G et al., *Proc. of Transducers'11*, pp.739-742 (2011)
[5] Suzuki Y et al., *J. Micromech. Microeng.*, 20, 104002, pp.1-8 (2010)
[6] Toyonaga T et al., *The Technical Digest of APCOT 2010*, SSASN5, p.290 (2010)
[7] Sonoda K et al., *Proc. of PowerMEMS 2013* (London, UK, Dec. 3–6), pp. 366–370 (2013)