

# MEMS ELECTRET GENERATOR WITH ELECTROSTATIC LEVITATION

Daigo Miki, Makoto Honzumi, Yuji Suzuki, and Nobuhide Kasagi  
Dept. of Mechanical Engineering, The University of Tokyo, Tokyo, Japan

**Abstract:** A MEMS electret generator has been developed for energy harvesting applications. Electret-based non-contact bearing is employed as the gap control method, and dual-phase electrode arrangement is adopted in order to reduce the horizontal electrostatic damping force. With the present prototype, about  $0.5 \mu\text{W}$  is obtained for both phases of the generator, and the total power output of  $1.0 \mu\text{W}$  has been obtained at an acceleration of 2 G with 63 Hz. With our electromechanical model of the generator, we have confirmed that the model can mimic response of the actual generator prototype.

**Keywords:** Energy harvesting, Electret, Electrostatic levitation, Electrostatic damping force

## INTRODUCTION

Among various techniques for energy harvesting, vibration-driven power generation from structural vibration attracts much attention due to its broad potential applications such as automotive sensors and structural health monitoring [1, 2]. Since the frequency range of vibration existing in the environment is below 100 Hz, electret power generators [3-7] should have advantages of higher output power than electromagnetic ones.

We recently developed a high-performance electret material based on amorphous perfluorinated polymer CYTOP [8] and obtained extremely-high surface charge density of  $1.5 \text{ mC/m}^2$ . Edamoto et al. [9] microfabricated a prototype of electret generator with parylene high-aspect-ratio springs, which allows low resonant frequency and large amplitude. However, power output remained as low as  $0.28 \mu\text{W}$ , because the air gap should be kept as large as  $170 \mu\text{m}$  to avoid electrostatically-induced stiction.

In the present study, we develop a prototype of MEMS electret generator with electrostatic levitation. Electret-based non-contact bearing [10] is employed as the gap control method between electret and the counter electrode to prevent stiction. In addition, we evaluate the performance of the present prototype in comparison with the electromechanical model [11].

## DESIGN OF ELECTRET GENERATOR

In electret generators, power output is increased with decreasing the gap between electret and the counter electrode. However, since electrostatic attraction force in the vertical direction is also increased, the gap control is crucial to avoid pull-in. Tsurumi et al. [10] found that electrostatic repulsion force can be obtained between opposed patterned electrets (Fig. 1a). In the present design, patterned electrets are formed both on the seismic mass and the bottom substrate.

Edamoto et al. [12] proposed a checker-board pattern to minimize unwanted effect of misalignment between the top and bottom substrates. However, this arrangement was turned out less effective for large-amplitude oscillation. In the present study, we employ simple stripe patterns. In order to reduce the amplitude of horizontal electrostatic force, dual-phase configuration [9] is adopted, in which two separate

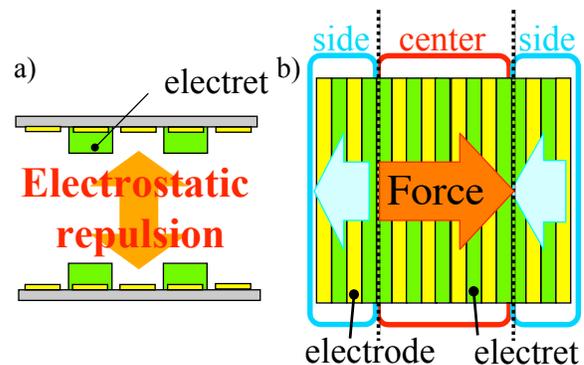


Fig. 1. Schematic of the patterned electrets and electrodes. a) Electret-based non-contact bearing using electrostatic repulsion, b) Dual-phase arrangement.

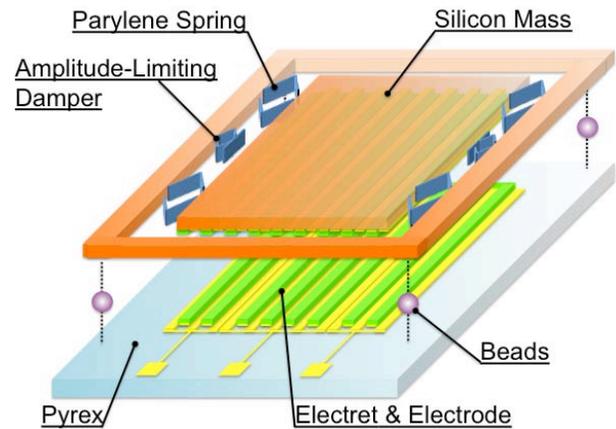


Fig. 2. Schematic of the micro electret generator.

generator circuits 180° out-of-phase each other are integrated on a single seismic mass (Fig. 1b).

Figure 2 shows a schematic of the micro electret generator designed in the present study. The top substrate consists of a Si proof mass supported with parylene high-aspect-ratio springs [13]. Patterned electrets and electrodes are formed both on the Si mass and the bottom Pyrex substrate. The gap between the substrates is defined with micro beads.

The dimension of device is 18.5 x 16.5 mm<sup>2</sup>, and the size of the mass is 11.6 x 10.2 mm<sup>2</sup>. Designed values of the resonant frequency and the amplitude are respectively 63 Hz and 2.0 mm<sub>p-p</sub>. Under this vibration condition, power output estimated with the numerical simulation [11] is 17 μW at surface voltage of -600 V.

### MEMS FABRICATION PROCESS

Fabrication process of the electret generator is shown in Fig. 3. For the top substrate with a seismic mass, the process starts with a 400 μm-thick 4" Si wafer with 1.5 μm-thick thermal oxide. The oxide layer on the front side is patterned with BOE for the etch mask of DRIE, and 20-μm-wide 350-μm-deep trenches are etched into the substrate (Fig. 3a). The trenches are used as the parylene molds. Some of the trenches also define boundaries of Si islands to be left. Then, bottom Cr/Au/Cr electrodes are evaporated on the backside and patterned with standard lithography process, followed by spun-on 15 μm-thick CYTOP (CTL-809M) films and curing at 185 °C for 1.5 hours (Fig. 3b). Next, 15 μm-thick parylene-C is deposited on the front side and etched back with O<sub>2</sub> plasma. This is followed by the second parylene-C deposition to fully refill the trenches (Fig. 3c). After the metal mask for the CYTOP and parylene etching is

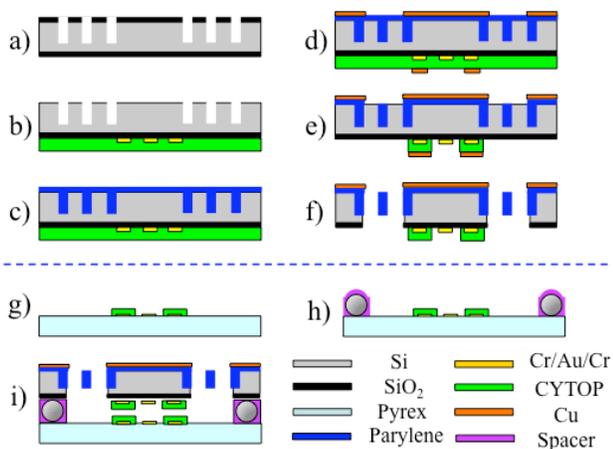


Fig. 3. Fabrication process of the electret generator.

patterned (Fig. 3d), the parylene and CYTOP films are patterned with O<sub>2</sub> plasma (Fig. 3e). Finally, the Si substrate surrounding the Si mass is etched away with XeF<sub>2</sub>, and the structures are released (Fig. 3f).

For the bottom substrate, the process starts with a 525 μm-thick 4" Pyrex wafer. Cr/Au/Cr electrodes and CYTOP film are patterned (Fig. 3g).

After these processes, charges are implanted into CYTOP electret using corona charging for 3 minutes at 120 °C, which is slightly higher than the glass

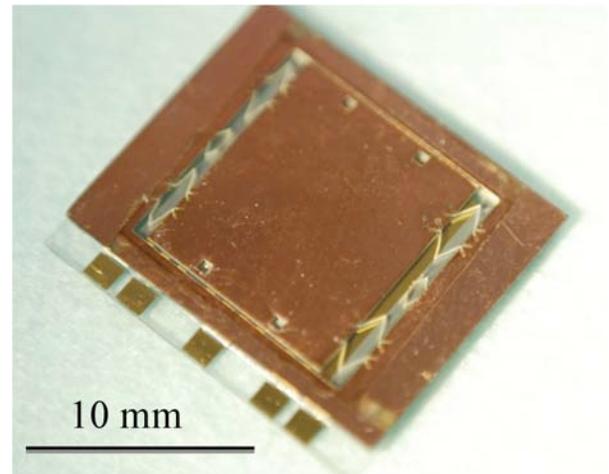


Fig. 4. MEMS electret generator prototype.

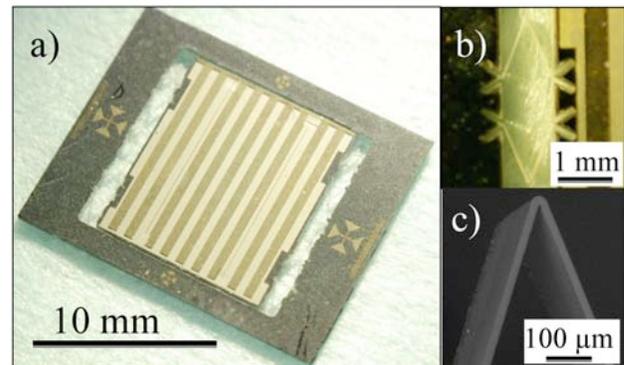


Fig. 5. Backside of the top Si structure, a) Overview, b) Parylene high-aspect-ratio spring, c) SEM image of the parylene spring.

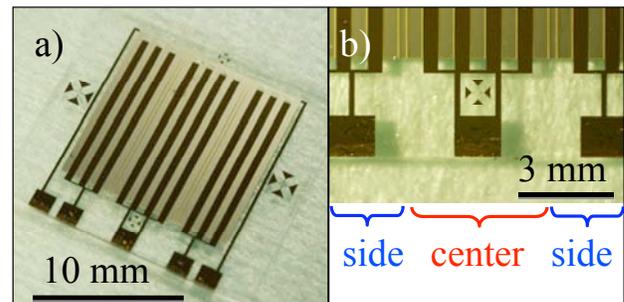


Fig. 6. Bottom substrate, a) Overview, b) Magnified view of electret and electrodes in the dual-phase arrangement.

transition temperature of CYTOP. The needle and grid voltages are respectively  $-8$  kV and  $-600$  V. The micro beads, of which diameter is well defined, are mixed with epoxy adhesive and applied to the Pyrex substrate (Fig. 3h) as the spacer. Finally, the top Si substrate and the bottom Pyrex substrate are aligned and bonded (Fig. 3i). The air gap between the substrates is  $70$   $\mu\text{m}$ .

Figures 4-6 show photographs of the generator prototype thus fabricated. The seismic mass is supported by  $20$   $\mu\text{m}$ -wide high-aspect-ratio parylene springs. The width of the patterned electret and electrode is  $480$   $\mu\text{m}$ . On the backside of the top substrate, 8 stripes of patterned electrets are formed for each phase of the generator (Fig. 5a). On the bottom Pyrex substrate, patterned electrodes as well as pads for external connection are formed.

### POWER GENERATION EXPERIMENT

Firstly, the mechanical response of the spring-mass system is examined. The seismic mass supported with the parylene springs is fixed on an electromagnetic shaker (APS-113, APS Dynamics), and the in-plane amplitude of the mass is measured by observing the motion with a digital microscope (CAMN80, Keyence). Figure 7 shows the frequency response of the seismic mass. Its resonant frequency is  $63$  Hz with a quality factor of  $8.6$ . In-plane amplitude at the resonance is as large as  $0.9$  mm<sub>p-p</sub>. Although the quality factor should be improved, the resonant frequency of the present seismic structure is sufficiently low for energy harvesting applications.

Figure 8 shows the experimental setup of the power generation experiment. The micro electret generator presently developed is fixed on the shaker, and the device is oscillated in the in-plane direction at its resonant frequency of  $63$  Hz.

We examined the power output of the generator

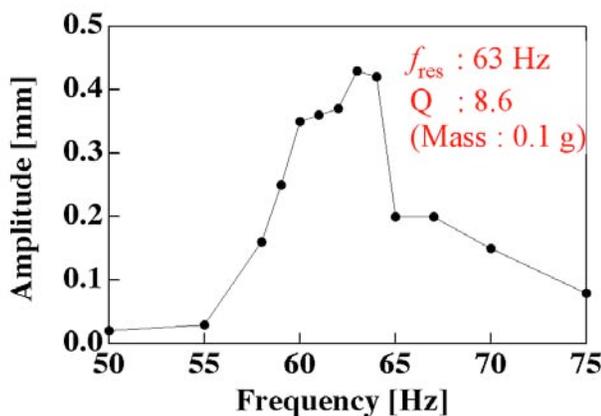


Fig. 7. Frequency response of the electret generator.

prototype at  $63$  Hz with the acceleration of  $2$  G. Figure 9 shows power output versus the external load, where purely resistive is employed. The output power of the center phase is  $0.56$   $\mu\text{W}$ , and that of the side phase is  $0.48$   $\mu\text{W}$ . About  $0.5$   $\mu\text{W}$  has been obtained for both phases of the generator, corresponding to the total power output of  $1.0$   $\mu\text{W}$ . In Fig. 9, numerical results based on our electromechanical model [11] are also plotted. The parameters are based on the present electret generator prototype, and summarized in Table 1. The present data are in reasonable agreement with the numerical data, while the power output near the matched impedance is leveled off. This is probably because the damping force becomes large near the matched impedance, and the amplitude of seismic mass is reduced. Another possibility is change of the air gap for different external load. Further investigation is required to explain this discrepancy.

Figure 10 shows the output voltage at a  $20$  M $\Omega$  external load. Peak-to-peak voltage of  $11.2$  V is obtained. Prediction with the present model is in good agreement with the experimental data. Note that, surface potential of the CYTOP electrets in this prototype is estimated to be as low as  $-180$  V. With higher surface potential and smaller air gap, we can expect power output more than  $10$   $\mu\text{W}$  at  $1$  G with the present configuration.

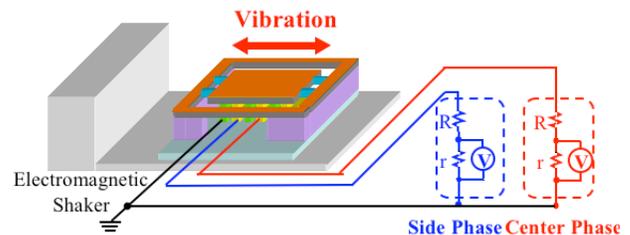


Fig. 8. Experimental setup of power generation.

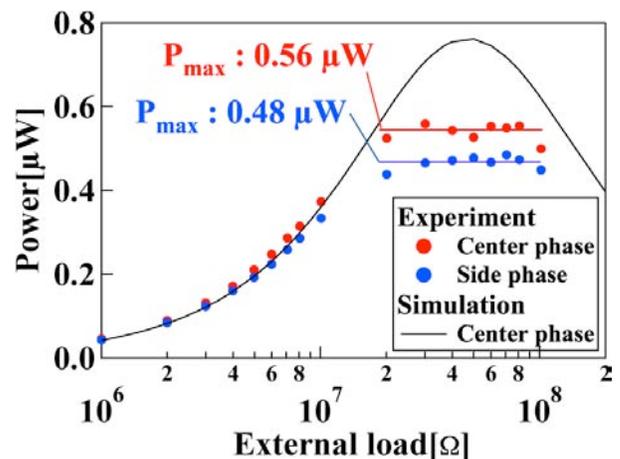


Fig. 9. Power output versus external load at an input acceleration of  $2$  G with  $63$  Hz. Surface voltage of the present simulation is  $-180$  V.

Table 1: Parameters of the numerical simulation.

Dimension of seismic mass	11.6 x 10.2 mm <sup>2</sup>
Width of patterned electrets and electrodes	480 μm
Thickness of electret film	15 μm
Seismic mass	0.1 g
Quality factor	8.6
Surface voltage*	-180 V
Parasitic capacitance	10 pF
Maximum traveling length	2.0 mm <sub>p-p</sub>
Oscillation frequency	63 Hz

\* Fitting value

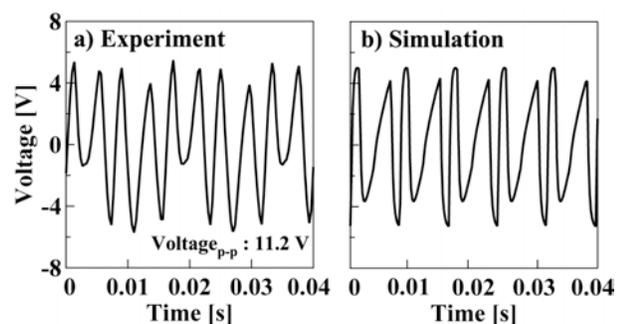


Fig. 10. Time trace of output voltage at 20 MΩ.

## CONCLUSION

We have developed a MEMS in-plane electret generator with electrostatic levitation for energy harvesting applications. Patterned CYTOP electret is formed on both the top and bottom substrates for gap control using electrostatic repulsive force. Dual-phase electrode arrangement is employed in order to reduce the unidirectional electrostatic damping force. The air gap is chosen as 70 μm. With an acceleration of 2 G at 63 Hz, about 0.5 μW has been obtained for both phases of the generator, corresponding to the total power output of 1.0 μW. We have also showed that the numerical model of generators can mimic the response of the actual MEMS electret generator prototype.

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