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ELECTRET-BASED ENERGY HARVESTING DEVICE WITH PARYLENE FLEXIBLE SPRINGS

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ABSTRACT

A MEMS vibration-driven electret generator for energy harvesting has been developed. Parylene high-aspect-ratio flexible spring is employed to support the seismic mass with high-performance patterned electret. The seismic structure enables large in-plane oscillation amplitude of 1 mm and low resonant frequency of 37Hz. With our early prototype, we have obtained 21 V_{p-p} voltage output, corresponding to output power of 0.27 μW with an external road of 100 MΩ.

Keywords: Energy harvesting, Electret, Micro power generation, Parylene flexible spring

1. INTRODUCTION

Recently, micro power generation attracts significant attention as mobile power source. Energy harvesting from environmental vibration has potential to replace button batteries used for low power applications such as RFIDs and automotive sensors [1-3]. Since the frequency range of vibration existing in the environment is tens of Hz, electrostatic power generators, especially erectret power generators, should have higher performance than electromagnetic ones [4-6].

We recently discover that CYTOP (Asahi Glass Co., Ltd.), which is MEMS-friendly amorphous perfluoro-polymer, can sustain a very high surface charge density as a stable electret material [6]. We also develop a new high-performance polymer electret material based on CYTOP, and demonstrate that up to 0.69 mW power can be obtained at an oscillation frequency as low as 20 Hz with the amplitude of 1.2 mm_{p-p} [7].

In order to realize an integrated power generation system, soft spring that offers low resonant frequency and large amplitude is required. In addition, the gap control between electret and the counter electrode is crucial to avoid the pull-in.

In the present study, we employ parylene high-aspect-ratio spring proposed by Suzuki & Tai [8] for the soft spring and electret-based non-contact bearing [9], and microfabricate a prototype of the energy harvesting device.

2. ELECTRET POWER GENERATOR

Figure 1 shows the principle of electret-based generator with electrostatic induction. When in-plane oscillation is applied, the amount of induced charge on the counter electrode is changed due to the change in the overlapping area, and electric current is generated in the external circuit. It is obvious that the power is increased with decreasing the gap between the electret and the counter electrode. However, since electrostatic attraction force in the vertical direction is also increased, the gap control is crucial to enable large amplitude oscillation. Tsurumi et al. [9] found that electrostatic repulsion force can be obtained between opposed patterned electrets. Thus, in the present design as shown in Fig. 1, interdigitized electrets are formed both on the seismic mass and the bottom substrate to keep the gap constant.

Marboutin et al. [10] have developed a numerical model of in-plane electret generators, and examined electrostatic force acting on the oscillating mass. When conventional interdigitized electrodes are employed, large unidirectional electrostatic force appears in the horizontal direction. In order to reduce the horizontal force, a two-phase arrangement is proposed, where two electrically independent generators with 180˚ phase difference are integrated on a single chip (Fig. 2a). By using this modified arrangement, the large in-plane force is cancelled out, and the net force becomes 10 times smaller. Note that, with this two-phase arrangement, the in-plane electrostatic force is almost the same as the one for the velocity-damped resonant generator (VDRG) model [3, 10].

In addition, to reduce the gap between the electret and the counter electrode, we propose electret with barrier metal electrode on its top; interdigitized electrode is used to implant charges selectively into the exposed erectret film by corona charging (Fig. 2b).

Figure 3 shows a schematic of the micro electret generator designed in the present study. The top substrate is composed of a silicon proof mass supported with parylene high-aspect-ratio springs. Patterned electrets and electrodes are formed both on the silicon mass and the bottom pyrex substrate. The gap between the substrates is defined with a PDMS layer.

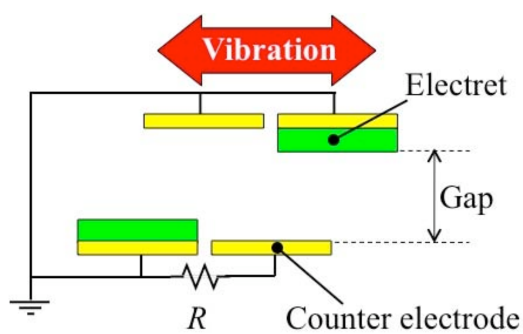

Figure 1. Schematic of electret power generation principle.

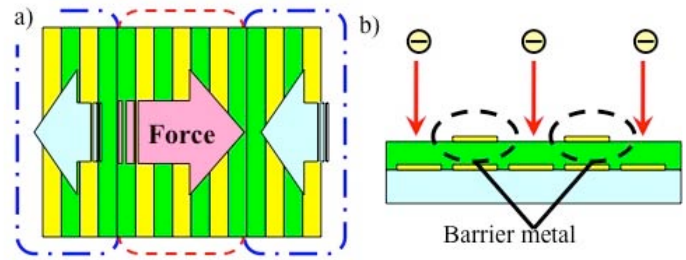

Figure 2. Schematic of the patterned electret in two-phase arrangement.

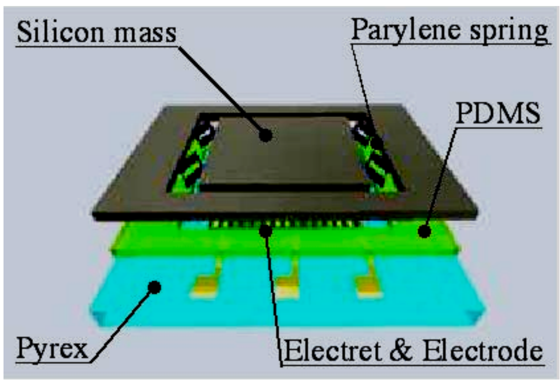

Figure 3. Schematic of the electret generator.

3. FABRICATION

Figure 4 shows the fabrication process of the electret generator. For the top Si substrate with a seismic mass, the process starts with a 400 μm-thick 4'' wafer with 2 μm-thick thermal oxide. The top oxide layer is patterned with BOE for the etch mask of DRIE, and 350 μm-deep trenches are etched into the substrate (Fig. 4a). The trenches are used as the parylene molds. Some of trenches also define the 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. 4b). Top Cr/Au/Cr electrodes and metal mask for CYTOP etching are evaporated and patterned (Fig. 4c). 15 μm-thick parylene-C is then deposited and etched back with O_2 plasma, and the second parylene layer 15 μm in thickness is deposited to fully refill the trenches (Fig. 4d). After metal mask for the parylene etching is patterned (Fig. 4e), the parylene films and the CYTOP films are etched with O_2 plasma (Fig. 4f). Finally, the silicon substrate surrounding the Si mass is etched away with XeF_2 (Fig. 4g), and the structures are released with BOE (Fig. 4h).

On the other hand, for the bottom substrate, the process starts with a 700 μm-thick 4'' Pyrex wafer. CYTOP film and Cr/Au/Cr electrodes are patterned (Fig. 4i). Then a PDMS spacer is bonded with O_2 plasma treatment (Fig. 4j).

After these processes, charges are implanted into the CYTOP electret using corona charging for 3 minutes at 120 ˚C. The needle and grid voltages are respectively -8 kV and -600 V. The top Si substrate and the bottom Pyrex substrate are finally bonded together with a PDMS spacer.

Figure 5 shows the schematic of preparing electrets. During the corona charging process, the barrier metal layer on the Si of the CYTOP layer must be disconnected from the bottom electrode, in order to effectively implant electrons into the electret film (Fig. 5a). On the other hand, during the power generation operation, the top metal layer has to be connected to the bottom electrodes, since they are used as the counter electrodes of the power generation (Fig. 5b). In order to make electronic contact between the top and bottom electrodes, through holes are fabricated in the CYTOP layer, and the conductive Ag paste (D-500, Fujikura Kasei Co., Ltd.) is applied into the holes after corona charging (Fig. 5c).

Figures 6-8 show photographs of the generator prototype thus fabricated. The dimension of the device is 3 x 3 cm^2 (Fig. 6), while the size of the mass is 14.6 x 16 mm^2. The width of the patterned electret and electrode is 150μm. The surface voltage of electret on the top substrate is -560 V, and that of on the bottom substrate is -450 V. The gap between the electret and the electrode is 170 μm. On the back side of the Si substrate, there are 14 poles of patterned electrets both on the center and the side phases (Fig. 7c). The dimension of the through hole is 500 x 500 μm^2 (Fig. 7b). The seismic mass is supported by 25μm-wide parylene springs (Fig. 7b, d). On the Pyrex substrate, three contact pads, which are insulated each other, are formed; the left one is connected to the bottom electrodes, the center one is to the counter electrodes for the center phase, and the right one is to the counter electrodes for the side phase (Fig. 8a). There are also three through holes for the electronic contact (Fig. 8b).

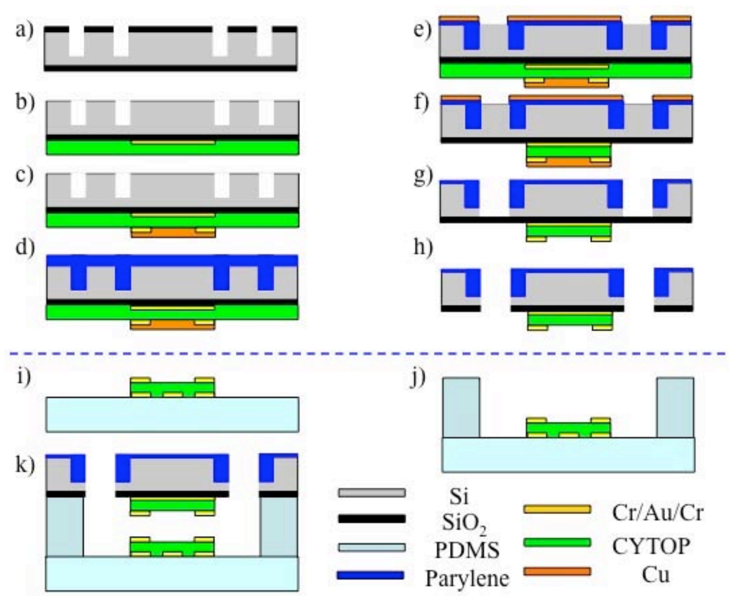

Figure 4. Fabrication process of the electret generator.

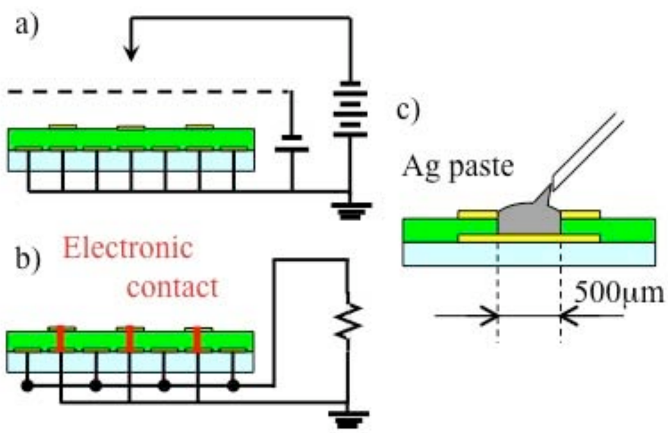

Figure 5. Process for preparing electrets. a)Corona charging, b)Electrical connection for power generation, b)Short-circuiting the top and bottom electrodes with Ag paste.

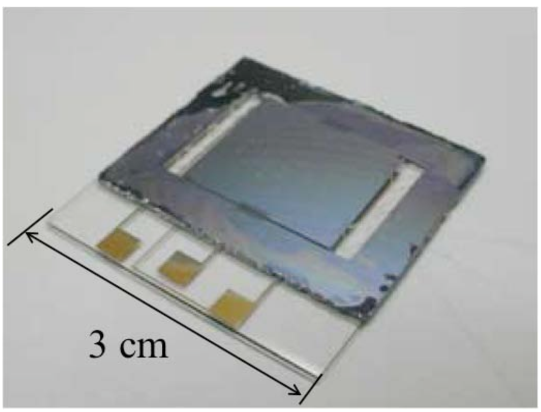

Figure 6. Assembled electret generator prototype.

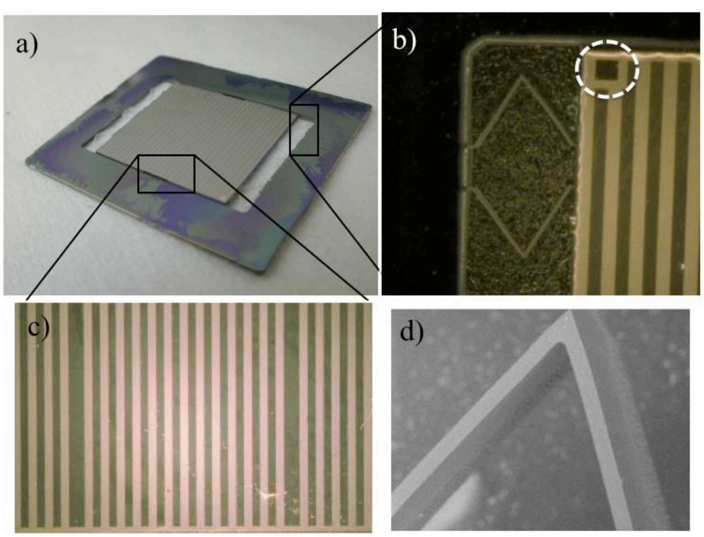

Figure 7. Back side of the Si substrate, a)Over view, b)Patterned electret on the seismic Si mass, c)Through hole on the electret and parylene high-aspect-ratio spring, d)SEM image of the parylene spring.

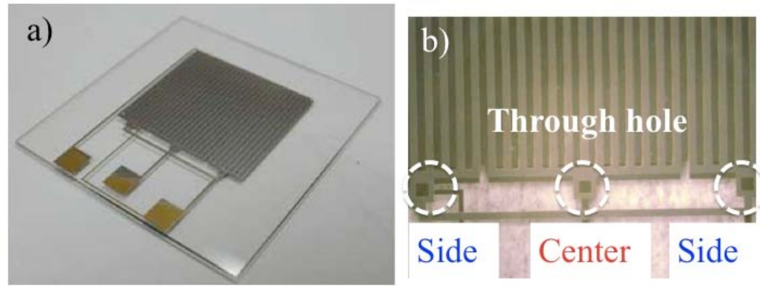

Figure 8. Bottom substrate. a)Overview, b)Magnified view of electret and electrodes in the two-phase configuration.

4. POWER GENERATION EXPREIMENT

Firstly, the mechanical response of the mass-spring system is investigated. The seismic mass supported with the parylene springs is fixed on an electromagnetic shaker (APS-113, APS Dynamics Inc.), and the in-plane amplitude of the mass is measured by observing the motion with a digital microscope (CA-MN80, Keyence Inc.). Figure 9 shows the frequency response of the seismic mass. Its resonant frequency is 37Hz with a quality factor of 7.8. In-plane amplitude at the resonance is as large as 0.8 mm. Although the quality factor should be improved, the parylene springs developed in the present study can be applicable to vibration-driven energy harvesting.

Figure 10 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 37 Hz. The center and side phases are respectively connected to the external load of 100 MΩ.

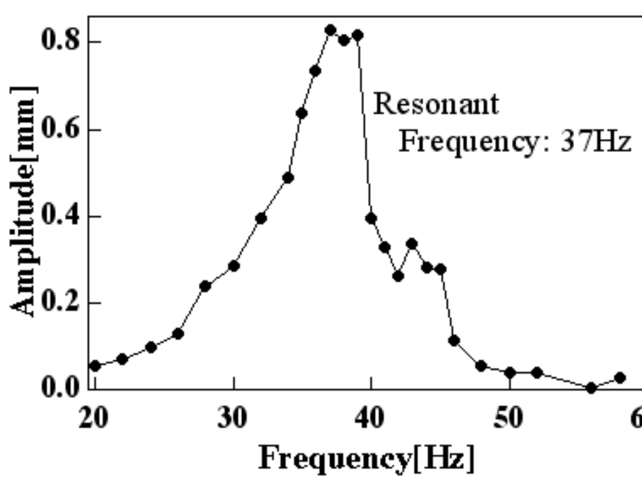

Figure 9. Frequency response of the generator.

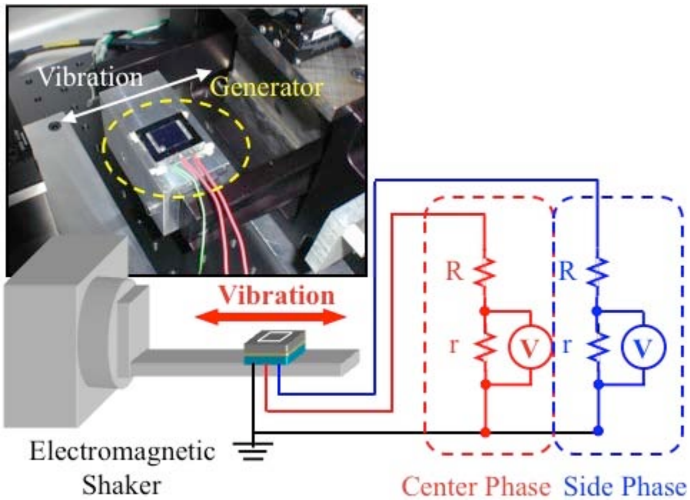

Figure 10. Experimental setup of power generation.

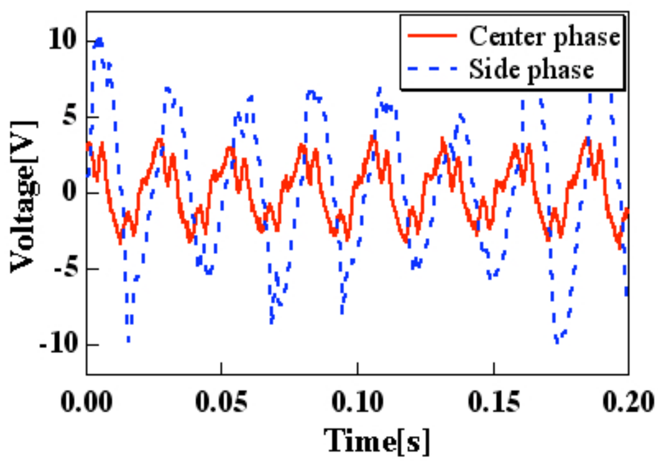

Figure 11. Time trace of the output voltage.

Figure 11 shows the time trace of the output voltage. The peak-to-peak voltage of the center and side phases are respectively 7.39 V and 20.8 V. The output power of the center phase is 0.036 μW, and that of the side phase is 0.239 μW. The total output power of the two phases is 0.28 μW, which is much smaller than expected from our designed value of 11.8 μW. This is partially due to the fact that the alignment between the top and bottom electrodes is poor, so that the velocity of overlapping area is much smaller than the designed value.

5. CONCLUSION

Vibration-driven electret generator for energy harvesting has been developed. Parylene high-aspect-ratio spring is successfully microfabricated to support an in-plane seismic mass. Patterned CYTOP electret is formed on both the top and the bottom substrates in order to keep the gap using electrostatic repulsive force. Resonant frequency as low as 37Hz has been achieved with a large in-plane amplitude of 1 mm. With our early prototype, we have obtained 21 V_{p-p} voltage output, corresponding to output power of 0.28 μW with an external road of 100 MΩ.

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