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Energy Harvesting from Vibration Using Polymer Electret

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ABSTRACT:

A vibration-driven electret generator has been developed for energy harvesting applications. Perfluorinated polymer electret with extremely-high surface charge density is employed for large power output. By using parylene as the spring material, a low-resonant-frequency MEMS generator is realized. Large in-plane amplitude of 0.8 mm at the resonant frequency as low as 37 Hz has been achieved. With our early prototype, output power of 0.28 μW has been obtained.

1. INTRODUCTION

Energy harvesting from environmental vibration attracts much attention in view of its potential to replace button batteries used for low power applications such as RFIDs and automotive sensors [1-3]. Various prototype devices using piezoelectric, electro-magnetic, and electrostatic principles are proposed.

Figure 1 shows a simplified model of vibration-driven power generator, where m, k, and C respectively represent the mass, the spring constant, and the damping coefficient. In this velocity-damped resonant generator (VDRG) [3], the maximum power output P_{max} with the maximum travelling distance of the mass z_{lim} can be written as:

$$P_{\max} = \frac{1}{2} m y_0^2 \omega^3 \frac{z_{\lim}}{y_0} . \quad (1)$$

When a specific application is chosen, the angular frequency ω and the amplitude of external vibration y_0 are given. Therefore, the output power of VDRG is dependent only on its mass and the travelling distance; in principle, large/heavy generator is necessary for large output power.

Figure 2 shows power spectra of vibration acceleration in a car cabin. Since high-frequency vibrations are damped out with the suspension system, vibration energy is concentrated below 100 Hz. Thus, the use of electromagnetic induction is problematic due to its low output voltage and power. On the other hand, electret-based electrostatic induction can produce high voltage even at low frequencies [4, 5].

More recently, MEMS generator using electrets are prototyped [6-11]. Boland et al. [6] microfabricated rotational electret power generator, and obtained 25 μW with a rotor 8 mm in diameter. Tsutsumino et al. [9, 10] developed a seismic electret generator with 20x20 mm^2 grid electrets/electrodes, and demonstrated 0.28 mW power generation at an oscillation frequency of 20 Hz. In this report, out recent efforts on MEMS electret generator are introduced.

2. POLYMER ELECTRET

Electret is a dielectric material with quasi-permanent charge. M. Eguchi [12] first developed carnauba wax electret using a thermal polarization method. Charge in carnauba wax thus prepared is stable after 36 years [13]. Since then, various applications of electrets such as acoustic/mechanical transducers and air filter have been proposed [14].

For conventional applications of electrets, fluorinated polymer materials such as PTFE and FEP are often used. However, they are not compatible with the MEMS processes, since they are insoluble in solvents. In addition, the surface charge density should be improved for higher performance of the devices. Hsieh et al. [15] and Boland et al. [6] employed Teflon® AF (Du Pont) as their electret film, which is perfluorinated amorphous polymer. Lo and Tai [16] found that fluorinated parylene (parylene HT®) provide very

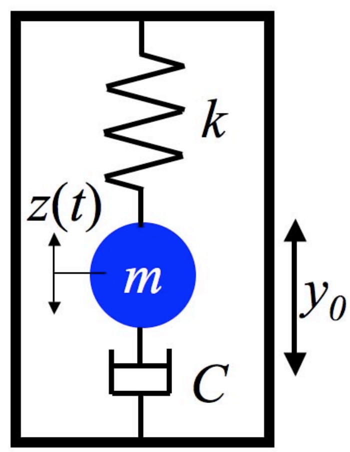

Figure 1. Vibration-driven power generator.

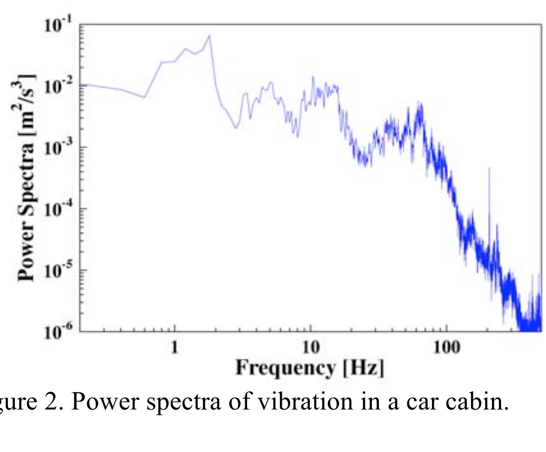

Figure 2. Power spectra of vibration in a car cabin.

high surface charge density.

We recently reported that CYTOP™ CTL-M (Asahi Glass Co., Ltd.), MEMS-friendly amorphous perfluorinated polymer, can provide 3 times higher surface charge density than Teflon AF [9, 10]. Since theoretical power output of electret generators is proportional to the square of the surface charge density [6], electret generators with CYTOP CTL-M should have potential to produce nine times larger power than similarly built generators with Teflon AF.

Figure 3 shows the molecular structure of CYTOP. There are three different types of commercial grade CYTOP depending upon their end group, i.e., trifluoromethyl (CTL-S), carboxyl (CTL-A), and amidosilyl (CTL-M). Corona discharge is employed for the charging, and a series of measurements of surface potential was made.

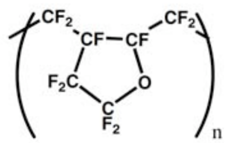

Figure 3. The molecular structure and the end groups of CYTOP.

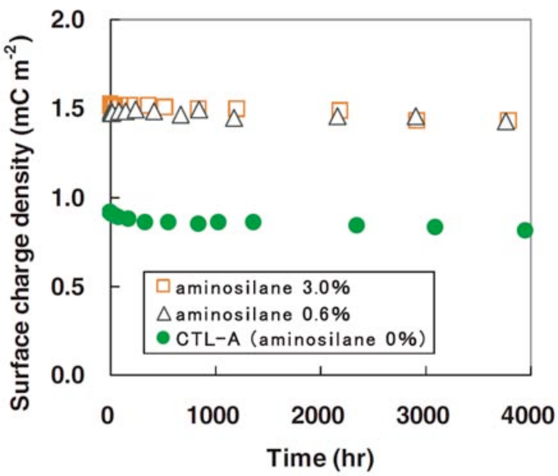

Figure 4. Time trace of the surface charge density of aminosilane-doped CYTOP (aminosilane 0.6 wt%, and 3.0 wt%; film thickness:15μm) [17].

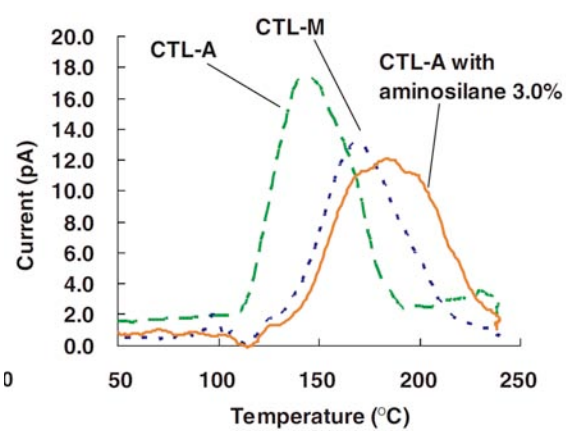

Figure 5. TSD spectra of CTL-A, CTL-M, and aminosilane-doped CYTOP (aminosilane 3.0 wt% ; film thickness:15 μm) [17].

Sakane et al. [17] found that the functional end group, especially amidosilyl in CTL-M, significantly enhances the surface charge density of CYTOP. Thus, they doped aminosilane into the CTL-A to increase the concentration of amidosilyl functional group. Figure 4 shows the surface charge density of 15 μm-thick CYTOP CTL-A film for different concentration of aminosilane. By doping only 0.6-3.0% of aminosilane into CTL-A, the surface charge density has been doubled; surface charge density as high as 1.5 mC/m^2 has been achieved, which is 3.5 times larger than that of Teflon AF. Note that the charges are stable and the surface voltage remains constant over 4,000 hours.

Figure 5 shows the thermally-stimulated-discharge (TSD) spectra of aminosilane-doped CTL-A in comparison with that of CTL-A and CTL-M. The peak temperature of TSD spectra of aminosilane-doped CTL-A is shifted to much higher temperature of 184°C. Therefore, not only the surface charge density but also the thermal stability are improved by doping of aminosilane into CYTOP.

3. Electret Power Generator

For electret generators, power output 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 avoid pull-in. Tsurumi et al. [18] found that electrostatic repulsion force can be obtained between opposed patterned electrets as shown in Fig. 6. Thus, in the present design, interdigitized electrets are formed both on the seismic mass and the bottom substrate to keep the gap constant. In addition, the two-phase arrangement [19] is employed to reduce the horizontal force.

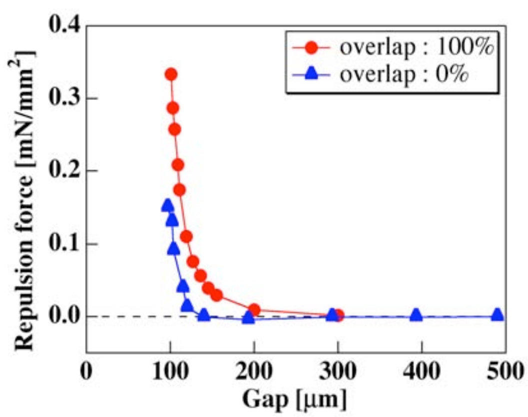

Figure 6. Repulsive electrostatic force between two patterned electret plates. Surface voltages of upper and lower electrets are respectively –1170 V and –980 V [18].

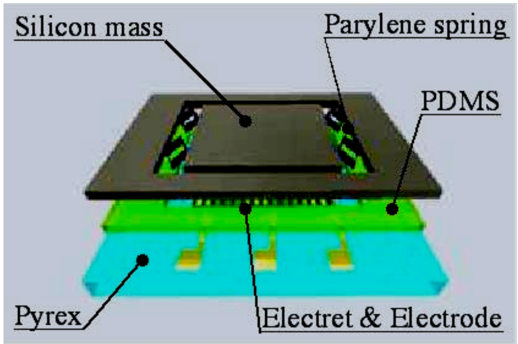

Figure 7. Schematic of the electret generator.

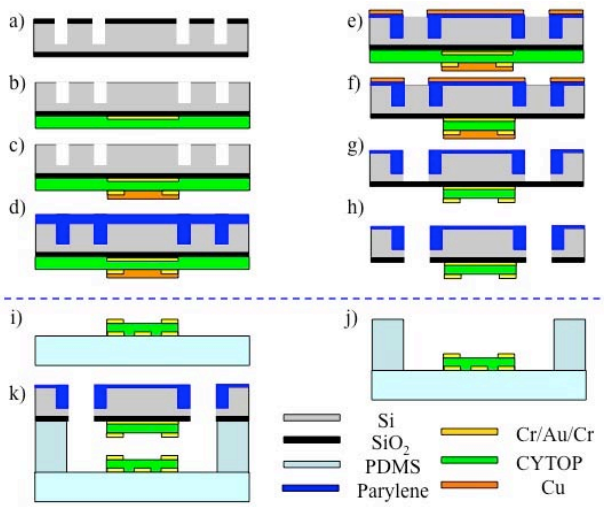

Figure 8. Fabrication process of the electret generator.

Figure 7 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 [20]. Patterned electrets and electrodes are formed both on the Si mass and the bottom Pyrex substrate. The gap between the substrates is defined with a PDMS layer. Designed values of the resonant frequency and the amplitude are respectively 37 Hz and 1.2 $mm_{p\text{-}p}$. Under this condition, theoretical power output estimated with the VDRG (Velocity-damped resonant generator) model [3] is 12 μW.

4. FABRICATION

Fabrication process of the electret generator is shown in Fig. 8. For the top substrate with a seismic mass, the process starts with a 400 μm-thick 4" Si wafer with 2 μm-thick thermal oxide. Using an oxide mask, 350 μm-deep trenches are etched into the substrate with DRIE (Fig. 8a). The trenches are used as the parylene molds. Then, bottom Cr/Au/Cr electrodes are evaporated on the backside and patterned, followed by forming of 15 μm-thick CYTOP (CTL-809M) films (Fig. 8b). Cr/Au/Cr electrodes on the top of CYTOP layer and a metal mask for CYTOP etching are evaporated and patterned (Fig. 8c). 15 μm-thick parylene-C is then deposited and etched back with O_2 plasma. Then, the second parylene layer 15 μm in thickness is deposited to fully refill the trenches (Fig. 8d). The parylene films and the CYTOP films are etched with O_2 plasma with the metal mask (Figs. 8ef). Finally, the Si substrate surrounding the mass is etched away with XeF_2 (Figs. 8gh). For the bottom Pyrex substrate, Cr/Au/Cr electrodes and CYTOP film are patterned (Fig. 8i). Then a PDMS spacer is bonded after O_2 plasma treatment (Fig. 8j).

After these processes, charges are implanted into CYTOP electret using corona charging for 3 minutes at 120 ˚C. The needle and grid voltages are respectively -8 kV and -600 V.

Figures 9 and 10 shows photographs of the generator prototype thus fabricated. The dimension of the device is 30 x 30 mm^2 (Fig. 9), while the size of the mass is 14.6 x 16 mm^2. The seismic mass is supported by the parylene springs, of which width is 25μm (Figs. 10bd). The width of the patterned electret and electrode is 150μm (Fig. 10c). The surface voltage of electret on the top Si substrate is -560 V,

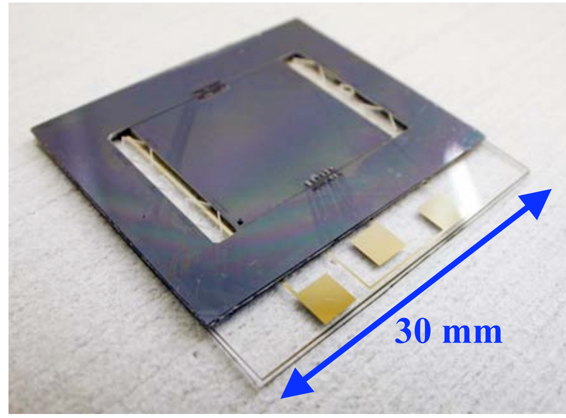

Figure 9. MEMS electret generator prototype.

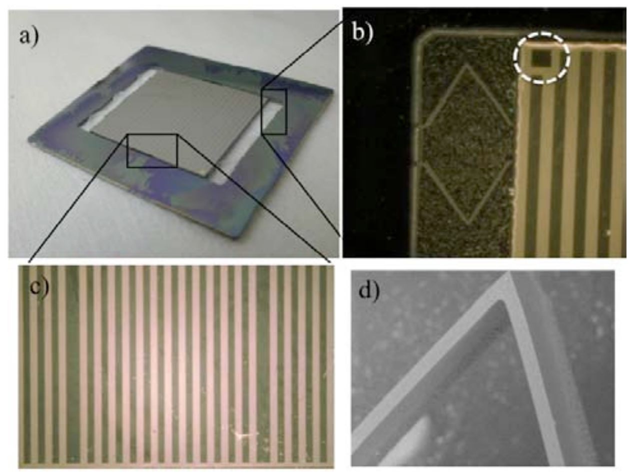

Figure 10. Backside of the top Si structure, a)Overview, b)Patterned electret on the seismic Si mass, c) Parylene high-aspect-ratio spring, d)SEM image of the parylene spring.

and that of on the bottom Pyrex substrate is -450 V. The gap between the electret and the electrode is 170 μm.

The micro electret generator is fixed on the shaker, and the device is oscillated in the in-plane direction at its resonant frequency of 37 Hz. Each phase is connected to an external load of 100 MΩ. The total output power is 0.28 μW, which is much smaller than the designed value of 12 μW [21]. 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. CONCLUSIONS

Vibration-driven electret generator for energy harvesting applications 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 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 output power of 0.28 μW with an external road of 100 MΩ.

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