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LOW-RESONANT-FREQUENCY MICRO ELECTRET GENERATOR FOR ENERGY HARVESTING APPLICATION

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ABSTRACT

A vibration-driven electret generator has been developed for energy harvesting applications. By using parylene as the spring material, a low-resonant-frequency MEMS generator is realized. Electrostatic levitation is adopted for the gap control. Large in-plane amplitude of 0.5 mm at the resonant frequency as low as 21 Hz has been achieved. We also demonstrate electret-powered operation of LED using a low-power-consumption impedance conversion circuit.

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 below 100 Hz, electret power generators [4-8] should have higher performance than electromagnetic counterparts.

We recently discover that CYTOP® (Asahi Glass), which is MEMS-friendly amorphous perfluoro-polymer, offers very high surface charge density [6]. Sakene et al. [9] has developed a new high-performance polymer electret material by doping aminosilane into CYTOP, and demonstrated 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.

In the present study, we microfabricate a prototype electret generator using the CYTOP electret and parylene high-aspect-ratio spring [10], which allows low resonant frequency and large amplitude. Electret-based non-contact bearing [11] is employed as the gap control method between electret and the counter electrode to prevent electrostatic pull-in. In addition, we also develop a novel energy managing circuit for impedance conversion and examine its performance systematically.

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. [11] found that electrostatic repulsion force can be obtained between opposed patterned electrets. Thus, in the present design, patterned electrets are formed both on the seismic mass and the bottom substrate to keep the gap constant.

In order to reduce the amplitude of horizontal eletrostatic force, two-phase configuration [12] is adopted, in which two separate generator circuits 180˚out-of-phase each other are integrated in a single seismic mass. A ceramic package filled with insulation gas is employed to prevent discharge between electrets and electrodes.

Figure 1 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 [10]. Patterned electrets and electrodes are formed both on the Si mass and the bottom Pyrex substrate. Designed values of the resonant frequency, the amplitude and the power output estimated with the VDRG (velocity-damped resonant generator) model [3] are respectively 74 Hz, 1.0 $mm_{p\text{-}p}$ and 2.0 μW. When 1.4 g mass is glued onto the seismic mass, the resonant frequency and the theoretical power output are respectively 20 Hz and 100 μW.

FABRICATION

Fabrication process of the electret generator is shown in Fig. 2. For the top Si 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 350 μm-deep trenches are etched into the substrate (Fig. 2a). 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. A metal mask for parylene etching is evaporated and patterned (Fig. 2b). Next, 15

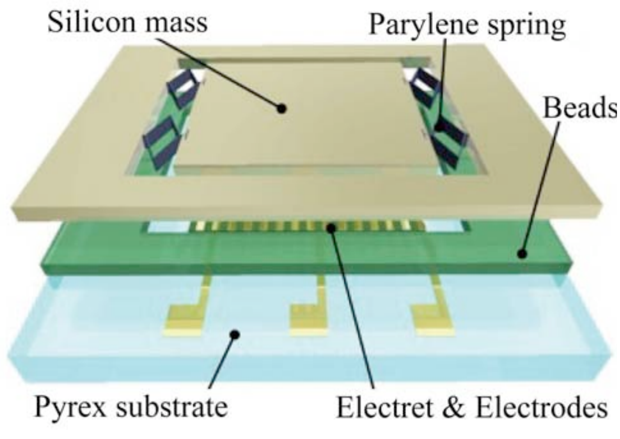

Figure 1. Schematic of the electret generator.

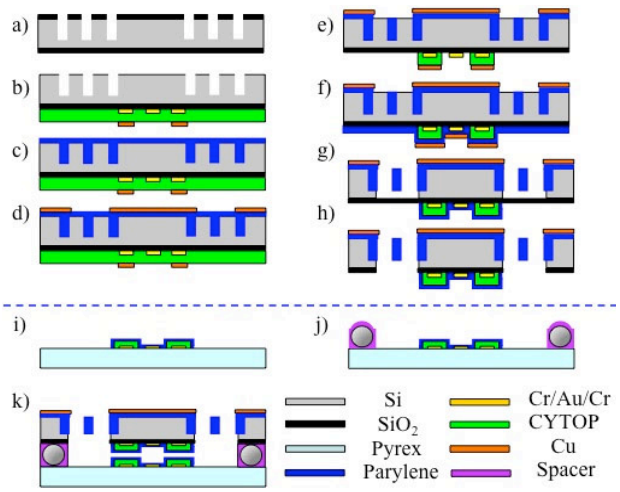

Figure 2. Fabrication process of the electret generator.

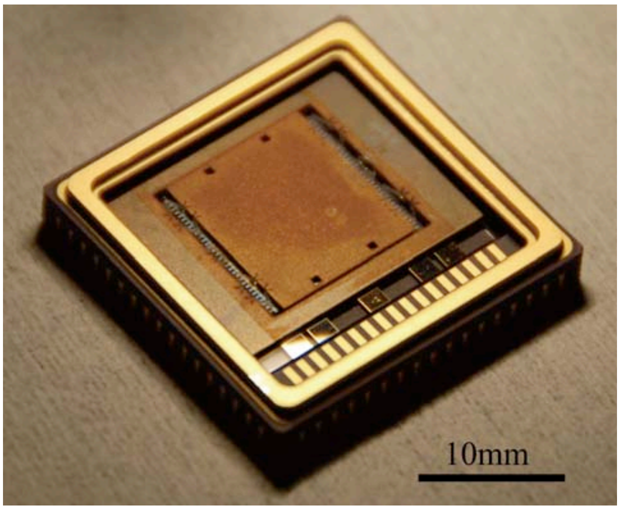

Figure 3. Electret generator prototype assembled in ceramic package.

µm-thick parylene-C is deposited on the front side and etched back with O_2 plasma. This is followed by the second parylene-C deposition to fully refill the trenches (Fig. 2c). After the metal mask for the parylene etching is patterned (Fig. 2d), the parylene and CYTOP films are etched with O_2 plasma (Fig. 2e). Another 5 µm-thick parylene layer is then deposited on the top of CYTOP and patterned with O_2 plasma (Fig. 2f). Finally, the Si substrate surrounding the Si mass is etched away with XeF_2 (Fig. 2g), and the structures are released with BOE (Fig. 2h). For the bottom substrate, after patterning Cr/Au/Cr electrodes on with a 700 µm-thick 4" Pyrex wafer, CYTOP and parylene films are deposited and patterned (Fig. 2i).

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 transition temperature of CYTOP. The needle and grid voltages are respectively -8 kV and -600 V. Then, micro beads, of which diameter is well defined, are mixed with epoxy adhesive and applied to the Pyrex substrate (Fig. 2j) as the spacer. Finally, the top Si substrate and the bottom Pyrex substrate are aligned and bonded in SF_6 atmosphere.

Figures 3-5 show photographs of the generator prototype thus fabricated. The dimensions of the device are 18.5 x 16.5 mm^2, while the size of the mass is 14.6 x 16 mm^2.

The seismic mass is supported by 25 µm-wide parylene springs (Figs. 4b, d). On the backside of the top substrate, 14 poles of patterned electrets are formed for each phase of the generator (Fig. 4c). The width of the patterned electret and electrode is 150 µm. On the bottom substrate, wire bonding pads for the two phase electrodes and the common ground are located.

MECHANICAL RESPONSE

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 with a digital microscope (CA-MN80, Keyence). Figure 6 shows the frequency response of the seismic mass. Its resonant frequency is 51 Hz with a quality factor of 7.49. When 1.4 g mass is added, the resonant

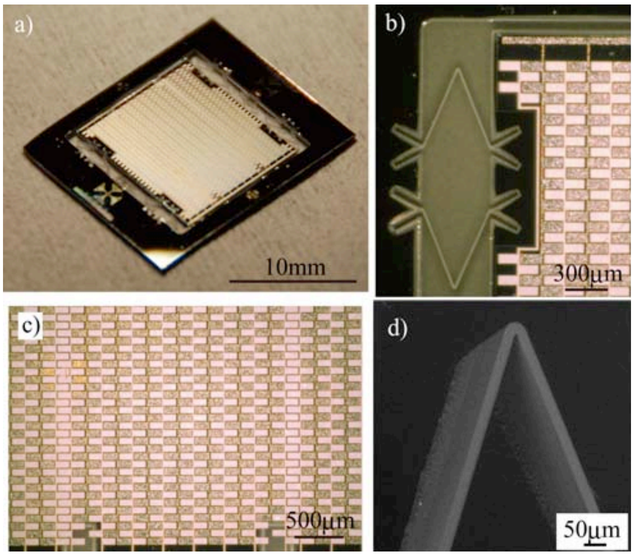

Figure 4. Backside of Si substrate. a)Overview, b)Parylene high-aspect-ratio spring and patterned electret, c)Magnified view of electret and electrodes in the two-phase configuration, d)SEM image of the parylene spring.

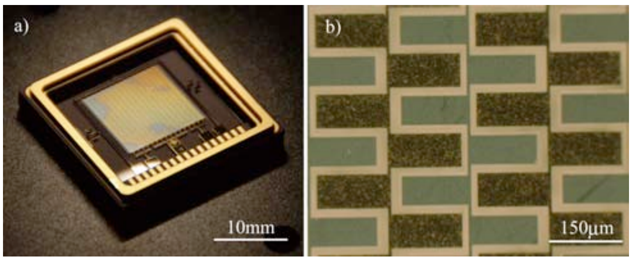

Figure 5. Bottom Pyrex substrate. a)Overview, b)Magnified view of checker-board-patterned electret and electrodes.

frequency becomes 21 Hz with a quality factor of 5.23. The maximum in-plane amplitude at the resonance is as large as 1.0 $mm_{p\text{-}p}$. Although the quality factor should be improved, the resonant frequency of the present seismic structure is sufficiently low for energy harvesting applications.

Figure 7 shows the experimental setup for the measurement of vertical electrostatic force between the top and bottom substrates. One of the substrates is fixed on an electric balance, and the other is mounted on a 5-axis alignment stage. The gap is measured with a high-precision laser displacement meter (LT-9500, Keyence). Figure 8 shows the electrostatic force. Repulsive force is obtained for the gap smaller than 150 μm when the both electrets are charged, while attractive force is induced when only one electret is charged. Thus, electrostatic levitation can be achieved with the present electret/electrode patterns.

Figure 9 shows the electrostatic force with alignment error of translational and rotational direction. With the present design, repulsive force is obtained even with translational alignment error of 1.2 mm and rotational alignment error of 1.4˚. Therefore, the repulsive force in the present design is robust for misalignment, which is inevitable during operation.

IMPEDANCE CONVERSION CIRCUIT

Since the output impedance of electret generators is inherently very high, an impedance conversion circuit is necessary to drive actual circuits. Figure 10 shows the circuit diagram of the energy managing circuit including rectifier, smoothing capacitor, and switching circuit. An array of transistors serves as a switch, which drives a LED intermittently. The present circuit requires no external power for wake-up, and consumes only 80 nA.

Figure 11a shows the output voltage of an electret generator with an output power of 12.5 μW and an output impedance of 8.2 MΩ. As shown in Fig. 11b, charges are continuously stored in the capacitor, and intermittently delivered to the LED. In this experiment, peak power

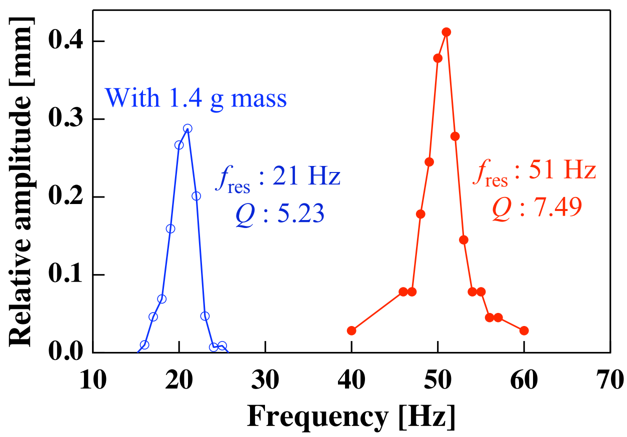

Figure 6. Frequency response of the electret generator.

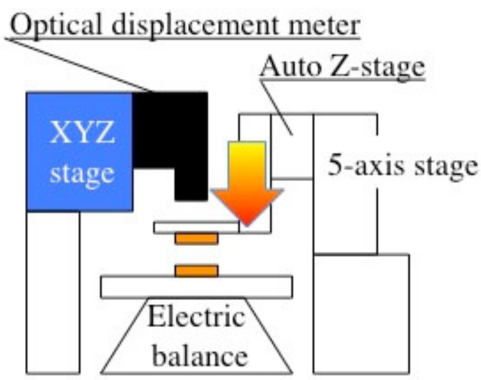

Figure 7. Schematic of the force measurement setup.

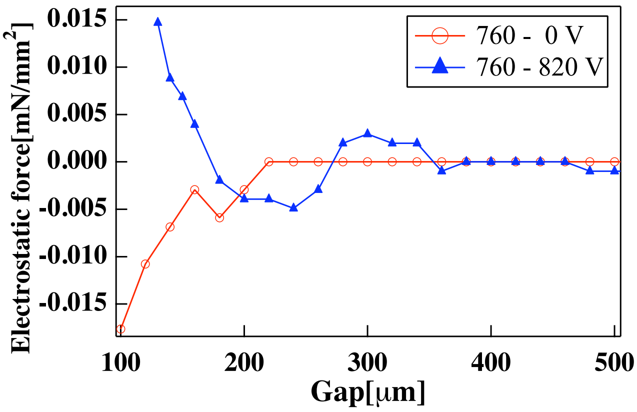

Figure 8. Electrostatic force between electret substrates versus the gap.

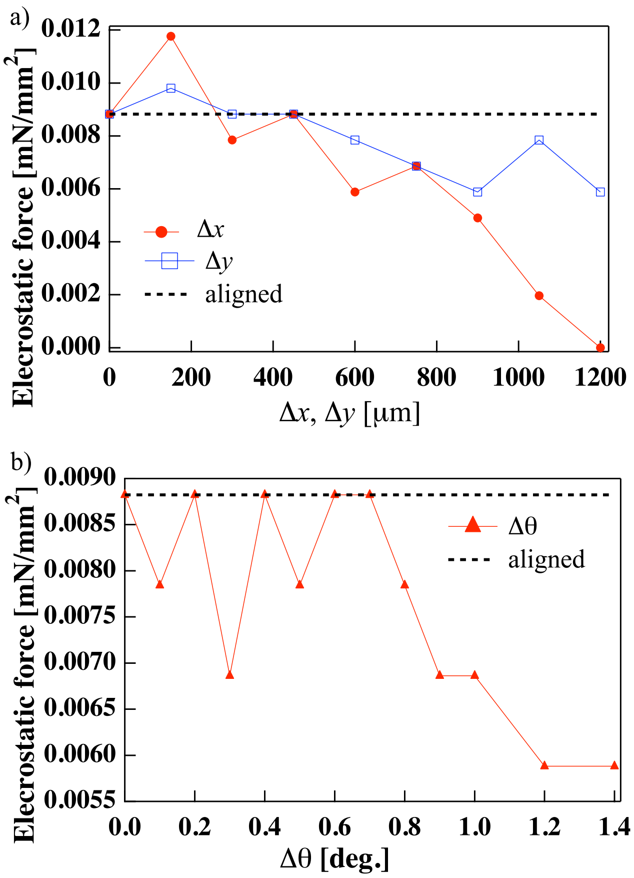

Figure 9. Electrostatic force between electret substrates with finite misalignment. a) Translational displacement, b) Rotational displacement.

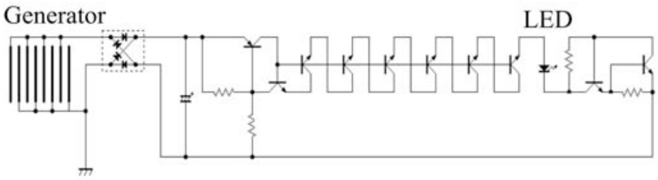

Figure 10. Power managing circuit for rectifying, smoothing and impedance conversion.

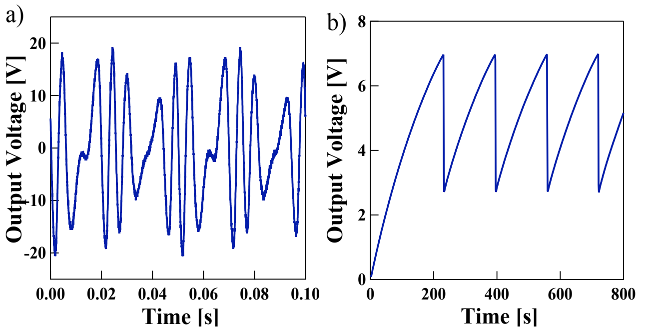

Figure 11. Time trace of the output voltage. a)Electret generator, b)Power managing circuit.

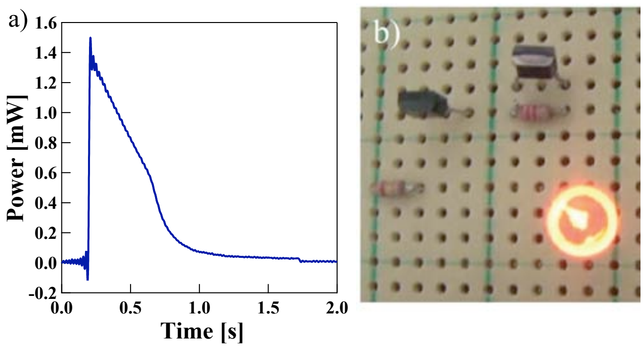

Figure 12. Intermittent operation of a LED. a)Output power, b)Photo. About 0.54 mJ is delivered to the LED for about 1 s with an interval of 165 s.

delivered to the LED is about 1.4 mW, and intermittent operation for about 1 s with an interval of 165 s is accomplished (Fig. 12). Since the output impedance of the present circuit is about 20 Ω, the impedance conversion ratio is as large as $4x10^5$.

CONCLCUSIONS

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 bottom substrates in order to keep the gap using electrostatic repulsive force. Resonant frequency as low as 21 Hz has been achieved with a large in-plane amplitude of 0.5 mm. With the aid of the patterned electrets on the both side of substrates, robust electrostatic levitation is achieved. We have also demonstrated that, with the present power management circuit, the impedance can be lowered by 400,000 times, and a LED can be intermittently operated using the power output of an electret generator with 12 μW output.

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