

Micro Electret Energy Harvesting Device with Analogue Impedance Conversion Circuit

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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. 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 μ W has been obtained. We also demonstrate electret-powered operation of LED using a low-power-consumption impedance conversion circuit.

Key words: Energy harvesting, Electret, CYTOP, Parylene spring, Impedance conversion

1. INTRODUCTION

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 [4-6] should have higher performance than electro-magnetic ones.

We recently discover that CYTOP® (Asahi Glass), which is MEMS-friendly amorphous perfluoro-polymer, can sustain very high surface charge density as a stable electret material [5]. We also develop a new high-performance polymer electret material based on CYTOP, and demonstrate that power output up to 0.69 mW can be obtained at an oscillation frequency as low as 20 Hz with the amplitude of 1.2 mm_{p-p} [7].

In the present study, we microfabricate a prototype electret generator using parylene high-aspect-ratio spring [8], which allows low resonant frequency and large amplitude, and electret-based non-contact bearing [9] for the gap control method between electret and the counter electrode. In addition, we also design a novel energy managing circuit for impedance conversion and examine its performance systematically.

2. IMPEDANCE CONVERSION CIRCUIT

Since the output impedance of electret generators is inherently very large, an impedance conversion circuit is necessary to drive actual electronic circuits. Figure 1 shows the circuit diagram of the energy managing circuit including rectifier, capacitor, and switching circuit using

discrete devices. 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 2a shows the output voltage of an electret generator with output power of 12.5 μ W and output impedance of 8.2 M Ω . As shown in Fig. 2b, charges are continuously stored in the capacitor, and intermittently delivered to the LED. In this experiment, peak power delivered to the LED is over 1 mW, and intermittent operation for about 1 s with an interval of 165 s is accomplished (Fig. 3). Since the output impedance of the present circuit is about 20 Ω , the impedance conversion ratio is as large as 4×10^5 .

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. [9] found that electrostatic repulsion force can be obtained between opposed patterned electrets. 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 [10] is employed to reduce the horizontal force.

Figure 4 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 [8]. 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-p}. Under this vibration condition, theoretical power output estimated with the VDRG (Velocity-damped resonant generator) model [3] is 12 μ W.

4. FABRICATION

Fabrication process of the electret generator is shown in Fig. 5. For the top substrate with a seismic mass, the process starts with a 400 μ m-thick 4" Si wafer with 2 μ m-thick thermal oxide. The oxide layer on the front side is patterned with BOE for the etch mask of DRIE, and 350 μ m-deep trenches are etched into the substrate

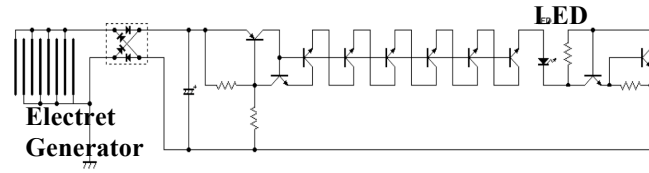


Figure 1. Power managing circuit for rectifying, smoothing and impedance conversion.

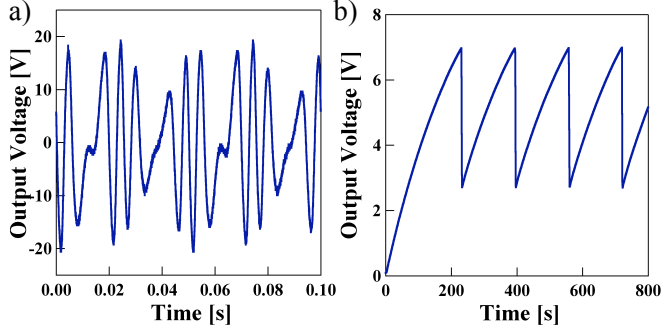


Figure 2. Time trace of the output voltage. a)Electret generator, b)Power managing circuit.

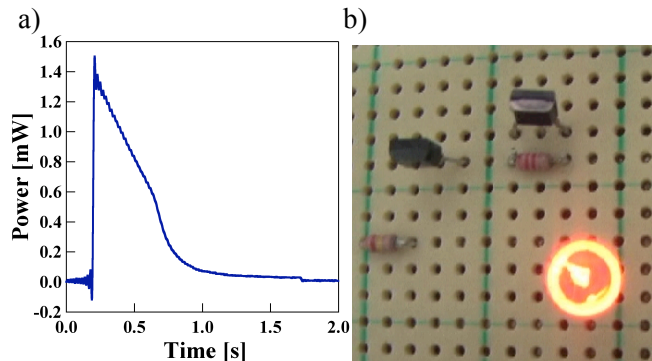


Figure 3. Intermittent operation of a LED. a)Output power, b)Photo. About 0.54 mJ is delivered to the LED for about 1 s with an interval of 165 s.

(Fig. 5a). The trenches are used as the parylene molds. Some of the 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 μ m-thick CYTOP (CTL-809M) films and curing at 185 $^{\circ}$ C for 1.5 hours (Fig. 5b). Cr/Au/Cr electrodes on the top of CYTOP layer and a metal mask for CYTOP etching are evaporated and patterned (Fig. 5c). 15 μ m-thick parylene-C is then deposited and etched back with O₂ plasma. Then, the second parylene layer 15 μ m in thickness is deposited to fully refill the trenches (Fig. 5d). After a metal mask for the parylene etching is patterned (Fig. 5e), the parylene films and the CYTOP films are etched with O₂ plasma (Fig. 5f). Finally, the Si substrate surrounding the mass is etched away with XeF₂ (Fig. 5g), and the structures are released with BOE (Fig. 5h).

For the bottom substrate, the process starts with a 700 μ m-thick 4" Pyrex wafer. Cr/Au/Cr electrodes and CYTOP film are patterned (Fig. 5i). Then a PDMS spacer is bonded after O₂ plasma treatment (Fig. 5j).

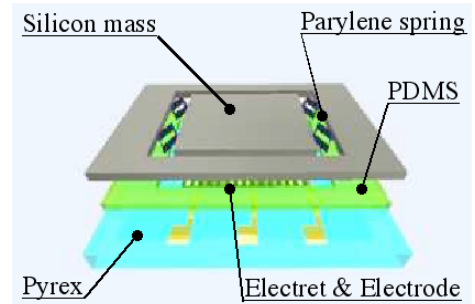


Figure 4. Schematic of the electret generator.

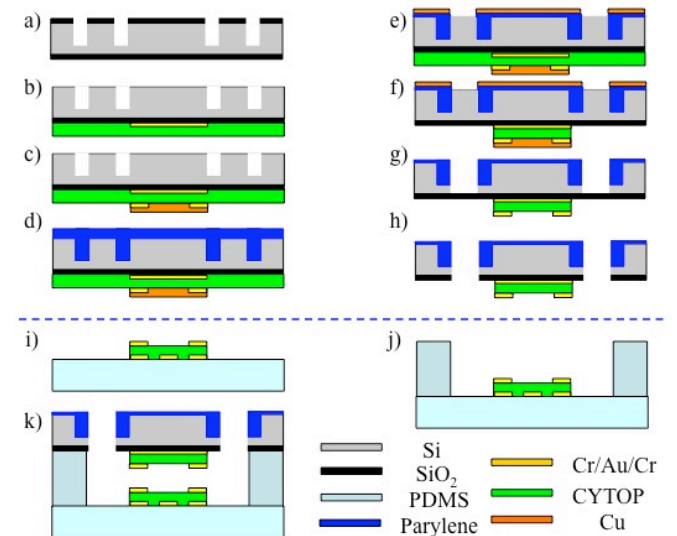


Figure 5. Fabrication process of the electret generator.

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. The top Si substrate and the bottom Pyrex substrate are finally bonded together with a PDMS spacer.

Figures 6 and 7 show photographs of the generator prototype thus fabricated. The dimension of the device is 30 x 30 mm² (Fig. 6), while the size of the mass is 14.6 x 16 mm². The seismic mass is supported by 25 μm-wide high-aspect-ratio parylene springs (Figs. 7b, d). On the backside of the top Si substrate, 14 poles of electrets are patterned for each phase of the generator (Fig. 7c). The width of the patterned electrets and electrodes is 150 μm. On the bottom Pyrex substrate, patterned electrets and electrodes as well as pads for external connection are located. The surface voltage of electrets on the Si substrate is -560 V, and that of on the Pyrex substrate is -450 V. The air gap between the substrates is 170 μm.

5. 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 (CA-MN80, Keyence). Figure 8 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 resonant frequency of the present seismic structure is sufficiently low for energy harvesting applications.

Figure 9 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. Each phase is connected to an external load of 100 MΩ.

Figure 10 shows the time trace of the output voltage. The peak-to-peak voltages 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 the designed value of 12 μW. This is partially due to the fact that the alignment between the top and bottom electrodes is poor, so that the rate of change of the overlapping area is much smaller than the designed value.

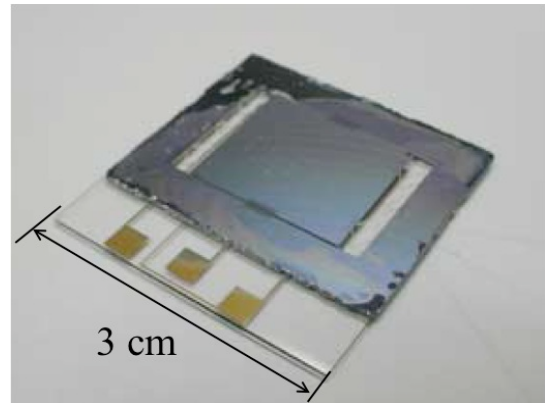


Figure 6. MEMS electret generator prototype.

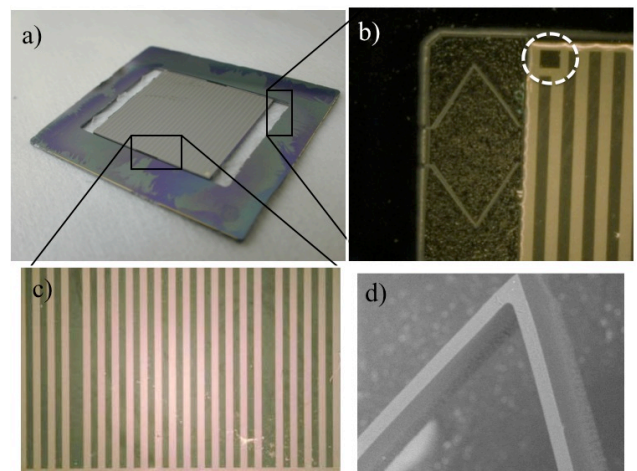


Figure 7. Backside of the top Si structure, a)Overview, b)Conduction hole on the electret and parylene high-aspect-ratio spring, c)Patterned electret on the seismic Si mass, d)SEM image of the parylene spring.

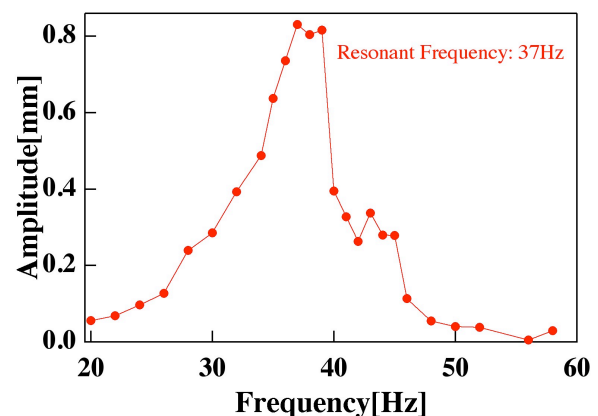


Figure 8. Frequency response of the generator.

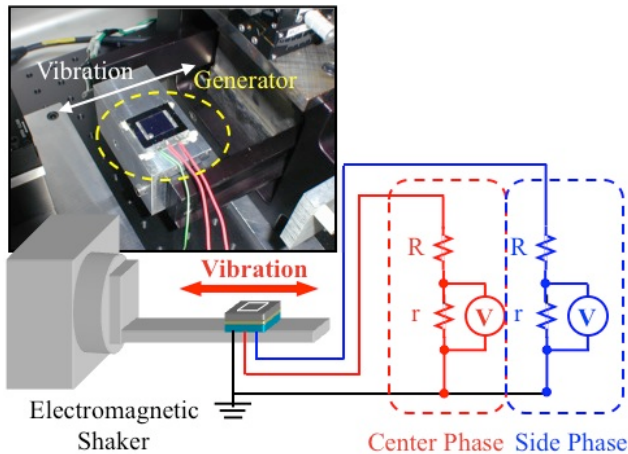


Figure 9. Experimental setup of power generation.

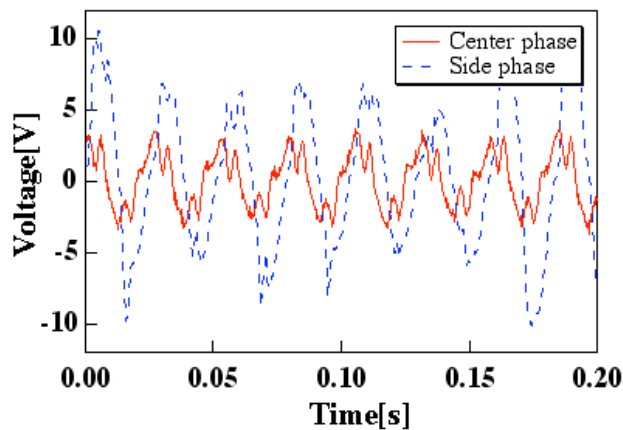


Figure 10. Time trace of the output voltage. The peak-to-peak voltages are 7.39 V and 20.8 V.

6. CONCLUSIONS

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 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 μ W with an external load of 100 M Ω . We have also demonstrated that 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 μ W output.

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REFERENCES

- [1] S. P. Beeby, M. J. Tudor, and N. M. White, "Energy harvesting vibration sources for micro systems applications," *Meas. Sci. Technol.*, Vol. 17, pp.175-195, 2006.
- [2] J. A. Paradiso, and T. Starner, "Energy scavenging for mobile and wireless electronics," *IEEE Pervasive Comp.*, Vol. 4, pp. 18-27, 2005.
- [3] P. D. Micheson, T. C. Green, E. M. Yeatman, and A. S. Holmes, "Architectures for vibration-driven micropower generators," *J. Microelectromech. Syst.*, Vol. 13, pp. 429-440, 2004.
- [4] J. Borland, Y.-H. Chao, Y. Suzuki, and Y.-C. Tai, "Micro electret power generator," *Proc. 16th IEEE Int. Conf. MEMS*, Kyoto, pp. 538-541, 2003.
- [5] T. Tsutsumino, Y. Suzuki, N. Kasagi, and Y. Sakane, "Seismic power generator using high-performance polymer electret," *Proc.19th IEEE Int. Conf. MEMS*, Istanbul, pp. 98-101, 2006.
- [6] H.-W. Lo, and Y.-C. Tai, "Parylene-based electret power generators," *J. Micromech. Microeng.*, Vol. 18, 104006, 8pp, 2008.
- [7] Y. Sakane, Y. Suzuki, and N. Kasagi, "Development of high-performance perfluorinated polymer electret film and its application to micro power generation," *J. Micromech. Microeng.*, Vol. 18, 104011, 6pp, 2008.
- [8] Y. Suzuki, and Y. Tai, "Micromachined high-aspect-ratio parylene spring and its application to low-frequency accelerometers," *J. Microelectromech. Syst.*, Vol. 15, pp.1364-1370, 2006.
- [9] Y. Tsurumi, Y. Suzuki, and N. Kasagi, "Non-contact electrostatic micro-bearing using polymer electret," *Proc. 21th IEEE Int. Conf. MEMS*, Tucson, pp. 511-514, 2008.
- [10] Marboutin, C., Suzuki, Y., and Kasagi, N., "Optimal design of micro electret generator for energy harvesting," *7th Int. Workshop Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2007)*, Freiburg, pp. 141-144, 2007.