

High-Performance Polymer Electret for Micro Seismic Generator

Takumi Tsutsumino, Yuji Suzuki, Nobuhide Kasagi, and Yukinori Tsurumi

Department of Mechanical Engineering, The University of Tokyo

7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-8656, Japan

Tel +81-3-5841-6419, Fax +81-3-5800-6999, E-mail tsutsumino@thtlab.t.u-tokyo.ac.jp

Abstract

Development of micro seismic generator for energy harvesting applications is presented. In order to fabricate MEMS-friendly high-performance electret film, CYTOP is adopted as an electret material and the charge density and the charge stability of CYTOP is experimentally characterized. When corona charging is employed, charge density as large as 2.8 mC/m² is obtained for 3 μm-thick CYTOP film, which is 3 times larger than that of Teflon AF. It is found in thermally-stimulated discharge measurement that charge implanted in CYTOP is stable at least up to its glass transition temperature. In power generation experiments using a prototype seismic generator, maximum output power of 6.4 μW is obtained with 1 mm_{p-p} oscillation at 20 Hz. It is also found that the trend of the experimental data is in good accordance with that of the theoretical prediction.

Keywords: Micro power generation, Energy harvesting, Polymer electret, CYTOP

1. INTRODUCTION

In the last decade, micro power generation systems that could replace conventional secondary batteries have received significant attention. For low power consumption applications such as RF tags and mobile sensor networks, vibration-driven energy harvesting devices are proposed [1, 2]. Since the frequency range of the vibration existing in the environment is a few Hz to a few tens of Hz, electret power generators [3] should have higher performance than electromagnetic ones. Boland et al. [4] developed the first MEMS rotary electret generator and obtained 15 μW power output at 6,000 rpm. Since then, various studies have been made for micro electret power generator [5-8]. However, conventional electret materials such as SiO₂ and Teflon AF are employed in their studies, and power output results obtained with their prototypes are not directly compared with the theoretical values.

Arakawa et al. [7] report that CYTOP (Asahi glass Co., Ltd.), which is a MEMS-compatible amorphous perfluoropolymer, can also be used for an electret material. In the present study, we examine the performance of CYTOP electret in more detail, and make a series of power generation experiment using a prototype micro seismic generator.

2. ELECTRET POWER GENERATOR

The principle of electret power generators had been already

reported elsewhere [4, 7]. Figure 1 shows a schematic of the simplified generator structure, where σ , d , g , and A are respectively surface charge density, thickness of electret, gap between the electret and the counter electrode, and the overlapping area. Using a simple capacitance model, Boland et al. [4] show that maximum output power P_{MAX} and optimal external load R_{MAX} of the electret power generator can be given as follows:

$$P_{MAX} = \frac{\sigma^2 \cdot \frac{dA(t)}{dt}}{4\epsilon_0 \epsilon_1 \left(\frac{\epsilon_1 g}{\epsilon_2 d} + 1 \right)}, \quad (1)$$

$$R_{MAX} = \frac{1}{\epsilon_0} \frac{dA(t)}{dt} \left(\frac{d}{\epsilon_1} + \frac{g}{\epsilon_2} \right), \quad (2)$$

where ϵ_0 , ϵ_1 and ϵ_2 are respectively the permittivity of vacuum, dielectric constant of the electret material and that of air. Therefore, P_{MAX} is proportional to the squared surface charge density σ^2 , and is increased with increasing the thickness of electret d . On the other hand, R_{MAX} is independent of σ and linearly dependent on d and g . Since P_{MAX} is proportional to the time derivative of the overlapping area $dA(t)/dt$, while R_{MAX} is inversely proportional to $dA(t)/dt$, vibration frequency, vibration amplitude and the number of poles should also have large impact on the generator performance.

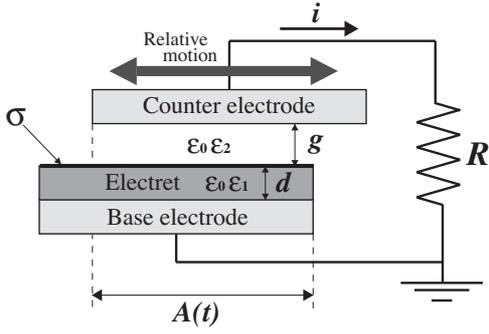


Figure 1. Schematic of electret generator.

3. POLYMER ELECTRET MATERIAL

Various kinds of materials have been examined for electrets [9]. Among them, polymer dielectric materials, especially fluoropolymer such as PTFE, are generally employed. Hsieh et al. [10] employ Teflon AF as the electret material for their MEMS microphone. In our previous study [7], we found that CYTOP (CTL-809M, Asahi Glass Co., Ltd.), which is also amorphous fluoropolymer, can be also used for electrets. The advantages of CYTOP over Teflon AF are three folds. Firstly, CYTOP has much larger dielectric strength of 110 kV/mm, so that the theoretical limit of the surface charge density is about five times as large as that of Teflon AF. Secondly, CYTOP can be spun-on multiple times, and films as thick as 20 μm can be easily made. Thirdly, CYTOP is easily patterned by O_2 plasma and compatible with MEMS fabrication process. Major properties of typical polymer electret materials are shown in Table 1. It is noted that the volume resistivity of CYTOP is two orders of magnitudes smaller than that of Teflon AF. However, Malecki [11] reports that resistivity of electret material has little effect on the time scale of the charge decay.

To evaluate the performance of CYTOP as an electret material, we measure temporal evolution of the surface charge density σ by a surface voltmeter (Model 279, Monroe Electronics). Figure 2 shows the data obtained for CYTOP and Teflon AF. Both samples have 3 μm in thickness, and corona-charged for 3 minutes. Although σ for CYTOP depends on the corona voltage, it is about 3 times larger than that of Teflon AF; σ as large as 2.8 mC/m^2 is obtained for -6 and -10 kV corona voltages. As mentioned previously in Eq. (1), maximum output power is proportional to square of σ , so that 9 times larger output power can be expected when CYTOP is employed as the electret material.

An open circuit thermally-stimulated discharge (TSD) measurement [12] is also performed for CYTOP and Teflon AF

electrets. Different TSD spectra peaks corresponds to a different charge trap mechanism in dielectric materials; the peak corresponding to the dipole appears at the lowest temperature near the glass transition temperature. Peaks at higher temperatures corresponds to the surface and bulk traps [12]. Therefore, TSD spectra are very useful for optimizing charging conditions and materials for more stable electrets. We fabricate 3 μm -thick CYTOP and Teflon AF electrets on 0.3 mm-thick copper plates having area of 30 x 30 mm^2 . The samples are corona-charged

Table 1. Properties of electret materials.

	CYTOP	Teflon AF	PTFE
Dielectric constant	2.1	1.9	2.1
Volume resistivity	$10^{17} \Omega\text{cm}$	$>10^{19} \Omega\text{cm}$	$>10^{18} \Omega\text{cm}$
Glass tans. temp.	108 $^\circ\text{C}$	160 $^\circ\text{C}$	130 $^\circ\text{C}$
Dielectric strength	110 kV/mm	21 kV/mm	18 kV/mm
Molecular structure	$[-\text{CF}_2-\text{CF}(\text{CF}_2)_2-\text{CF}(\text{CF}_2)-]_n$	$[(\text{CF}_2-\text{CF}_2)_x(\text{CF}-\text{CF}_2)_y]_n$	$[-\text{CF}_2-\text{CF}_2-]_n$

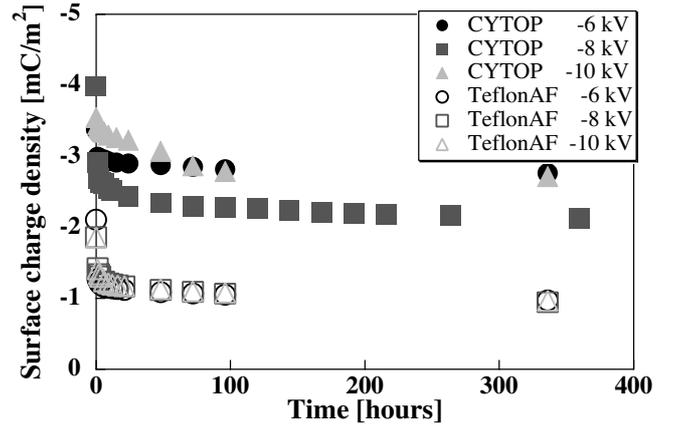


Figure 2. Temporal evolution of surface charge density for corona-charged CYTOP and Teflon AF.

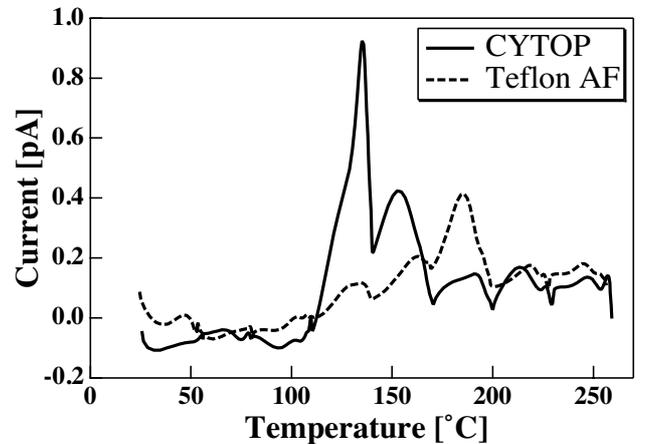


Figure 3. TSD current spectra of CYTOP and Teflon AF charged at 120 $^\circ\text{C}$.

with -8 kV voltage for 3 minutes at 120 °C, and then their temperature is ramped at a rate of 1 °C/min. The discharge current is measured with an electrometer (R8340A, Advantest Corp.).

Figure 3 shows the TSD spectra obtained in our preliminary experiment. The spectra for CYTOP exhibit 2 peaks at 135 °C and 150 °C. Since the glass transition temperature T_g of CYTOP is 108 °C, it is clear that the electret using CYTOP is stable at higher temperature than T_g . Similarly, the spectra for Teflon AF also have a peak at 185 °C that is higher than T_g of Teflon AF (= 160 °C). Since TSD spectra should depend on various conditions including the film thickness and the charging temperature, more detailed analysis should be needed to characterize the stability of CYTOP electrets.

4. POWER GENERATION

For power generation experiments, we develop a prototype electret generator using MEMS techniques. Figure 4 shows a patterned electret film on a glass substrate. Firstly, 20 μm thick CYTOP film is formed with multiple spin-on on Cr/Au/Cr interdigitized electrodes, and fully-cured by a bake at 185 °C for 90 minutes. Then, Cu is evaporated onto CYTOP and patterned for a metal mask. Finally, CYTOP is etched into a comb-like pattern using O₂ plasma, in order to increase the time derivative of the overlapping area $dA(t)/dt$. The width and the spacing of the electret is 1 mm, and the total area of the electret is 10 x 20 mm². For decreasing the unwanted effect of the parasitic capacitance, guard electrodes are formed between electret poles. Table 2 shows variation of the capacitance between the

Table 2. Variation of capacitance between a patterned electret and a patterned counter electrode.

Overlapping area	Without guard electrodes	With guard electrodes	Theoretical value
100%	39.8 pF	22.4 pF	17.7 pF
0%	25.4 pF	2.3 pF	0.0 pF

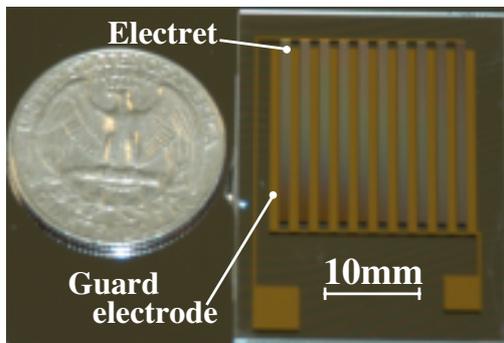


Figure 4. Glass substrate with patterned electret.

electret plate and the counter electrode plate for the gap $g = 100 \mu\text{m}$. It is found that the parasitic capacitance is significantly decreased with the guard electrodes.

Figure 5 shows an experimental setup for power generation, which consists of the electret plate, the counter electrode plate, an alignment stage, and an electromagnetic shaker (ET-140, Labworks Inc.). The electret plate and the counter electrode plate are respectively fixed to the shaker and the alignment stage, and the gap is set to be 100 μm. The counter electrode plate is moved sinusoidally in the horizontal direction by the shaker. Its oscillation amplitude is set to 1 mm_{p-p} and the frequency f is changed between 5 and 20 Hz. The surface potential of the electret is about 600 V. In order to measure the output voltage for various external loads, a simple measuring circuit with a voltmeter and two resistances in series is employed.

Figure 6 shows the time trace of the output voltage obtained at 20 Hz with $R = 100 \text{ M}\Omega$. The output wave pattern is almost sinusoidal and its peak-to-peak voltage is as large as 80 V.

Figure 7 shows the power output versus the external load R at 5-20 Hz oscillation. Maximum output power of 6.4 μW is

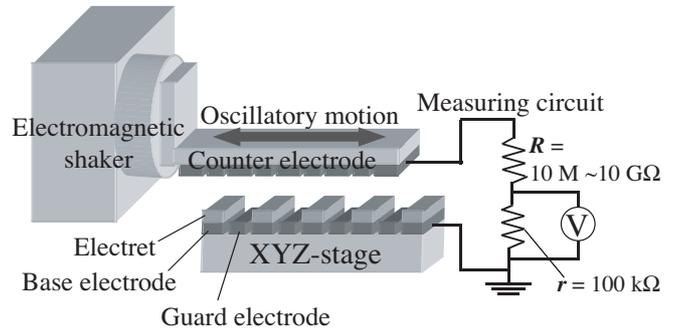


Figure 5. Schematic diagram of the experimental setup for power generation.

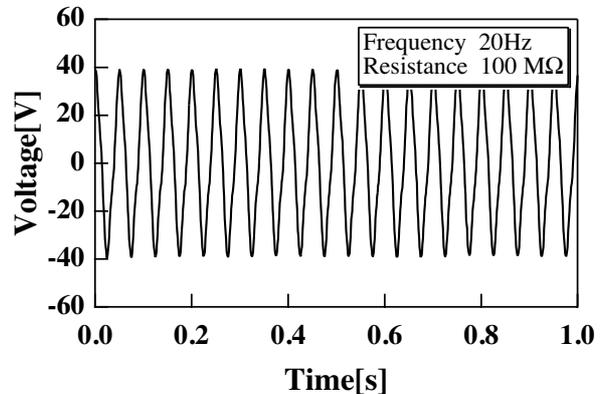


Figure 6. Time trace of the output voltage obtained with an electret generator prototype at 20Hz oscillation.

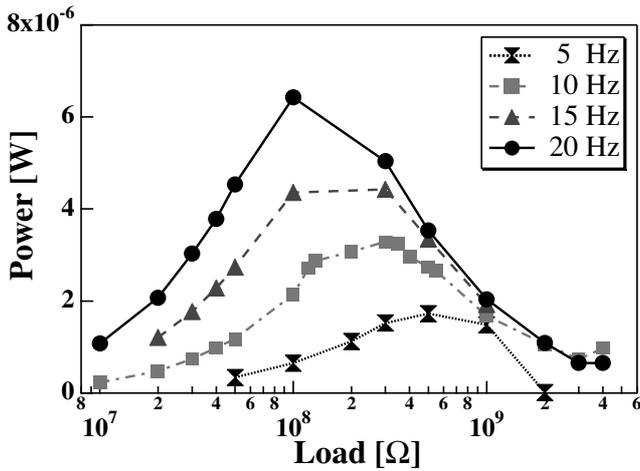


Figure 7. Power output versus external load.

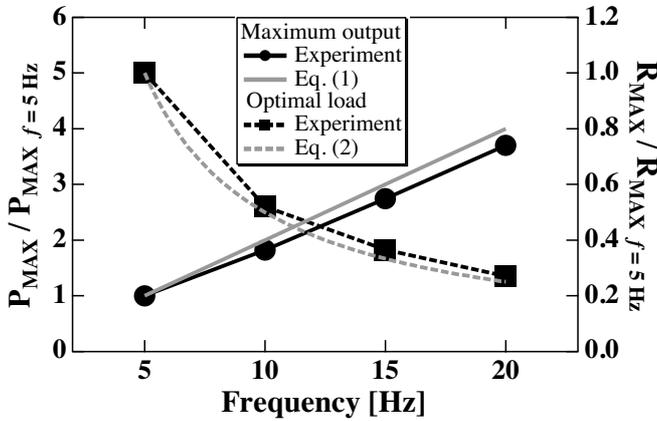


Figure 8. Maximum output power and optimal load versus oscillatory frequency. Both quantities are normalized with those values at $f = 5$ Hz.

obtained at $f = 20$ Hz and $R = 100$ M Ω . At each frequency, the maximum output power and the optimal load are estimated with a curve fit to the experimental data and plotted in Fig. 8. Each quantity is normalized by its value at $f = 5$ Hz. It is found that the experimental data are in good agreement with the predicted values using Eqs. (1) and (2); the power output is proportional to the frequency, and the optimal load is inversely proportional to f .

5. CONCLUSION

We investigate the performance of CYTOP as an electret material, and develop a prototype of micro seismic power generator using MEMS technologies. The following conclusions can be drawn.

(1) CYTOP is superior to Teflon AF as an electret material. Surface charge density obtained is about 3 times larger than

that of Teflon AF.

(2) Charges trapped in CYTOP are found to be stable at least up to its glass transition temperature.

(3) With a prototype seismic generator, maximum output power of 6.4 μ W is obtained. The trend of the maximum output and the optimal load is in good accordance with that of the theoretical values.

ACKNOWLEDGMENT

We thank Messrs. K. Aosaki and Y. Sakane in Asahi Glass Co., Ltd. for fruitful discussion during the course of this study. The work is partially supported through Grant-in-Aid for Scientific Research (B) (No. 17360092) by MEXT, Japan.

REFERENCE

- [1] C. B. Williams, and R. B. Yates, *Sensors and Actuators, A*, Vol. 52, 1996, pp. 8-11.
- [2] N. N. H. Ching, H. Y. Wong, W. J. Li, P. W. H. Leong, and Z. Wen, *Sensors and Actuators*, Vol. 97-98, 2002, pp. 685-690.
- [3] Y. Tada, *IEEE Trans. Electrical Insulation*, Vol. 21, 1986, pp. 457-464.
- [4] J. Boland, C.-H. Chao, Y. Suzuki, and Y.-C. Tai, *Proc. 16th IEEE Int. Conf. MEMS*, Kyoto, 2003, pp. 538-541.
- [5] T. Sterken, P. Fiorini, K. Baert, G. Borghs, and R. Puers, *Proc. PowerMEMS 2004*, Kyoto, 2004, pp. 18-21.
- [6] T. Genda, S. Tanaka, and M. Esashi, *Proc. PowerMEMS 2004*, Kyoto, 2004, pp. 183-186.
- [7] Y. Arakawa, Y. Suzuki, and N. Kasagi, *Proc. PowerMEMS 2004*, Kyoto, 2004, pp. 187-190.
- [8] J. Boland, J. D. M. Messenger, H. W. Lo, and Y.-C. Tai, *Proc. 18th IEEE Int. Conf. MEMS*, Miami, 2005, pp. 618-621.
- [9] G. M. Sessler, *Electrets 3rd Edition*, Laplacian Press, 1998.
- [10] W. H. Hsieh, T. J. Yao, and Y.-C. Tai, *Int. Conf. Solid-state Sensors Actuators (Transducers' 99)*, Sendai, Japan.
- [11] J. A. Malecki, *Phys. Rev. B*, Vol. 59, 1999, pp. 9954-9960.
- [12] H. Seggern, *J. Appl. Phys.*, Vol. 50, 1979, pp. 2817-2821.