PARYLENE-HT-BASED ELECTRET ROTOR GENERATOR

Hsi-wen Lo and Yu-Chong Tai
California Institute of Technology, Pasadena, California, USA

ABSTRACT

A new micro power generator with parylene HT electret rotor is made. This generator uses parylene HT as a new electret material with a much superior charge density compared to teflon and CYTOP. The highest surface potential observed is 204.58 V/μm, equivalent to a surface charge density of 3.69 mC/m^2. The generator uses an electret rotor. The rotor is a piece of PEEK insulator block coated with a layer of corona-charged parylene HT. Both output electrodes are on the stator. The generator produces 17.98μW with 80MΩ load at 50Hz and 7.77μW with an 800MΩ load at 10Hz.

1. INTRODUCTION

To harvest energy from natural vibrations, human body motions and other vibration sources such as running cars has received much interest recently. With such energy harvesters, portable devices can have endless energy supply and remote sensors such as RFID can be "set and forget". Researchers have developed several methods to harvest vibration energy.

Most of the published works were focused on only two approaches: the electromagnetic paradigm [1-3], and the piezoelectric paradigm [4-6]. However, these approaches all have to count on the spring-proof-mass design so their performance is always limited to certain narrow bandwidth around the mechanical resonant frequency, while natural harvestable vibration power spectrum usually spans from low to ~100 Hz with higher energy in the low frequency end. To overcome these fundamental problems, the third approach of electret power generators without springs (hence no resonant frequency) emerged to have a major advantage of broadband operation, especially towards low frequency.

2. PARYLENE HT AS ELECTRET

Boland et al first introduced the Teflon AF electret power generator [7]. Since then, many researchers have explored new electret materials for power generation. Tsutsumino et al used CYTOP as the electret material and achieved 38μW at 20Hz [8]. Sterken et al demonstrated a generator using oxide as electret and generated 5μW at 500Hz with external biased voltages of 100V [9]. Among these explored materials, CYTOP is reported to have highest surface charge density, 1.37mC/m^2 [8].

Boland et al showed the maximum power output of an electret power generator is proportional to the surface charge density squared [10]. Therefore, it is desirable to find an electret material with high surface charge densities. Specialty Coating Systems introduced a new parylene variant, SCS Parylene HT, shown in Figure 1. Like other parylene variants, parylene HT is deposited via a room temperature chemical vapor deposition (CVD) process.

To implant charges onto parylene HT surfaces, corona charging technique is employed. The corona charging conditions are listed in Table 1. Automatic isoprobe surface potential measurement equipment is used to measure the special distribution of the surface potential of parylene HT. Figure 2 shows the distribution of surface potential per micron of parylene HT. The highest surface potential observed is 204.58 V/μm, equivalent to a surface charge density of 3.69 mC/m^2.

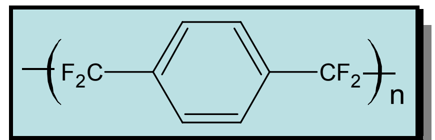

Figure 1. SCS Parylene HT from Specialty Coating Systems.

Base current	0.02 μA
Grid current	0.2 μA
Substrate Temperature	100 ^{o}C
Charging time	60 minutes

Table 1. Corona charging conditions

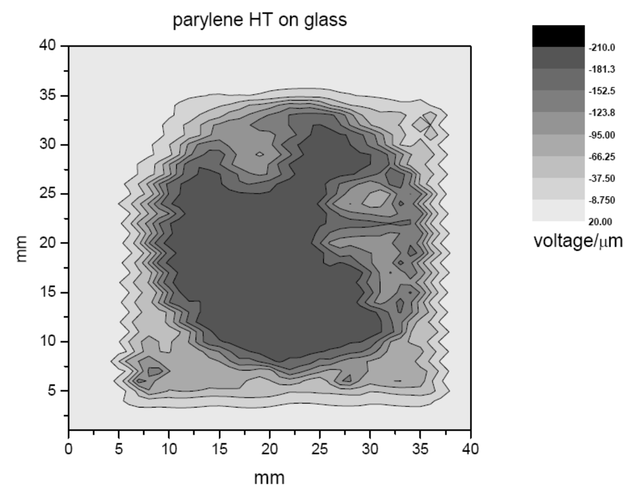

Figure 2. Distribution of surface potential per micron of 7.32-μm parylene HT film after corona charging.

To further improve the stability and long-term reliability of charged parylene HT film, we annealed parylene HT in nitrogen ambient at 500 ^{o}C, 400 ^{o}C and 300 ^{o}C for 1 hour and monitored the change of surface potential over time. Figure 3 shows the time evolution of surface potential of parylene HT annealed at different temperature. Compared to unannealed parylene HT, films annealed at 400^{o}C show improved stability. After 274 days, the surface charge density of parylene HT annealed at 400^{o}C was 1.477 mC/m^2, dropping from 1.625

mC/m^2 on the first day. The charging conditions for these samples are not optimized and therefore these samples don't have as high surface potential as shown in Figure 1.

3. ELECTRET ROTOR

Boland et al demonstrated the first design of micro electret power generators [10]. A capacitor-like configuration was employed, as shown in Figure 4. Since then, almost all electret power generators use the same design [8, 9]. Power generators taking such designs inevitably have internal capacitive impedance in addition to external loads.

From Boland et al [10] and Tsutsumino et al [8], the maximum power output can be given as

$$P_{MAX} = \frac{\sigma^2}{\frac{4\varepsilon_0\varepsilon_1}{d}\left(\frac{\varepsilon_1 g}{\varepsilon_2 d}+1\right)} \cdot \frac{dA(t)}{dt} \qquad (1)$$

Where ε_1, ε_2 are dielectric constants of electret and air respectively, ε_0 is vacuum permittivity, g is gap distance between top rotor and electret and d is the thickness of the electret. From this equation, the maximum power decreases as the gap distance increases. That said, careful and precise gap control is required to achieve high power output.

To eliminate hassles and complexity of gap control, we introduce a new design that put two output electrodes on the same sides. Besides, based on the fact that parylene HT deposition is a room-temperature CVD conformal coating process, we are able to make an electret rotor by coating an insulator with parylene HT and implanting charges on it while the stator is only a plate with predefined metal electrodes. The schematic of the generator with an electret rotor is shown in Figure 5.

Similarly, electricity is produced when a relative motion occurs between the rotor and the stator. This design requires no spring/proof-mass structure and does not have a resonant frequency so it's not frequency-limited. This gives a wider operating bandwidth extended into the important low-frequency end as long as the relative motion between the rotor and stator is created. As a result, this generator design is promising for human motion based power generation.

4. DEVICE FABRICATION

The fabrication of the device began with machining the rotor blocks, made of PEEK. The dimensions of the rotor blocks are 5mm by 6mm by 9mm (L by W by H). The stator is simply a piece of glass with predefined electrodes. 1500Å gold with 100Å Chromium is deposited on soda lime wafers and is then patterned to be 5mm by 5mm square pads with conventional photolithography.

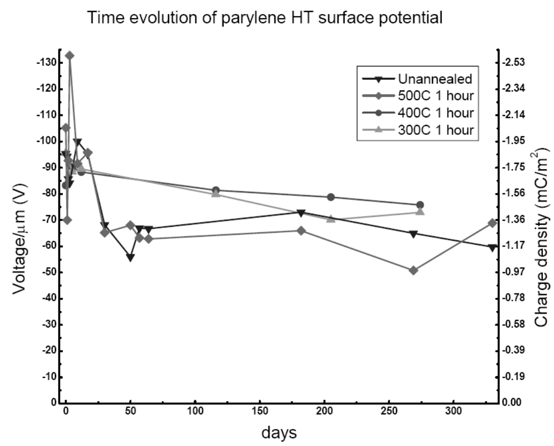

Figure 3. Time evolution of parylene HT surface potential after annealing at 500°C, 400°C and 300°C. Surface potential of unannealed samples was also measured as the baseline.

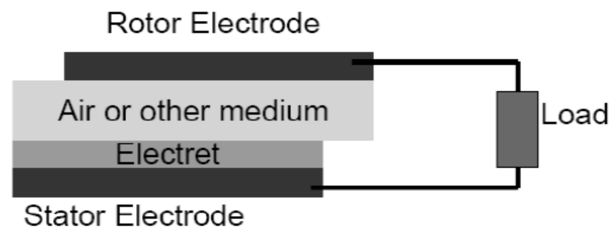

Figure 4. Conventional design of micro electret generator.

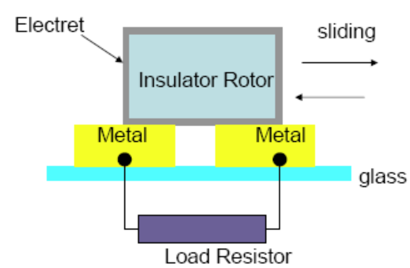

Figure 5. New design of micro electret generator with electret rotors. The output electrodes are both placed on the stator.

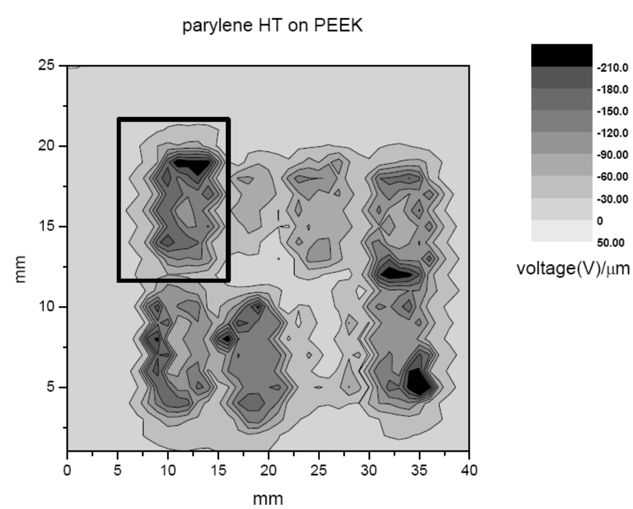

Figure 6. Distribution of surface potential per micron of 8 PEEK rotor blocks coated with parylene HT after charging.

7.32-μm Parylene HT is deposited onto the PEEK (polyetheretherkeytone) rotor, and is then charged via corona charging. Charging conditions are the same as Table 1.

Figure 6 shows the surface potential distribution of 8 pieces of PEEK rotor blocks after charging. An external acrylic packaging container was made to confine the movement of rotors. Figure 7 shows the PEEK rotor block, the electrode stator and the device assembly.

5. POWER GENERATION

The generator assembly was mounted onto a CNC-machined acrylic stage that is fixed to the electrodynamic shaker, as shown in Figure 7. All necessary wires were soldered. Power generation experiments were performed using a Labworks Inc. ET-132-2 electrodynamic shaker, which was driven sinusoidally by a HP33120A function generator through a power amplifier. The acceleration of the power generator was measured using an Endevco256HX-10 accelerometer. The micro electret power generator was connected to a resistive load. In order to measure large output voltages, a simple two-resistor voltage divider is used as the load. The output voltage was measured through a National Semiconductor LF356N op-amp, which is a 10^{12}-ohm input impedance voltage buffer. The shaking amplitude is defined by the external packaging container. For this device, the shaking amplitude is $1mm_{p-p}$. The frequency is varied from 10Hz to 70Hz and the load resistance from 50Mohm to 2000Mohm.

Figure 8 shows power output as a function of load resistance and Figure 9 shows power output as a function of frequency. The maximum power output, 17.98 μW was obtained at 50Hz with an external load of 80Mohm.

As the device is aimed to harvest power from natural vibrations, the low-frequency performance is of special interests. The parylene HT generator can harvest 7.7μW at 10Hz and 8.23μW at 20Hz.
Figure 10 and 11 show the time traces of voltage outputs at 50Hz and 10Hz with optimal loads.

To correctly assess the capability of a micro power generator, power density should be used. For our devices, the total volume including the external container is 50 cm^3. Taking that into consideration, the power density of this device is around 0.36μW per c.c. at 50Hz. It seemed very low. However, this device has a lot of unnecessary volume. Most of the unused volume comes from external package and the PEEK rotor blocks. To improve the power densities, one can carefully design an external packaging container that requires the least amount of volume. Besides, the PEEK rotor has a dimension of 5mm by 6mm by 9mm so that it has enough mass to overcome the electrostatic attraction forces between the rotor and stator electrodes during vibration. Choosing other insulating materials that have higher densities may further reduce the volume of the electret rotors and thus the total volume of the fabricated generator. Power density may further improved. Large-area and stackable designs can increase total power output.

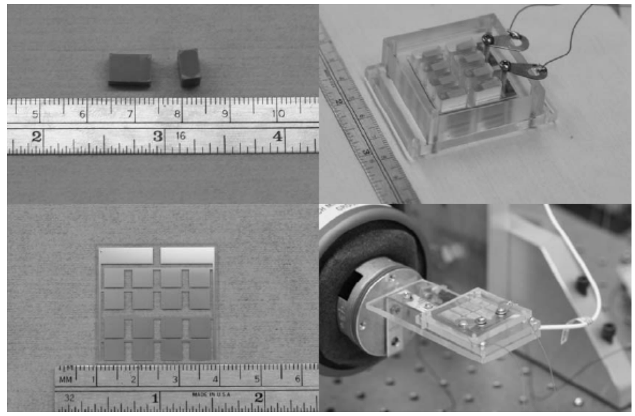

Figure 7. Device photographs. Top-left: PEEK rotors. Bottom left: stator with electrodes. Top-right: Assembled device. Bottom right: Generator mounted on the shaker.

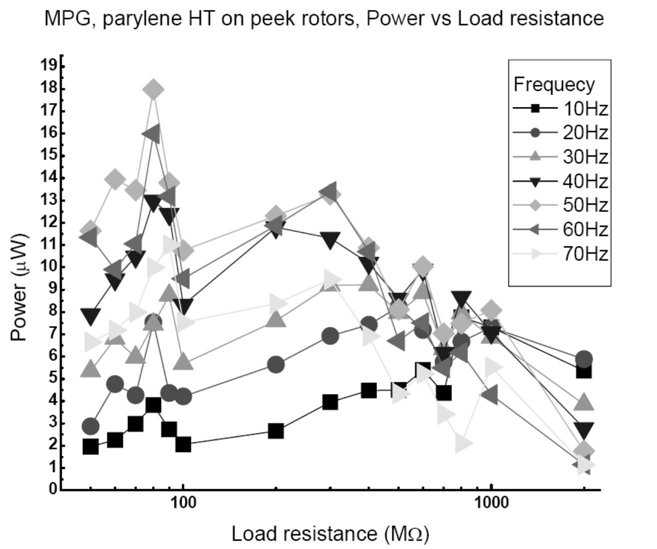

Figure 8. Power output at various frequencies versus load resistance.

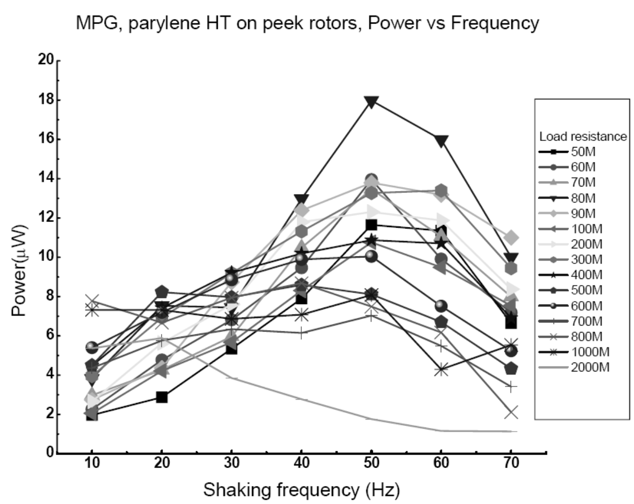

Figure 9. Power output with different load resistance versus frequencies.

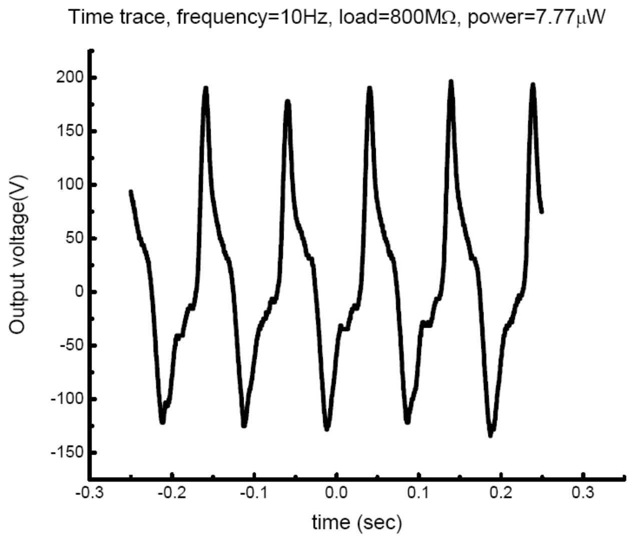

Figure 10. Output voltage at 10Hz with 800Mohm load.

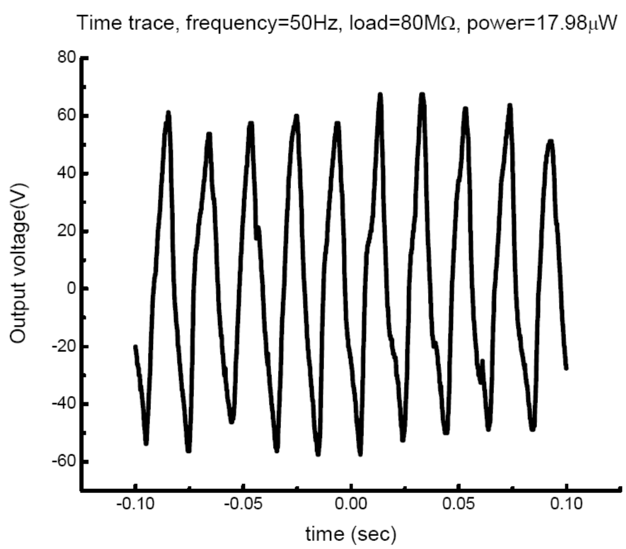

Figure 11. Output voltage at 50Hz with 80Mohm load.

6. CONCLUSION

We successfully demonstrated a new micro power electret generator that used parylene HT as the electret material and took a new design that both electrodes are on the stator plate and the rotor is an insulator blocks coated with electret material, parylene HT.

Charges were successfully implanted onto parylene HT film via corona charging. The highest surface charge density observed is 3.69 mC/m^2. To improve long-term charge-storing capability and stability, parylene HT film were annealed in nitrogen ambient. Parylene HT film annealed at 400^{o}C and 300^{o}C both show improved stability, compared to unannealed samples.

Power output from linear vibration motion was also measured. The maximum power output was 17.98 μW at 50Hz with an external load of 80Mohm. At low frequency ranges, this generator also produced decent power output. The power output was 7.7μW at 10Hz and 8.23μW at 20Hz.

ACKNOWLEGEMENT

The authors thank all members from Caltech Micromaching Laboratory for their assistance on design, fabrication and testing of this device.

REFERENCE

[1] S. Roundy, P. K. Wright, and K. S. J. Pister, "Micro-electrostatic vibration-to-electricity converters", *Proc. IMECE'02*, 2002.

[2] W. J. Li, Z. Wen, P. K. Wong, G. M. H. Chan, P. H. W. Leong, "A Micromachined Vibration-Induced Power Generator for Low Power Sensors of Robotic Systems", *Proc, World Automation Congress: 8th Intl. Symp. on Robotics with Applications,* 2000.

[3] C. B. Williams, and R. B. Yates," Analysis of a Micro-electric Generator for Microsystems," *Sensors and Actuators, A*, Vol. 52, 1996, pp. 8-11.

[4] G. K. Ottman, H. F. Hofmann, A. C. Bhatt, and G. A. Lesieutre, "Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply", I*EEE transaction on Power Electronics*, Vol. 17, No. 5, 2002.

[5] J.Kymissis, C. Kendall, J. Paradiso, and N. Gerhenfeld, "Parasitic power harvesting in shoes," *Proc. 2nd Int. Symp. Wearable Comput.*, Pittsburgh, PA, Oct. 19–20, 1998, pp. 132–139.

[6] N. Shenck and J. A. Paradiso, "Energy scavenging with shoe-mounted piezoelectrics," *IEEE Micro*, vol. 21, pp. 30–42, May-June 2001.

[7] J. S. Boland and Y. C. Tai, "Liquid-rotor electret micropower generator", *Solid-State Sensor, Actuator, and Microsystems Workshop*, 2004.

[8] T. Tsutsumino, Y. Suzuki, N. Kasagi, and Y. Sakane, "Seismic power generator using high-performance polymer electret", *Proc. Int. Conf. MEMS'06*, 2006

[9] T. Sterken, P. Fiorini, G. Altena, C. Van Hoof, and R. Puer, "Harvesting energy from vibrations by a micromachined electret generator", *Proc. Int. Conf. Transducers 2007*, 2007

[10] J. Boland, C.-H. Chao, Y. Suzuki, and Y.-C. Tai," Micro Electret Power Generator," *Proc. Int. Conf. MEMS'03*, 2003