DEVELOPMENT OF A MEMS ENERGY HARVESTER WITH HIGH-PERFORMANCE POLYMER ELECTRETS

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Abstract: Recent progress on high-performance polymer electrets based on CYTOP, novel charging methods using soft X-ray and vacuum UV, and development of MEMS energy harvesters are discussed. With the parylene high-aspect-ratio nonlinear springs and high-performance polymer electrets, we have successfully developed a MEMS electret generator for energy harvesting applications. With an acceleration of 1 G, about 4 µW has been obtained for a broad frequency range of 40-70 Hz.

Keywords: Energy harvesting, Polymer electret, Parylene springs, CYTOP

INTRODUCTION

Energy harvesting is a method to capture energy naturally present in the environment for powering low-power electronics [1-6]. As shown in Fig. 1, body heat, human motion, mechanical/structural vibration, radio frequency, and ambient light could be the energy source. Unlike solar or wind power plants for grid systems, energy harvesting devices provide electricity with high-added-value lasting for extremely long time period. Possible applications include wireless sensors for structural health monitoring, home/building energy management system (HEMS/BEMS), wireless ID tag for livestock industry, and automotive sensor such as tire pressure monitoring systems (TPMS). It is believed that energy harvesting devices could make contribution to reduce button battery consumption leading to reduction of hazardous waste in batteries.

Among the energy sources shown in Fig. 1, structural vibration is widely available in various applications. Since the vibration frequency range existing in the environment is below 100 Hz, electromagnetic/electret power generators should have higher power output than electromagnetic ones. In this paper, our recent progress of electret materials and electret generators for energy harvesting applications are discussed.

As energy conversion principles from kinetic energy of mass to electricity for energy harvesting, electromagnetic induction, piezoelectric, and electrostatic induction are used. Electromagnetic induction [7-9] prevails in macro scale, but it is not always the case in energy harvesting; since induction voltage is proportional to the area of coil and the relative speed between permanent magnet and coil, the power output is proportional to square values of those. Thus, the power output is decreased drastically for small-scale generators operating at low frequencies. In contrast, power output of piezoelectric and electrostatic induction is proportional to the frequency, which makes those principles are superior to electromagnetic counterpart.

Recently, various kinds of piezoelectric generators are prototyped using bulk PZT, thin-film PZT and AlN thin film [10-14]. In electrostatic induction generators in a narrow sense, electricity charged with an external circuit is magnified using variable capacitors [15-18].

The other type of electrostatic generators is the electret generator with self-bias voltage using electrets. Figure 2 shows three different configurations of electret generators. In this paper, our recent progress on high-performance polymer electrets, new charging methods, and MEMS generators are described with some brief review of the field.

Figure 1 Principles of energy harvesting.

Figure 2 Different configurations of electret generators (Top: gap closing type, middle: in-plane type, bottom: in-plane type with oscillating dielectric).
HIGH-PERFORMANCE ELECTRET AND CHARGING TECHNOLOGIES

Electret material can be divided into two groups, i.e., SiO$_2$-based inorganic electret and polymer-based organic electret [19]. SiO$_2$ offers extremely high surface charge density, but long-term stability of charges is of concern. To solve this problem, multi-layer structures using SiO$_2$ and Si$_3$N$_4$ are often used [20, 21]. On the other hand, fluorinated polymer materials such as PTFE and FEP provide better long-term stability. However, they are not compatible with MEMS processes, since they are insoluble in solvents. In addition, the surface charge density is insufficient for generators with high power output.

Hsieh et al. [22] and Boland et al. [23] employed Teflon AF (Du Pont Inc.) as their electret film, which is perfluorinated amorphous polymer. Lo and Tai [24] found that fluorinated parylene (parylene HT, SCS) provide very high surface charge density of 3.7 mC/m$^2$ with a 7.3-µm-thick film.

Sakane et al. [25, 26] recently reported that amorphous perfluorinated polymer CYTOP (Asahi Glass Co., Ltd.) can provide up to 4 times higher surface charge density than Teflon AF. They found that the end group of CYTOP has large effect on the charging characteristics. Figure 3 shows surface charge density of 15-µm-thick corona-charged electret samples. The needle voltage is -8 kV. During the corona charging, the samples were kept at 120 °C, which is slightly higher than the glass transition temperature ($T_g=108$ °C) of CYTOP. Surface potential was measured with a surface voltmeter (Model 279, Monroe Electronics). The surface charge density of CTL-M (amidosilyl end group) is as high as 1.3 mC/m$^2$, and is kept for more than 4,000 hrs. Implanted charges in CTL-A (carboxyl end group) are also stable, but the surface charge density is lower than that of CTL-M. On the other hand, CYTOP with no functional end group (CTL-S) and Teflon AF give low surface charge density. Also shown in Fig. 3 is the surface charge density of 15-µm-thick CTL-A with 3% aminosilane (3-aminopropyl (diethoxyl) methylsilane) coupling reagents in order to introduce larger number of amidosilyl molecules into the CYTOP structure. By doping only 3% of aminosilane into CTL-A, the surface charge density has been almost doubled; surface charge density as high as 1.5 mC/m$^2$ has been achieved.

Kashiwagi et al. [27] also developed aminosilane-doped CYTOP electrets, in which aminosilane-based nano clusters are formed. They have obtained extremely-high surface charge density more than 2 mC/m$^2$ with 15-µm-thick films (Fig. 4). It is also noted that additives to CYTOP also give better thermal stability of charges. Figure 5 shows the thermal stimulated discharge (TSD) spectra of aminosilanedoped CTL-A compared with that of CTL-S, CTL-A, CTL-M, and Teflon AF. The peak location of aminosilane-doped CYTOP is 184°C, which is much higher than other CYTOP materials and Teflon AF [26].

Corona charging, thermal poling, contact charging, and electron-beam irradiation are the methods for poling electrets [19]. Among them, corona charging is mostly widely used. By attracting corona ions with the electrostatic field between the grid and the substrate, charges are transferred from the ions to the electret surface. The surface potential of electrets after charging is usually the same as the grid voltage. It is
noted that optimization of various parameters in corona charging such as needle voltage, needle-grid and grid-sample distances is not a straightforward process and sometimes tricky.

Hsieh et al. [22] employed a back-lighted thyratron (BLT), in which a pulsed electron beam several millimeters in diameter and several keV in energy is formed. They charged 1.2-µm-thick Teflon AF for MEMS electret microphone, and obtained 0.6 mC/m². Mescheder et al. [28] employed ion implantation using phosphorous/boron to charge 500-nm-thick SiO₂ electrets, and obtained stable surface charge density of 7.5 mC/m².

Hagiwara et al. [29] recently developed a novel charging method using soft X-rays, in which X-rays ionize gas molecules and the ions are attracted to the electret surface by imposed electric field (Fig. 6). Since soft X-rays can penetrate substrates, even electrets can be charged after packaging the device. Hagiwara et al. [30, 31] also examined soft-X-ray-charged CYTOP electrets, and found that their stability is almost the same as those charged with corona discharge.

With the soft X-ray charging, Honzumi et al. [32] have developed vertical electrets in narrow gaps. While assembling is necessary for corona-charged electrets, comb-drive electret transducers can be developed with a single wafer approach as shown in Fig. 7. Yamashita et al. [33] has obtained 4 nW at 500 Hz and 15 G acceleration with their early prototype.

Honzumi et al. [34] has developed a high-speed charging method using vacuum UV. Since ionization rate of vacuum UV is much higher than that of soft X-ray, only a few seconds is necessary to achieve sufficiently-high stable surface potential of electrets as shown in Fig. 8.

**MEMS ELECTRET GENERATOR USING PARYLENE SPRINGS**

In in-plane electret generators, it is challenging to design a low-resonant-frequency spring system that enables large in-plane amplitude. In addition, the spring should have large out-of-plane spring constant in order to avoid stiction due to electrostatic force between electrets and electrodes.

High-aspect-ratio Si springs microfabricated on a Si or SOI substrate are often employed [35, 36]. Advantage of Si springs is that large Q factor can be obtained with relatively simple fabrication process. However, since Si is brittle, maximum amplitudes of those Si springs are on the order of 10 µm. Since power output is proportional to the oscillation amplitude, spring systems for larger amplitudes are required for large power output.

Suzuki and Tai [37] developed high-aspect-ratio parylene springs. Using parylene-C deposition onto a deep trench etched into a Si substrate as a mold, parylene springs with the aspect ratio up to 20 can be microfabricated. Since the Young’s modulus and the yield strain of parylene are respectively 4 GPa and 3 %, soft but robust springs can be realized.

Kamezawa et al. [38] examined thermal stability and fatigue strength of parylene high-aspect-ratio springs. As shown in Fig. 9, whereas parylene-C degrades in oxygen environment over 100 ºC, diX-HR (KISCO), which is a thermally-stable-grade parylene,
has better thermal tolerance over 140 ºC. Note that, in terms of thermal stability, fluorinated parylene such as parylene HT is superior to diX-HR. However, unlike parylene HT, diX-HR has almost the same deposition speed and large yield strain as parylene-C, so that diX-HR is suitable for mechanical elements. Kamezawa et al. also examined fatigue characteristics of the parylene beams at room temperature through cyclic load tests. They found no mechanical degradation up to 10^7 cycles at 1 % strain, indicating robustness of the parylene springs.

Various gap control methods have been investigated in order to avoid stiction. For instance, Naruse et al. [39] adopted the micro ball bearing [40] to realize large amplitude oscillation in their electret generator. Tsurumi et al. [41] and Suzuki et al. [42] developed a non-contact gap control method based on electrets as shown in Fig. 10. Both substrates have patterned electret strips with bottom electrodes. With the fringe field around the patterned electrets, repulsive force can be obtained between the substrates.

Figure 11 shows a schematic of our MEMS electret generator [42, 43]. The dimension of device is 18.5 x 16.5 mm^2. The top substrate consists of a Si proof mass supported with 20-µm-wide parylene high-aspect-ratio springs. Patterned electrets and electrodes in the dual-phase arrangement [44] are formed both on the Si mass and the bottom Pyrex substrate. The gap between the substrates is defined with micro beads. The size of the mass is 11.6 x 10.2 mm^2, of which weight is 0.1 g. The width of the patterned electret and electrode is 480 µm. Power output estimated with the present numerical simulation is 17 µW at the surface voltage of ~600 V.

Figures 12 show photographs of the generator prototype. The resonant frequency without added mass is 63 Hz with a quality factor of 8.6. In-plane amplitude at the resonance is as large as 1.8 mm_p-p_.

Another important feature of the present MEMS generator is the nonlinearity of the spring system for broadband response [45]. When the amplitude becomes large, the secondary spring is engaged and the effective spring constant is increased. Thus, the spring system behaves as a hardening spring, which broadens the frequency range of resonance.

Figure 13 shows the frequency response with 0.4 g mass at 1G, where large amplitude is obtained for a broad frequency range between 40 – 70 Hz when the

![Figure 9](image1.png)  
**Figure 9** Free-standing parylene-C (left) and diX-HR (right) beams after thermal annealing at 140 ºC for 5 hours [38]. Beam width and height are respectively 30 µm and 350 µm.

![Figure 10](image2.png)  
**Figure 10** Principle of electrostatic micro-bearing using polymer electret strips on both sides of the substrates [41, 42].

![Figure 11](image3.png)  
**Figure 11** In-plane electret generator with parylene high-aspect-ratio spring.

![Figure 12](image4.png)  
**Figure 12** MEMS electret generator [41,42]. a) Overview of the Si mass suspended with parylene springs. b) Integrated device in a ceramic package.
CONCLUSIONS

Our recent progress on high-performance electret materials, novel charging methods and MEMS energy harvesters are discussed. Applications of electret transducers should be enlarged by the new electret materials and the novel charging methods. With the parylene high-aspect-ratio nonlinear springs and high-performance polymer electrets, we have successfully developed a MEMS electret generator for energy harvesting applications. With an acceleration of 1 G, about 4 μW has been obtained for a broad frequency range of 40-70 Hz.

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REFERENCES


