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# A paper-based electrostatic kinetic energy harvester with stacked multiple electret films made of electrospun polymer nanofibers

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**Abstract.** This paper reports the first flexible electrostatic kinetic energy harvester (e-KEH) with electret nanofibrous films obtained by electrospinning and paper-based electrodes. The nanofibrous electret outperforms plenary thin film Parylene in the storage stability of charge: the surface potential is stabilized within 1 day, without any obvious minishing during the following 9 days. The output power of the device is improved by implementing multiple electret layers, where the optimal number of electret layer is 3. With a finger tapping activation, this first prototype with the optimal configuration gives a maximum peak power of 45.6  $\mu\text{W}$  with the optimal load of 16 M $\Omega$ . Working with a full-wave diode rectifier and a storage capacitor of 10nF, the voltage reaches 8.5 V with 450 strokes.

## 1. Introduction

Kinetic energy harvesters on soft substrates are applicable to wearable electronics. Previously reported works are mostly focused on either piezoelectric harvesters [1-3] or triboelectric nanogenerator [4]. Few others used thick materials as electret [5]. Both types can provide repetitive narrow peaks with pressing or bending external forces. In this work we present a flexible nanogenerator using multi-layered nanofibrous electret as the electrostatic source. The electret material is based on electrospun nanofibers with a thin layer of Parylene C, providing a charge storage stability even better than plenary Parylene films. The proposed device has a simple sandwich structure, and gives a maximum peak power of 45.6  $\mu\text{W}$ . The design is light-weighted and is less than 1mm in thickness.

## 2. Device geometry

A schematic and a photograph of the proposed device are shown in Figure 1. The device has a sandwich structure with top and bottom electrodes of copper tapes sticking on paper. Between the two electrodes is a foam-like structure – a stack of negatively-charged nanofibrous films.

The working principle of the device is shown in Figure 1(c). By applying a mechanical force on the electrodes, the gaps between the nanofibrous films reduce and the capacitance of the device changes. Consequently, the distribution of the induced charges in the two electrodes vary, according to the principle of the electrostatic transduction [6].



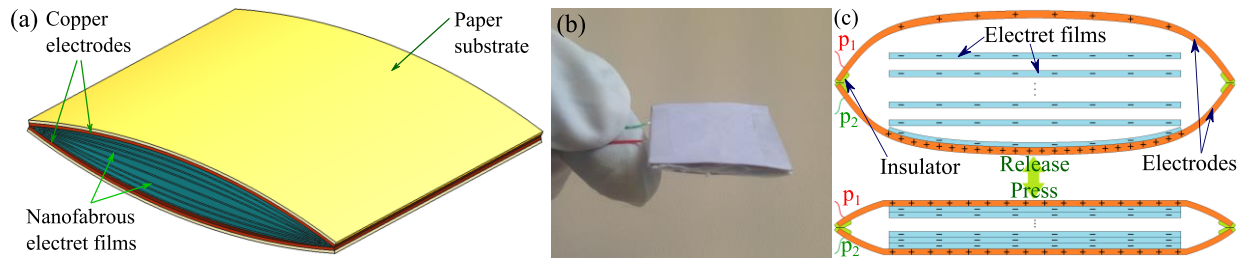


Figure 1. Schematic (a), photograph (b), and working principle (c) of the paper-based low-frequency e-KEH.

### 3. Material preparation

#### 3.1. Preparation of nanofibrous electret

The nanofibrous films are fabricated from PVDF/PTFE solution through electrospinning. The component of the solvent is acetone and DMF with the volume ratio of 1:1 at room temperature (weight ratio 1:1.32), while the weight ratio of PVDF and PTFE is 5:1. The total weight proportion of the polymers in the solution is 18%. To prepare the solution, the 2 solvents are mixed by magneto stirring method at 60 °C for 30 min, and the powder of the 2 polymers are put into the solvent and stirred for 24 h at the constant temperature of 60 °C. The stirring speed is 50 rpm.

During the electrospinning process, the distance between the point and the receiver electrodes is 15 cm, where the receiver is grounded and the high voltage of 13 kV is applied at the point electrode. The supply rate of the solution is 0.7 mL/h, and the electrospinning process lasts for 2 h in total. The nanofibrous materials obtained are then processed by an additional deposition of Parylene C through Chemical Vapor Deposition process. Shown in Figure 2 are the microscopic photographs of the electrospun nanofibers before and after Parylene C deposition.

#### 3.2. Precharging

The electret films are then charged by corona discharge at 12 kV/ 500 V/ 90 °C for 30 min. In Figure 3a, the comparison of the surface potential decay after corona charging are made between different materials: a) plenary Parylene C film, b) bare PVDF/PTFE nanofiber, c) PVDF/ PTFE nanofiber with Parylene C on top. Despite that the storage stability of charge in pure PVDF/PTFE nanofibrous material is quite poor (due to the property of the polymers themselves), the nanofibers covered by Parylene C provide even a higher storage stability than that of the plenary Parylene C. It is shown that the charge storage (surface potential) of the precharged PVDF/PTFE/Parylene material is stabilized within one day. With 2- $\mu$ m-thick Parylene C, the nanofiber film provides both (i) a highly porous and flexible structure and (ii) a relatively more stable surface potential.

As shown in Figure 3b, the initial surface potential of a stack of electret films increases linearly with the number of electret layers. Thus, the density of the induced charge on the electrodes is multiplied by increasing the number of electret layers, and increases the output capability of the device. However, this statement is true only for the case where the total thickness of the electret films is negligible compared to the size of the films, otherwise the adding effect of the surface potential minishes with the increase of the total film thickness: as for any e-KEH, energy conversion is obtained thanks to the device capacitance variation under external force.

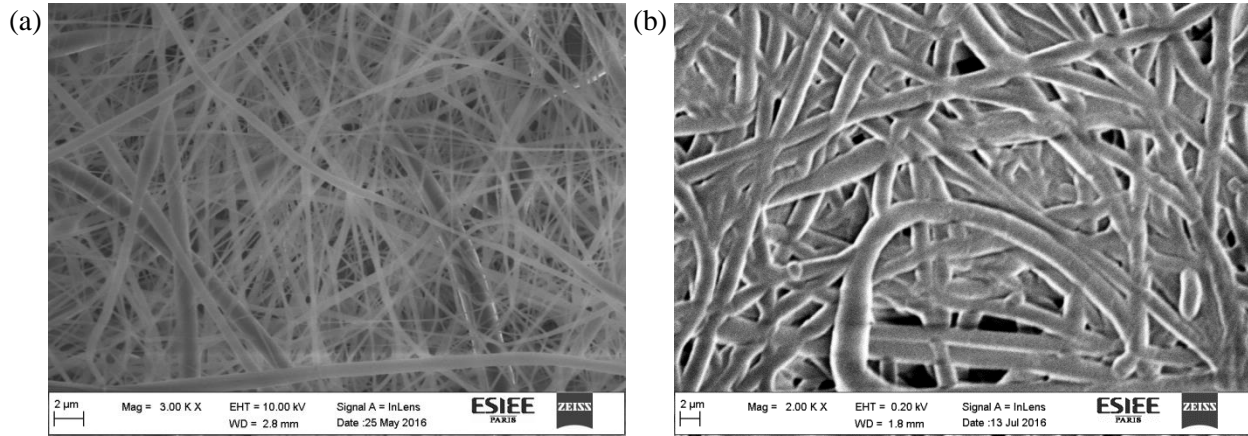


Figure 2. SEM Photograph of the electrospun nanofiber of PVDF/PTFE before (a) and after (b) CVD deposition of Parylene C

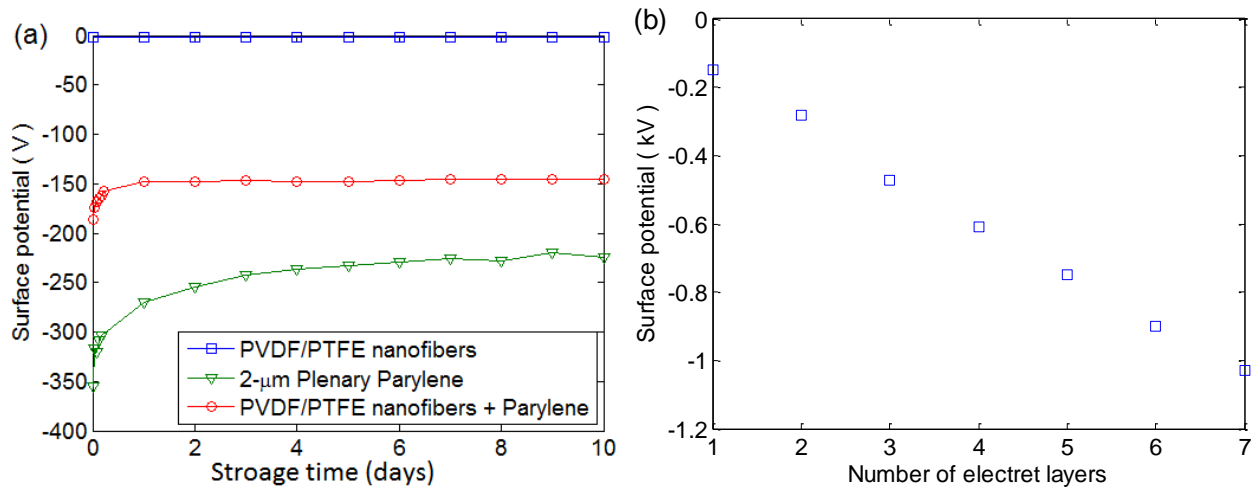


Figure 3. (a) Surface potential evolution of single-layer nanofabrous film after corona charging with and without parylene C. (b) Initial surface potential of stacked multi-layered nanofabrous electret.

#### 4. Device performance

The device is tested with a varying number of electret layers and with a sweeping load. The output performance of the device is shown in Figure 4. The transient output signal during the test is plotted as the inset of Figure 4a. The average peak value of the output pulses (voltage and power) are calculated accordingly, and the variation of these values are plotted with varied load and varied number of electret layers in Figures 4a-b. As shown in this inset, sharp pulses with large amplitudes and small timespan are generated repetitively with the same frequency of the excitation force.

The increased number of electret layers results in an increased amount of induced charge on the electrodes. At the same time the maximum capacitance is reduced due to a larger gap between electrodes while the minimum capacitance is kept approximately the same. Therefore, there is an optimal number of electret layers. By pressing and releasing the device with finger, we get the average peak voltage of 27 V with the load of 16 MΩ and 3 layers of electret material (optimal condition), corresponding to the optimal instantaneous output power of 45.6 μW.

In an experiment charging a 10 nF capacitor with a full-wave diode rectifier, the voltage reaches 8.5 V with 450 strokes. In this experiment, the energy harvested by each cycle is far less than the case with the optimal resistive load. The reason for this difference comes from the voltage drop of the diodes and the impedance mismatch effect. The power transmitted through the rectifier can be further improved if a better matching is reached, or reduce the voltage drop from the rectifier.

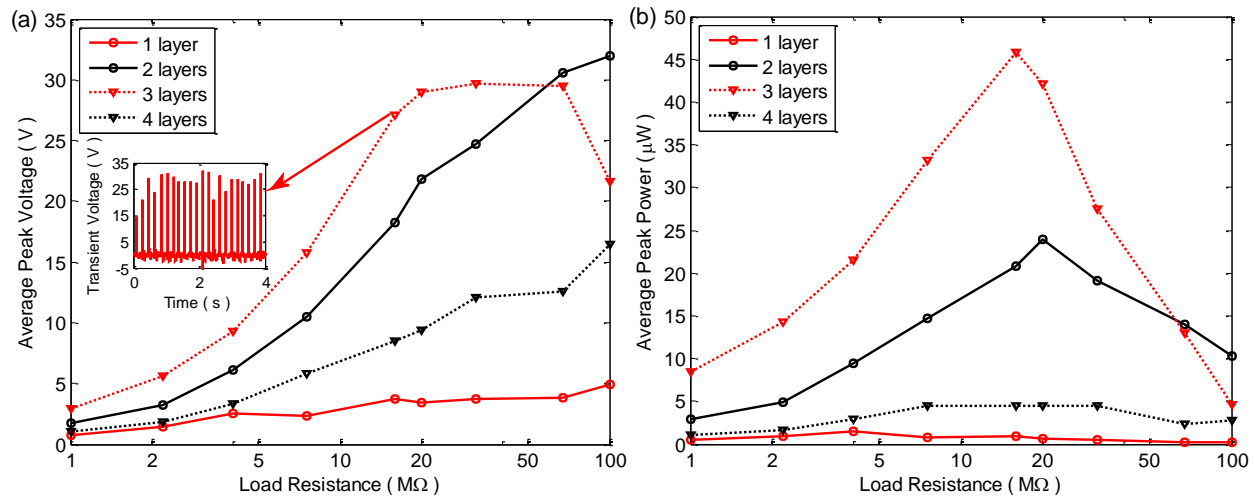


Figure 4. (a) Average peak voltage and (b) power with sweeping load. The inset plot in (a) is the transient output voltage when the device is working with the optimal configuration (3 layers of thin film electret, with the load of 16 MΩ), corresponding to the peak power of 45.6 μW.

## 5. Conclusion

In this article, we have proposed a non-resonant electrostatic KEH with soft substrate and stacked thin film nanofibrous electret. The charge storage stability of the proposed new type of electret is better than that of the plenary Parylene film electret. The power measurement shows the optimal resistive load of the device to be 16 MΩ, and the optimal number of the stacked electret films to be 3. The maximum peak power obtained is 45.6 μW. When the device is working with a full-wave rectifier and a storage capacitor of 10 nF, the voltage reaches 8.5 V with 450 strokes.

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