Silicon rubber/expandable microsphere based triboelectric nanogenerator for harvesting biomechanical energy

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Abstract—Triboelectric nanogenerator (TENG) is favorable for harvesting adaptable and complex biomechanical energy in our daily life. Here, silicon rubber/expandable microsphere TENG was achieved by spin-coating a mixture of expandable microspheres and silicon rubber on a flat plate with conductive fabric. Furthermore, self-made flexible TPU/MWCNTs electrodes replaced commercial conductive fabric to make TENG more adapt to skin of human body. Finally, the optimized TENG in this work demonstrates energy harvesting capabilities and can be applied in self-powered sensor systems and provides new dimensions for biomechanical energy harvesters and wearable self-powered electronics.

1. Introduction

Nowadays, people are paying more and more attention to healthcare monitoring, disease prevention and therapy [1,2]. Thus, for the power supply issues, harvesting renewable and clean energy resources is urgent. The adaptable and complex mechanical energy contained in human movement such as walking, running and patting that is ubiquitous but wasted in everyday life [3]. While TENG has the advantages of low cost, light weight, various working modes and high output power density, which make them favorable for harvesting biomechanical energy.

Silicon rubber is a good candidate when constructing flexible TENG due to its superb electrification characteristics, excellent elasticity and biocompatibility [4]. And, hollow expandable microspheres are particles with thermoplastic shells that encapsulate gas [5]. When heated, the shell is softened, and the gas pressure in the shell increases to cause the microsphere to expand to approximately 10 times its original volume. After cooling, the particle is very soft, which maintains resilience shape, good thermomechanical properties and environmental protection.

In this work, we present a simple and low-cost strategy to achieve silicon rubber/expandable microsphere (SREM) TENG. Specifically, the best result is obtained for the SREM-TENG composed of silicon rubber and 120°C expandable microsphere at 0.3% weight percentages, whose performance in terms of the output voltage, current could be up to 300 V and 4.2 µA, respectively. Furthermore, we use self-made TPU/MWCNTs electrodes to make SREM-TENG more flexible and adapt to skin of human body. Finally, the optimized TENG in this work demonstrates energy harvesting capabilities and can be applied in self-powered sensor systems used in finger angle monitoring. This work provides new dimensions for biomechanical energy harvesters and wearable self-powered electronics.
2. Experiment section

2.1 Preparation of the SREM-Based Triboelectric Nanogenerator

Firstly, put an appropriate amount of expandable microspheres into oven, to make it expand different size under 100°C, 120°C, 150°C for 5 min, respectively. Secondly, above 25°C, 100°C, 120°C, 150°C expandable microspheres were added into Ecoflex A at same weight percentages of 0.1%, and the mixtures were mechanically stirred for 30 min. Thirdly, ecoflex B were added into above mixtures, and the resulting mixtures were mechanically stirred for 5 min. Finally, films of equal 100 µm thickness were manufactured by spreading the Ecoflex-microsphere mixtures on a 40×55 mm² portion of conductive fabric, which had been adhered to a flexible rectangular polyethylene terephthalate (PET) film with same size. And, Cu tapes were attached to the bottom of the conductive fabric as conductive wires. The SREM-based triboelectric nanogenerators were obtained at room temperature for 20 min.

The preparation of different weight percentages of 0.05%, 0.1%, 0.3%, 0.5% for silicon rubber/120°C expandable microsphere films were the same as above.

2.2 Preparation of the TPU/MWCNTs electrode

A TPU solution (20 wt%) was prepared by dissolving TPU particles in Analytical reagent-grade N,N-dimethylformamide (DMF) at 80 °C for 24 h. The MWCNTs were added to the TPU solution and the resulting mixture was mechanically stirred for 30 min. Finally, film of 50 µm thickness was manufactured by spreading the TPU/MWCNT solution on a glass substrate, followed by vacuum deaeration. The MWCNT-doped TPU electrode was obtained after the solvent had evaporated at room temperature.

3. Results and discussion

Fig.1 displays a schematic diagram of the fabrication process and the microscopic morphology of expandable microspheres at different heating temperatures. Fig.1a shows a model diagram of expandable microsphere, which is a hollow microsphere. Fig. 1b is mixing the hollow microspheres and A, B Ecoflex silicon rubber uniformly to prepare a composite film (The specific process is shown in the experiment section). The scanning electron microscopy (SEM) image in Fig.1c show the cross-sectional morphology of the silicon rubber/expandable microspheres film, it reveals that the hollow microspheres are well distributed inside the silicon rubber. The microstructures of the expandable microsphere at different heating temperatures are shown in the SEM images in Fig.1d. At room temperature, the microspheres are sunken ball with a diameter of 15 µm. When heated to 100°C and 120°C, the diameters of the ball expand to approximately 50 µm and 60 µm, respectively. However, when heated to 150°C, the microsphere were ruptured and depressed with a diameter of 15µm.
Fig. 1 (a) The model diagram of hollow expandable microsphere. (b) The fabrication process of silicon rubber/expandable microspheres composite film. (c) The SEM image of the silicon rubber/expandable microspheres film cross-sectional morphology. (d) The SEM images of the microstructures of the expandable microsphere at different heating temperatures.

To achieve the high electrical performance of the SREM-TENG, the effects of the expandable temperature of expandable microspheres on electrical outputs were systematically explored. As shown in Fig. 3a and b, SREM-TENG delivered considerable output voltage and current signals, and Fig. 3c is absolute value of the peak voltage and current of SREM-TENGs fabricated with different expandable temperature. Particularly, the voltage and current of the device with the 120 °C expandable microsphere could reach the maximum value. The considerable output enhancement could be attributed to the reasonable adjustment of the pore size and content. The scanning electron microscopy (SEM) image in Fig. 3 d1–g1 show the cross-sectional morphology of the SREM-film, the expandable microspheres at 25°C and 150°C are small in size, while at 100°C and 120°C are larger in size. Ultra depth of field microscope in Fig. 3 d2–g2 more intuitively shows that the content of expanded microspheres at 25°C and 150°C is less, while the content of expanded microspheres at 100°C and 120°C is higher. Among them, the microspheres at 120°C are largest in size and high in content.
Fig. 2 (a) (b) Comparison of output voltage and current of SREM-TENGs fabricated with different expandable temperature. (c) Bar chart showing the absolute value of the peak voltage and current. (d1 ~ g1) (d2 ~ g2) show the cross-sectional morphology and ultra depth of field microscope of the SREM-film at 25°C, 100°C, 120°C, 150°C.

Furthermore, to achieve the higher electrical performance of the SREM-TENG, the content of expandable microspheres electrical outputs were also explored. As shown in Fig. 3 a and b, the output of SREM-TENG showed a trend of first increasing and then decreasing with the increase of content from 0% to 0.5% for silicon rubber/120°C expandable microsphere films. Fig. 3c is absolute value of the peak voltage and current of SREM-TENGs fabricated with different content of expandable microsphere. Specifically, the voltage and current of the device with the 0.3% expandable microsphere could be up to 300 V and 4.2 µA, respectively. Compared with SREM-TENG with none expandable microsphere, the voltage and current were enhanced 230% and 60%, respectively. Ultra depth of field microscope in Fig.3d more intuitively shows that the content increases from 0.05% to 0.5%. The output performance of a TENG under practical conditions depends on its load resistance. Therefore, we investigated the variations in output current and voltage while patting the optimal TENG at a frequency of 3 Hz under increasing loads (from 100 KΩ to 1000 MΩ). The current decreased with increasing load resistance, whereas the voltage exhibited the opposite behavior and saturated at approximately 300 V (Fig. 3e). The instantaneous power under loading reached a maximum of 1.26 mW at a load resistance of 70 MΩ (Fig. 3f). The charging capability of the SREM-TENG through a bridge rectifier is shown in Fig. 4g, which exhibited a trend similar to that of the output voltage and current.
Fig. 3 (a) (b) Comparison of output voltage and current of SREM-TENGs fabricated with different content. (c) Bar chart showing the absolute value of the peak voltage and current. (d) The depth of field microscope of the SREM-film at 0.05%, 0.1%, 0.3%, 0.5%. (e) The output voltage, current, and (f) instantaneous power of the optimized TENG, plotted as a function of load resistance. (g) The charging capability of the SREM-TENG through a bridge rectifier.

What’s more, in order to make TENG more flexible and adapt to skin of human body, we replaced commercial conductive cloth with self-made TPU/MWCNTs electrodes (The specific process is shown in the experiment section). As shown in the Fig.4a, the resistance is 0.651 KΩ through using a multimeter to test the electrode, and there is a little stretchable by pulling the TPU/MWCNTs film. And, Fig.4b shows the microstructure of the electrode, which was composed with MWCNTs layers less than 200 nm. Fig. 4c shows the output voltage of the SREM-TENG with self-made electrode at vibration frequencies ranging from 1.5 to 3.5 Hz, where an increased output voltage was observed with increasing frequency, from 180 V at 1.5 Hz to 300 V at 3.5 Hz. In addition, the optimized SREM-TENG can be applied in self-powered finger angle sensor systems. As shown in Fig.4d, when the bending angle of the finger is from 30° to 120°, the electrical signal output of TENG will increase, which will have a certain application prospect in the field of patient finger recovery. Furthermore, Fig.4e shows the output tends to increase as the force increases when the TENG is tapped with different magnitudes of force with the palm of the hand. When the SREM-TENG is placed on the back of the hand and tapped, it will directly light up 35 LED lights (Fig.4f and g). There is a certain application prospect in the self-supply of electronic skin.
4. Conclusion
In summary, we have demonstrated a silicon rubber/expandable microsphere TENG by spin-coating a mixture of expandable microspheres and silicon rubber. Furthermore, we replaced commercial conductive fabric with self-made TPU/MWCNTs electrodes to make SREM-TENG more flexible and adapt to skin of human body. Finally, the optimized TENG in this work demonstrates energy harvesting capabilities and can be applied in self-powered sensor systems used in finger angle monitoring. This work provides new dimensions for biomechanical energy harvesters and wearable self-powered electronics.

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