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ABSTRACT
In this study, we report a flexible single-electrode-based triboelectric nanogenerator based on double-sided polymer surface nanostructures. The triboelectric nanogenerators have been applied to harvest all kinds of mechanical energy in our daily life and convert them into electricity, and also used as a self-powered sensor system for touching pad and smart skin technologies. To enhance the performance of triboelectric nanogenerator, we fabricate a single-electrode-based triboelectric nanogenerator based on double-sided polydimethylsiloxane nanostructures and indium tin oxide electrode film using nanoimprint lithography. The nanostructures are nanopillar arrays with the diameter of about 200 nm to enhance the triboelectric effect. Open-circuit voltage and short-circuit current of the as-prepared samples are recorded using an oscilloscope with applying different external force at room temperature. The single-electrode-based triboelectric nanogenerator delivers an open-circuit voltage up to about 160 V, a short-circuit current of about 3 μA, and power density of 423.8 mW/m², which provides an attractive solution to work as self-powered devices. This study greatly expands the applications of triboelectric nanogenerator as energy harvesting, environmental monitoring, and self-powered sensor systems.

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I. INTRODUCTION
Owing to the rapid development of powering wireless, portable, and wearable electronics, energy harvesting for mobile self-powered sources has attracted increasing attention in the past decade.1-5 Currently, many technologies to harvest energy in the nature environment into the electricity have been developed based on photovoltaic, piezoelectric, electrostatic, thermoelectric, and electromagnetic effect. Based on the coupling of triboelectrification and electrostatic induction, triboelectric nanogenerators (TENGs) have recently been utilized to harvest random ambient mechanical energy, which have many advantages such as low cost, simple construction, relatively high energy-conversion efficiency, flexibility, and scalability.1-11 The conventional TENGs consist of two friction layers coated with metal electrode for the electrostatic induction and electric output, which increases fabrication complicated and cost to bring inconvenience in some application fields.1-10 In order to overcome these problems, single-electrode-based TENGs (S-TENGs) have been introduced for more practical and feasible design, which has only one electrode and one triboelectric layer, and employs an external object as the other triboelectric layer such as human skin, clothes, or mechanical devices.12-20 The single electrode of S-TENG is connected to the ground and the current can flow between the electrode and the ground by contact and separation of two triboelectric layers.12-20 Therefore, the S-TENG can detect micro-movement of the contact external object when harvesting energy, which has potential applications in self-powered sensors system and...
wearable devices to collect micro-energy in the natural environment.25–27

Though the S-TENG has many advantages such as simple structure, easily integrated with other devices, and miniaturization, the energy conversion efficiency is commonly less than 50%.28,29 In order to enhance the conversion efficiency to broaden the applications, many efforts have been made to increase the surface charge density of triboelectric layer. For example, large-area nanostructures are introduced onto the triboelectric layer surface to increase the frictional contact area and roughness.30–33 Or two triboelectric layer with nanostructures and a metal electrode film between them are developed to improve the power generation.34 These works observed good experimental results to promote the developments and applications of TENGs. However, the configuration of the S-TENG and fabrication technologies limits its practical applications and products promotion.

In this paper, we propose a novel, simple, and flexible S-TENG based on double-sided polymer surface nanostructures. The elastic polydimethylsiloxane (PDMS) material is used as the triboelectric layer and the intermediate indium tin oxide (ITO) film is the single electrode. The nanopillar arrays with the diameter of about 200 nm are fabricated onto the outside surface of two PDMS layers. The S-TENG based on double-sided nanostructures consists of two PDMS triboelectric layers and ITO film as the intermediate electrode layer using nanoimprint lithography that is simple, low-cost, and high-throughput. The electrical characteristics of the S-TENG samples are measured when the external objects contact with them and apply pressure force, such as open-circuit voltage and short-circuit current. This work will provide interest on the different S-TENGs structures with more potential applications in harvesting mechanical energies and self-powered systems.

II. EXPERIMENTAL DETAILS
A. Flexible S-TENG based on double-sided nanostructures

The schematic diagram of the S-TENG is illustrated in Figure 1a, which consists of double-sided elastic PDMS nanostructures triboelectric layers and intermediate ITO electrode layer. The nanostructures on the outside surface of two PDMS layers could be same or different, so they are represented by different colors. The ITO electrode and parts of external touch objects such as skin or clothes are connected with the ground to form a closed circuit. The working mechanism of the flexible S-TENG is schematically depicted in Figure 1b–e. At the original state, the touch objects fully contact with the tow PDMS layers, leasing to charge transfer between surfaces (Figure 1b). For example, human body is the external object and skin contact with the triboelectric layers, and the human feet are connected with the ground. According to the triboelectric effect, electrons are injected from skin to PDMS layers because the PDMS material is more triboelectrically negative than skin. The charges with opposite polarities are produced on the skin surface to fully balance, resulting in no electron flow in the external circuit. Once separating the skin and PDMS layers, the triboelectric charges lost the balance. The negative charges on the surface of the PDMS layers induce the potential difference between PDMS layer and ITO, driving free electrons flowing from the ITO electrode to ground shown in Figure 1c. The separating distance between skin and PDMS surface is appreciably comparable to the size of PDMS layer, resulting in an output voltage/current signal. With the increase of the separation distance between skin and PDMS layer, the negative triboelectric charges on the PDMS are fully balanced from the positive charges on the ITO electrode and no output electrical signals can be observed as shown in Figure 1d. Subsequently, the skin

FIG. 1. (a) Schematic diagram of the flexible S-TENG based on double-sided nanostructures. (b–e) Sketches that illustrate the electricity generation process in a full cycle.
approaches the PDMS in turn, the produced positive charges on the ITO electrode decrease. Therefore, electrons flow from ground to the ITO electrode until the skin fully contacts with PDMS again, and a reversed output voltage/current signal is observed shown in Figure 1e. This is the electricity generation process of the flexible S-TENG based on double-sided nanostructures in a full cycle.

**B. Fabrication of the double-sided nanostructures of flexible S-TENG**

The fabrication process based on nanoimprint lithography of flexible S-TENG with PDMS double-sided nanostructures is depicted in Figure 2. To start with, the PDMS (Sylgard 184, Dow Corning) is prepared by mixing base and curing agent with the ratio of 10:1, which is coated onto the nanostructures mold (the first imprinting) to form a thin film. It is kept at room temperature for 30 min to remove the bubblies, then fully cured at 80 °C for 1 h. Releasing the mold, single-sided PDMS triboelectric layer with nanostructures is observed. The ITO electrode film is pasted onto the back of the PDMS layer. The prepared PDMS mixture is spin-coated onto the ITO electrode film again. The same nanostructures mold (the second imprinting) imprint into the PDMS film and it is fully heat cured. Releasing the mold, the S-TENG consisting of double-sided PDMS nanostructures layers and intermediate ITO electrode layer is fabricated, which is ultra-thin, flexible, and integrated.

**C. Characterization and electrical measurement of the fabricated S-TENG**

The fabricated S-TENG is fixed on a measurement platform and the two PDMS triboelectric layers contact with clothes attached to the electric linear motor (E1100-RS-HC) that can apply adjustable pressure force within the range of 0.5 N~50 N. The morphology and nanostructures of the PDMS layers are characterized by scanning electron microscopy (SEM). The output electrical performance of the S-TENG is measured using Keithley 6514 and low noise amplifier (Stanford SR570) to record the voltage and current.

**III. RESULTS AND DISCUSSION**

The fabricated S-TENG has double-sided PDMS triboelectric layers with same nanostructures onto the outside surfaces, as displayed in Figure 3, which are random nanopillar arrays with the diameter of about 200 nm. The SEM images of imprinting porous...
aluminum oxide (PAO) template and PDMS nanopillar arrays are shown in Figure 3a and b. These high-resolution nanostructures increase the friction contact area and roughness of the PDMS triboelectric layers to enhance the electrical performance of the flexible S-TENG. The nanostructure dimension of the S-TENG sample is about $2 \times 2 \times 0.2 \text{ cm}^2$.

The electrical performances of the fabricated flexible S-TENG are measured, and the measurement results for the single-sided triboelectric layer are shown in Figure 4, including the output open-circuit voltage and short-circuit current at different frequency (Figure 4a and b) and different pressure force (Figure 4c and d). As can be seen, the intensity of electricity properties depends strongly on frequency and pressure force. With the increase of measurement frequency, the open-circuit voltage has no obvious changes, while the short-circuit current rapid increases up to 1.5 $\mu$A for the frequency of 5 Hz. We analyze the major reason.

At the small displacement, the triboelectric surface area of S-TENG is much larger than the separation distance. According to the previous researches,$^{35–37}$ the open-circuit voltage and the maximum short-circuit current when $x(t)=0$ can be calculated as following:

$$V_{\text{TENG}}^{\text{OC}}(t) = \frac{Q_{\text{SC}}(x(t))}{C(x(t))} = \frac{\sigma x(t)}{\varepsilon_0}.$$  \hspace{1cm} (1)

$$I_{\text{TENG}}^{\text{SC,max}} = \frac{S \sigma v(t)}{d_0} = \frac{2\pi S \sigma f x_{\text{max}}}{d_0}.$$  \hspace{1cm} (2)

Where $C(x)$ is the capacitance between two electrode subject to various displacement $x$, $\varepsilon_0$ is the permittivity of vacuum, $S$ is the triboelectric surface area, $d_0$ is the effective thickness of the dielectric layer, $\sigma$ is the triboelectric surface charge density, $Q_{\text{SC}}(x)$ is the short-circuit charge transfer amount subject to the displacement $x$, and $f$ is the frequency. Therefore, according equation 1 and 2, we can observe that the open-circuit voltage of the TENG is independent of the frequency $f$ and only increases with the larger displacement between two contact surfaces, while the short-circuit current is proportional to the frequency $f$ and the measured maximum short-circuit current increases with the increasing of the frequency $f$. These results show that TENGs have good output performance at low frequency to harvest low-frequency energy such as water wave energy.

The pressure force has significant influence on the electrical performance. The open-circuit voltage increases to 80 V when the force increases to 30.5 N, which doesn’t increase when the force increases form 30.5 N to 42.6 N. In contrast, the short-circuit current continues to increase rapidly with the increase of the force. The triboelectric surface charge density doesn’t increase with the increasing of the pressure and the amount of the conduction electrons continues to increase.

The experimental results above are observed for single-sided nanostructure layer, and the performance will double for the flexible S-TENG with double-sided nanostructures layer to obtain the
open-circuit voltage of 160 V and short-circuit current of 3 μA at the frequency of 5 Hz and the pressure force of about 42.6 N. To sum up, the power generation performances of S-TENG improve with the increase of the frequency and pressure force. However, because the flexible S-TENG samples will be destroyed by the too much pressure force and the frequency will not too high under practical conditions, the power generation has limit.

Usually, the effective output power of the S-TENG depends on the match with the loading resistance. The resistance dependence of both short-circuit current and power density with the resistance form 10 Ω to 10 GΩ shown in Figure 5. The short-circuit current drops with the increase of the resistance. The power density remains close to zero when the resistance is below 1 MΩ and then increases in the resistance region from 1 MΩ to 1GΩ. When the loading resistance continues to increase (> 1GΩ), the power density decreases. The maximum value of the output power density reaches 423.8 mW/m² at the loading resistance of 1 GΩ.

IV. CONCLUSIONS

In summary, we have demonstrated a flexible S-TENG based on double-sided PDMS surface nanostructures. The mechanism of the flexible S-TENG is based on both contact-induced electrification and electrostatic induction. The nanopillar arrays with the diameter of about 200 nm on the outside surface of two PDMS layers improve the output performance of S-TENG. The open-circuit voltage is up to about 160 V, the short-circuit current is about 3 μA, and power density is 423.8 mW/m². The dependence of the electric output on the frequency and external pressure force and the power density as the function of the loading resistance are experimental measured. The experimental results show that the open-circuit voltage is independent of the frequency. So the S-TENG has good output performance at low frequency, which has potential applications in harvesting low-frequency energy. These results indicate that designed flexible S-TENG has potential applications in self-powered sensors system, pressure detectors, vibration detectors, and environmental monitoring.

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