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Nanofibrous membrane constructed wearable triboelectric nanogenerator for high performance biomechanical energy harvesting

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ABSTRACT

With a rapid expansion in the field of wearable electronics, powering them entirely by batteries has become more and more unpractical and unfavorable. Here, we developed a lightweight, flexible and sustainable power source by fabricating a nanofibrous membrane constructed wearable triboelectric nanogenerator (NM-TENG), which is capable of converting human biomechanical energy into electricity for next-generation wearables. With an effective device area of 16 cm^2 under gentle hand tapping, it can deliver a current and voltage output respectively up to 110 μA and 540 V. And the electrospun nanofibrous membranes were tailored to enhance the triboelectric polarity, mechanical strength as well as surface hydrophobicity, which will eventually improve the device output performance, robustness and capability of operation even with high environmental humidity. *Via* harvesting the biomechanical energy from body motion, the wearable NM-TENG was demonstrated to sustainably power a commercial thermal meter, electronic watch, and light up about 560 LEDs. Given a collection of compelling features of being flexible, breathable, environmentally friendly and cost-effective, the NM-TENG can be extensively applied not only to self-powered wearable electronics but also possibly to power generation at a large scale.

1. Introduction

In recent years, holding remarkable application potentials to bring revolution to our way of life, rapidly increasing research progress has been made in the field of wearable electronics [1–3]. Powering them entirely by batteries has become more and more unpractical and unfavorable, since batteries have limited lifetime and may cause environmental detriment due to the possible leakage of electrolyte solutions [4,5]. One critical challenge identified in this field is how to develop lightweight, flexible, sustainable and stable power sources, which are indispensable parts to power up the functioning devices in a wearable system [6].

Human biomechanical motions, such as walking, arm swinging, typewriting, finger motion, and even breathing, available in large quantities, are clean and renewable energy sources with great potential [7–11]. The bottleneck in the development of wearable electronics could be broke if these energy sources could be effectively harnessed. Reliance on the coupling effect of contact electrification and electrostatic induction, triboelectric nanogenerators (TENG) have been proven to be a fundamentally new green energy technology for ambient mechanical energy harvesting, featured as being simple, reliable, cost effective as well as high efficiency [12–18].

In this work, we present a solution to power the wearable electronics by fabricating a nanofibrous membrane constructed wearable triboelectric nanogenerator (NM-TENG), using economically viable materials and scalable fabrication technologies. Electrospinng method was rationally introduced to prepare the triboelectric layers of NM-TENG, since it is a versatile approach to make micro/nanofibers with advantageous features for surface triboelectrification, such as ultrathin diameters, good connectivity, easy to scale up, tunable wettability, fine flexibility, adjustable porosity and controllable compositions. Under a gentle human hand tapping, the electric output of the NM-TENG can reach as high as 110 μA and 540 V with an effective area of 16 cm^2. And electric power was demonstrated to be delivered from wide range of biomechanical motions, such as hand tapping, body shaking, shoe insole from human walking and so on, which was capable of sustainably powering a commercial thermal meter, electronic watch, and lighting up about 560 LEDs. Given the combinatorial advantages of low-cost, excellent flexibility and mechanical durability, and remarkable scalability in the materials synthesis and device fabrication, the nanofibrous membrane constructed wearable triboelectric nanogenerator is not only a milestone work in the field of wearable electronics, but

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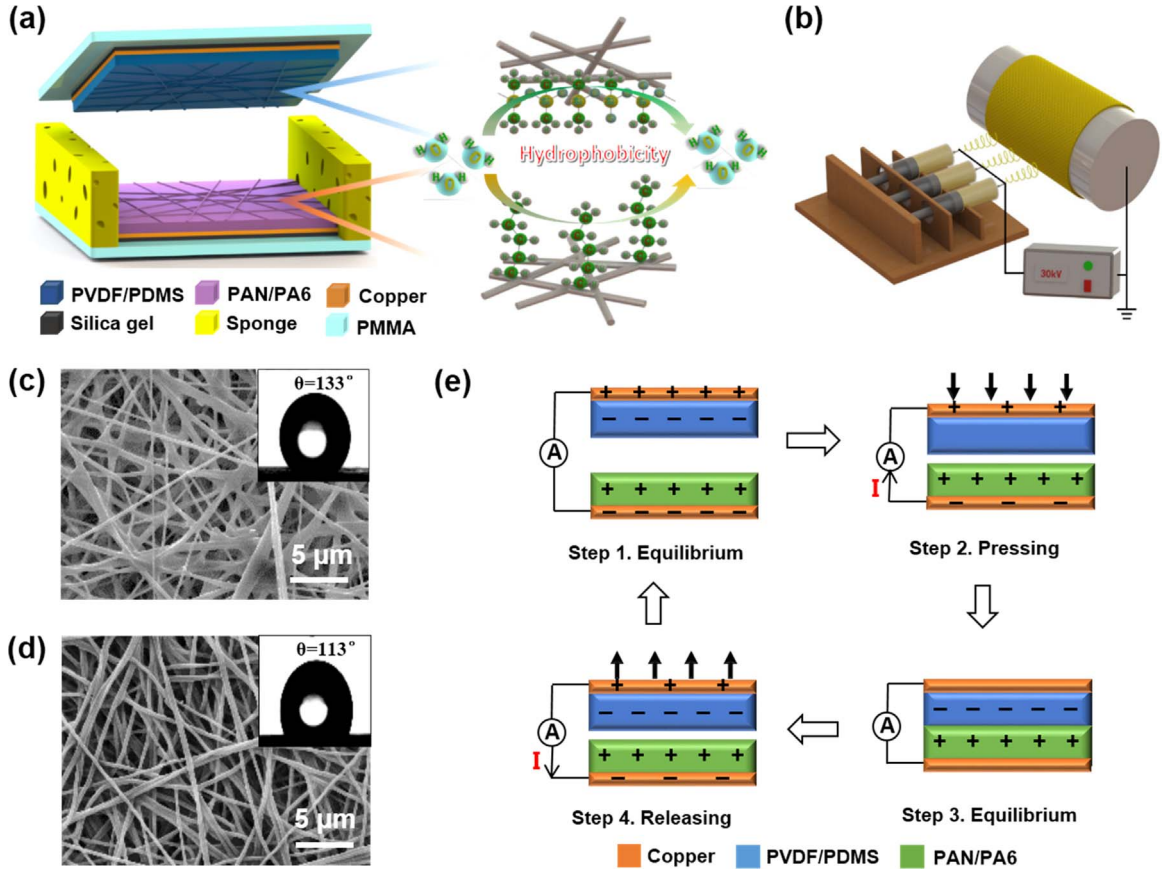

Fig. 1. Structural design of the nanofibrous membrane-based triboelectric nanogenerator (NM-TENG). (a) Structure design of the NM-TENG. (b) Schematic illustration of the electrospinning for nanofibers synthesis. (c) SEM image of PVDF/PDMS nanofibrous membrane etched by NaOH. (d) SEM image of the PAN/PA6 nanofibrous membrane etched by HCl. (e) Electricity generation mechanism of the NM-TENG.

also renders a green and alternative to traditional methods potentially for large-scale energy generation.

2. Experimental section

2.1. Materials

Polyvinylidene fluoride (PVDF) powders (Mw=57 000) was purchased from Solvay Co., Ltd., USA. Polydimethylsiloxane (PDMS) prepolymer and cross-linker (Sylgard 184) were manufactured by Dow Corning Co., America. Polyacrylonitrile (PAN) powders (Mw=90 000) was bought from Kaneka Co., Ltd., Japan. Polyamide 6 (PA 6) powders (Mw=18 000) was supplied by UBE Industries Ltd., Japan. N,N-Dimethylfomamide (DMF) was obtained through Macklin Biochemical Co., Ltd., China. N,N- dimethylacetamide (DMAc) and n-hexane were supplied by Shanghai Lindi Chemical Reagent Co., Ltd., China. All reagents were employed without any further processing.

2.2. Electrospinning

PVDF/DMF homogeneous solution with a concentration of 16 wt% to 22 wt% was prepared by stirring for 10 h. PVDF nanofibrous membrane was fabricated under spinning environment (25 ± 3 ℃ and 45 ± 5%) through a DXES-3 electrospinning machine (SOF Nanotechnology Co., Ltd., China). The electrospinning process was operated with a feed rate of 2.0 mL h^{-1} , an applied voltage of 30 kV, and a distance between spinneret and collector of 20 cm.

PAN/DMAc transparent solution with a concentration of 7 wt% to 13 wt%was prepared by stirring for 10 h. PAN nanofibrous membrane was fabricated under spinning environment (25 ± 3 ℃ and 45 ± 5%) through a DXES-3 electrospinning machine. The electrospinning process was operated with a feed rate of 1.0 mL h^{-1}, an applied voltage of 30 kV, and a distance between spinneret and collector of 20 cm.

2.3. Modification

PDMS prepolymer was blended with cross-linker at constant 10:1 ratio for stirring 20 min and then degassed to remove bubbles. PVDF nanofibrous membrane was coated with PDMS/n-hexane solutions and then dried in a vacuum oven at curing temperature of 100 ℃. The prepared PVDF/PDMS composite membrane was finally sprinkled with a 1 M solution of NaOH to produce the secondary nanostructure on the surface of PDMS.

PAN nanofibrous membrane was coated with PA6/acetic acid solutions and then dried in a vacuum oven at the curing temperature of 100 ℃. The prepared PAN/PA6 composite membrane was finally sprinkled with a 1 M solution of HCl to produce the secondary nanostructure on the surface of PA6. The HCl-etched PAN/PA6 membrane was grafted by octadecyl isothiocyanate/methyl cyclohexane solutions. Subsequently, the treated membrane was rinsed with n-hexane solution and dried naturally in air.

2.4. Characterization and measurements

Mechanical properties of pristine and modified membranes were tested using instrument XQ-1A testing machine (China). FT-IR spectroscopic analysis was performed on Nicolet 8700 Spectrometer (Thermo Fisher, America). XPS measurement was conducted on a Kratos Axis Ultra