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FULL PAPER

An Ultrathin Flexible Single-Electrode Triboelectric-Nanogenerator for Mechanical Energy Harvesting and Instantaneous Force Sensing

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The trends in miniaturization of electronic devices give rise to the attention of energy harvesting technologies that gathers tiny wattages of power. Here this study demonstrates an ultrathin flexible single electrode triboelectric nanogenerator (S-TENG) which not only could harvest mechanical energy from human movements and ambient sources, but also could sense instantaneous force without extra energy. The S-TENG, which features an extremely simple structure, has an average output current of 78 µA, lightening up at least 70 LEDs (light-emitting diode). Even tapped by bare finger, it exhibits an output current of 1 µA. The detection sensitivity for instantaneous force sensing is about 0.947 µA MPa^{-1}. Performances of the device are also systematically investigated under various motion types, press force, and triboelectric materials. The S-TENG has great application prospects in sustainable wearable devices, sustainable medical devices, and smart wireless sensor networks owning to its thinness, light weight, energy harvesting, and sensing capacities.

1. Introduction

Energy harvesting about gathering tiny wattages of power from motions and vibrations has attracted increasing interest, as the decrease in size and power consumption of electronic devices.[1] Many devices with communication abilities such as wearable devices and wireless sensor networks are created. However, most of these devices are powered by batteries, thus its lifespan and stability of power are restricted. An exciting way to overcome these limitations is to harvest mechanical energy from the environment to directly power electronic device. Various principles for harvesting mechanical energy into electrical energy has been proposed, such as piezoelectric,[2] electromagnetic,[3] electrostatic,[4] and triboelectric.[5]

Triboelectric nanogenerator (TENG), basing on triboelectric effect and electrostatic induction, has been successfully developed to harvest mechanical energy and has attracted massive attention.[6] However, most TENGs presently consists of multiple components with a thickness of 0.5–5 cm and has a relative structural complexity. Generally, two components which incorporate two triboelectric layers with electrode layer on the back are assembled to the device. Even more components are vertically or laterally assembled into the device to achieve a higher output. Thus, it is necessary to develop an extreme simple and thin TENG with super agility and operational flexibility, since electronic devices are tending toward miniaturization. Moreover, most force sensors adopt piezoelectric effect of quartz, and few attempts have been done on triboelectric-effect-based force sensor.

Herein, we present a single electrode triboelectric nanogenerator (S-TENG) which is simply-fabricated, flexible, and ultrathin. It consists of only one thin sheet, harvesting mechanical energy from human activities and ambient environment through rubbing with objects. Only in working condition, the triboelectric layer is needed to contact with the S-TENG, thus simplifying the structural complexity. The S-TENG, which is fabricated transparent or nontransparent through sputtering method or simple adhesion, could bend up to curvature radius of 0.84 mm with a strain of 5.4% and 1.29 mm with a strain of 7.5% respectively. The transparent S-TENG (65 mm × 100 mm) is only 0.09 mm with a weight of 1.2113 g. Its output current could reach 78 µA and lighten up at least 70 LEDs. Even tapped by bare finger, it exhibits an output current of 1 µA. Experimental results imply its great application prospects for fabricating sustainable wearable devices such as self-powered light-up shoes and clothes. Furthermore, the S-TENG can be

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utilized as instantaneous force sensor to detect instantaneous impact force, where the detection sensitivity is 0.947 μA MPa^{-1}. This work may have great effect on sustainable wearable or portable electronics and smart sensor networks.

2. Results and Discussion

The flexible S-TENG can be fabricated in transparent and nontransparent structure. Each structure can be assembled through two methods: magnetron sputtering method and adhesion method. Here, we demonstrate two S-TENGs: a nontransparent S-TENG fabricated through adhesion method; a transparent S-TENG fabricated through magnetron sputtering method.

The nontransparent S-TENG includes three layers: polytetrafluoroethylene (PTFE) layer (triboelectric layer), an aluminum (Al) layer (electrode layer) and polyethylene terephthalate (PET) layer (substrate layer), as shown in **Figure 1**a. Detailed assembling process is demonstrated in experimental section. PTFE was chosen as the triboelectric material for its greatest tendency of gathering electrons. And PET was chosen as the substrate material for its high toughness and flexibility. Figure 1b displays a photograph of an as-fabricated S-TENG (100 mm × 65 mm). Because the output of TENG could be significantly improved through enhancing the roughness of the triboelectric surface,[7] so the PTFE surface was etched with nanopores (diameter ≈ 1 μm) through inductively coupled plasma (ICP) reactive ion-etching method. The PTFE surface before and after etching was characterized by scanning electron microscopy (SEM) and shown in Figure 1c,d. Figure 1e shows the magnified nanopore SEM picture. As can be seen, densely suffused nanopores are created. The nontransparent S-TENG is so flexible that it can bend up to a curvature radius of 1.29 mm with a strain of 7.5%, as shown in Figure 1f. It has a thickness of 0.27 mm (Figure 1g) and weighs 3.0324 g (Figure S1, Supporting Information). In fact, it can be thinner than 0.27 mm if assembled by magnetron sputtering method. However, price will go up for more complicated fabrication process.

The transparent S-TENG also consists of three layers: the fluorinated ethylene propylene (FEP) layer which act as triboelectric surface, the indium tin oxides (ITO) layer which act as electrode layer, and the polypropylene (PP) layer which act as substrate layer (**Figure 2**a). The ITO layer is sputtered on the FEP layer through magnetron sputtering method, and the PP layer is coated on the ITO layer by adhesion. The S-TENG is about 100 mm × 5 mm. Figure 2b shows the transparency of the as-fabricated transparent S-TENG, and we could see the logo beneath it clearly. Figure 2c shows the transparent S-TENG could bend up to curvature radius of 0.84 mm with a strain of 5.4%. It only has a thickness of 0.09 mm (Figure 2d) and a weight of 1.2113 g (Figure 2d).

The working mechanism of the S-TENG is based on the collaboration of triboelectric effect and electrostatic induction effect, which is schematically demonstrated in **Figure 3**. When an active object (such as glove, hand or foot) contacts with the friction layer (PTFE or FEP), triboelectrification occurs (the object surface and the friction layer surface forms a friction pair). Equivalent negative and positive charges generate, and

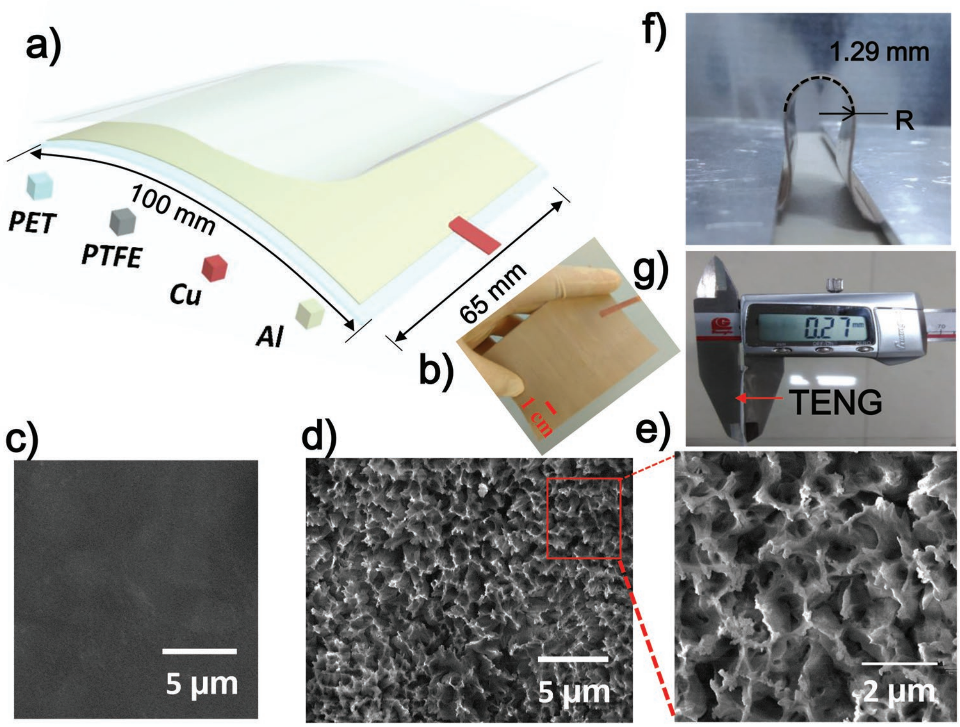

Figure 1. Structure and some properties of a nontransparent S-TENG. a) Schematic illustration of the single electrode TENG where the PTFE film is peeled off the Al film for better visualization. b) Photograph of the S-TENG.SEM images of the PTFE surface, c) before and d,e) after etching. f) Photograph of the nontransparent S-TENG during a bending test, and the bending radius is 1.29 mm. g) The thickness and h) the weight of the fabricated S-TENG.

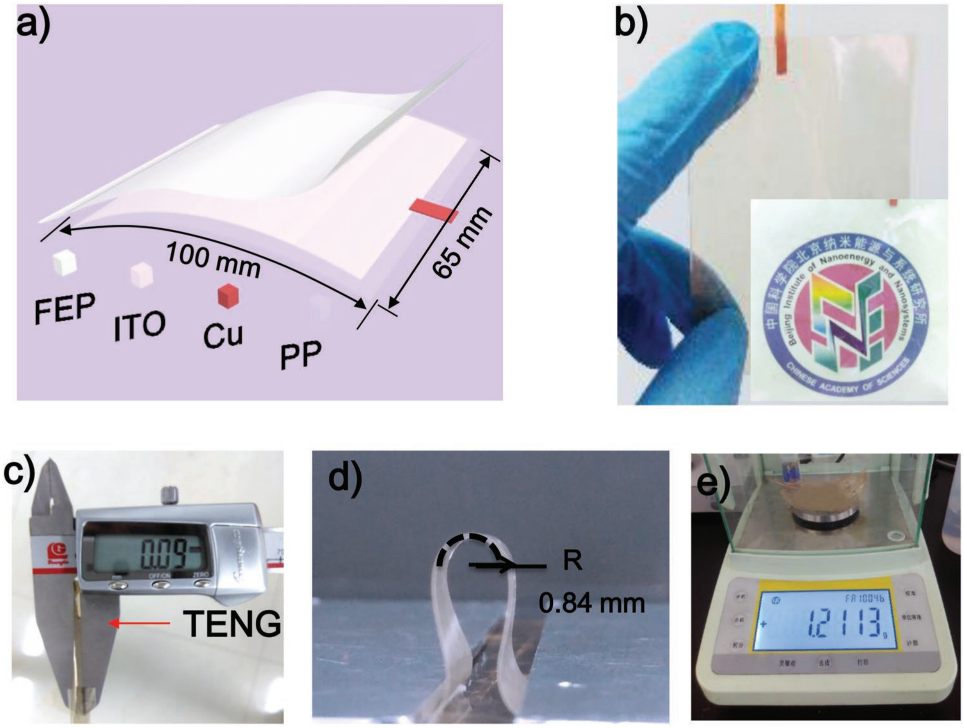

Figure 2. Structure and some properties of the transparent S-TENG. a) Schematic illustration of the transparent S-TENG where the FEP film is peeled off the ITO film for better visualization. b) Transparency of the as-fabricated S-TENG. c) Thickness, d) bending radius (0.84 mm), and e) weight of the S-TNG.

then separate rapidly due to different triboelectric series when the object tends to leave away (Figure 3a). During the departure process of the object, positive charges will be induced on electrode layer because of electrostatic induction effect. Potential difference between the electrode layer and the ground prompts electrons flowing, resulting in an electrical current (Figure 3b). Until the active object is quite far away, an electrical equilibrium achieves and the electrons stop moving (Figure 3c). As the object approaches the friction layer again (Figure 3d), electrons flow inversely from the ground to electrode layer to make a charge balance (Figure 3e). When the active object contacts with the friction layer, charge neutralization occurs immediately.

To obtain a more quantitative understanding of the electricity generating process, we establish a theoretical model of S-TENG to simulate the electric potential distribution of every component of S-TENG by COMSOL during the motion process of the active object. In this model, the active object, the friction layer and the electrode layer are made of nylon, PTFE, and aluminum (Al) respectively. And the electrode is connected to the ground (Figure 3e). Figure 3f shows the electrical potential between ground and the electrode layer changes when the active object departs from the friction layer. Inserted colored figures show the simulated results of the electrical potential distributions of S-TENG as the active object move apart. At the initial state, the PTFE film (with an assumed tribocharge density of -8×10^{-6} C m^{-2}) and the object (with an assumed tribocharge density of 8×10^{-6} C m^{-2}) fit closely together. As can be seen through the color change of COMSOL simulation results, when the object departs from the friction surface, the electrical potential of the active object gets higher, the electrical potential of the electrode layer gets lower, and the open-circuit voltage (electrical potential between electrode layer and ground) increases.

Then, we characterized the performance of the nontransparent S-TENG for harvesting energy from human motions. A human controlled testing mode is presented (shown in **Figure 4**a), where a person's hand covered by latex glove presses the S-TENG in a reciprocating way from the height of about 30 cm under the press force of about 140 N. 0.1 μC charges (Figure 4b) are transferred at the collision moment. The output current is about 60 μA (Figure 4c), displaying pulse-like sharp peaks in a single direction. Corresponding current density is 0.58 μA cm^{-2} (Figure S2, Supporting Information). The voltage also exhibits pulse-like sharp peaks with average amplitude of 150 V (Figure 4d). Figure 4e indicates the output voltage and current varies under different external loads. It suggests that the maximum output current drops with the increasing of the external load resistance, while the maximum output voltage across the resistors follows a reverse trend, which is due to ohm's law. The instantaneous peak power (UI) is maximized at a load resistance of 6 MΩ, corresponding to a peak power of 8.58 mW (Figure 4f), which means the optimal matched external resistance is about 6 MΩ.

As for the transparent S-TENG, its current and voltage output could be high up to 78 μA (**Figure 5**a) and 340 V (Figure 5b) respectively when the S-TENG is impacted by palm covered by latex under a force of about 140 N. To evaluate the electric performance of the transparent S-TENG for harvesting human motion energy, we also characterized the electric output of transparent S-TENG when pressed by palm or taped

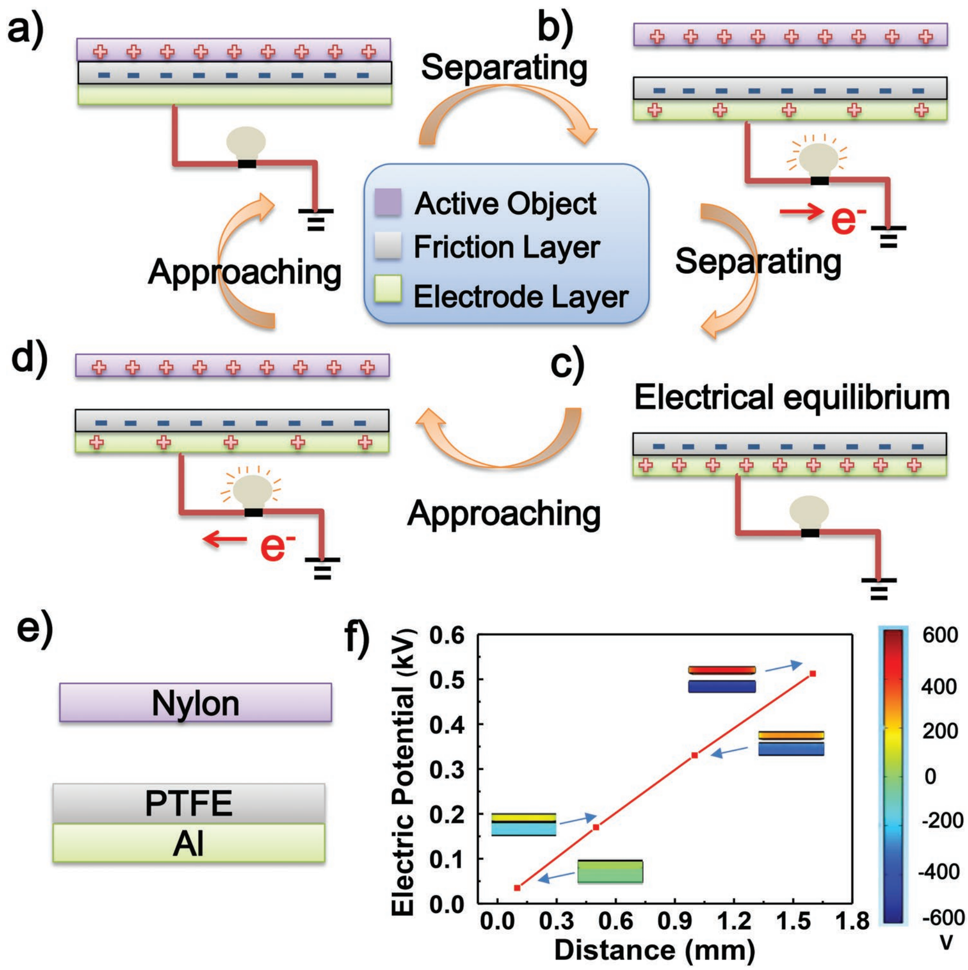

Figure 3. Working mechanism of the S-TENG. a–d) Charge distribution of the device during a complete recycle: an active object a) rubs with, b) departs from, c) is far away from and d) approaches the friction surface. e) COMSOL simulation model. f) Simulated electric potential between the electrode layer and the ground when active object departs from the friction layer. Inserts are the COMSOL simulation results of S-TENG at different distance between object and friction layer.

by finger in different conditions. The current output of the S-TENG decreases from about 29.75 to 3.77 μA when objects rubbing with the S-TENG change from palm covered by latex glove to a bare palm under the force about 60 N (Figure 5c). The current output is about 1.87 and 1.00 μA when the S-TENG is pressed by a finger covered by latex and a bare finger under an impact force of about 8 N (Figure 5c). It indicates that the output current is higher when the S-TENG is rubbed with latex than with bare skin. To get a better sense of the difference, we illustrated the schematic and equivalent electric circuit of the models when the S-TENG is pressed by bare palm and palm covered by latex (Figure 5d–f).[8] Here, R_B and C_B represents the body resistance and the body capacitance respectively, C_T is the capacitance between triboelectric surface and the glove, C_E is the corresponding capacitance between triboelectric surface and electrode layer, and R_L corresponds to the load resistance. As can be seen, the electric circuit of the two models is quite different.

Consecutively, we systematically investigate three main factors influencing the S-TENG's performance: impact force, material of the triboelectric layer of S-TENG (the first triboelectric surface) and material of an active object surface (the second triboelectric surface). To make the impact force quantitative and controllable, a computer controlled model is used to stimulate the S-TENG, as shown in **Figure 6**a. In this model, a linear motor is controlled by a computer and the force exerted on the motor slider (90 mm in length, 45 mm in width) can be controlled through computer. At first, the slider surface is adhered with foam (90 mm × 45 mm) to increase the buffering capacity during collision. Then a friction film (90 mm × 45 mm) such as latex film is adhered onto the foam layer to act as a triboelectric layer. To ensure the impact force equally exerted on S-TENG, the S-TENG is cut into the same size of the slider and screwed onto a fixed block opposite to the motor slider.

Figure 6b shows the output current of a PP based and a PTFE based S-TENG (90 mm × 45 mm) under different impact force. Inserts are their photographs. During the experiment, a latex film is fixed on the linear motor slider, taking the role of another triboelectric layer. As we can see, when the impact force is 1.05 N, the peak to peak current (P–P current) of the PTFE based and the PP based S-TENG is 1.18 and 0.46 μA; when the impact force is 23.01 N, the P–P current of the PTFE based and

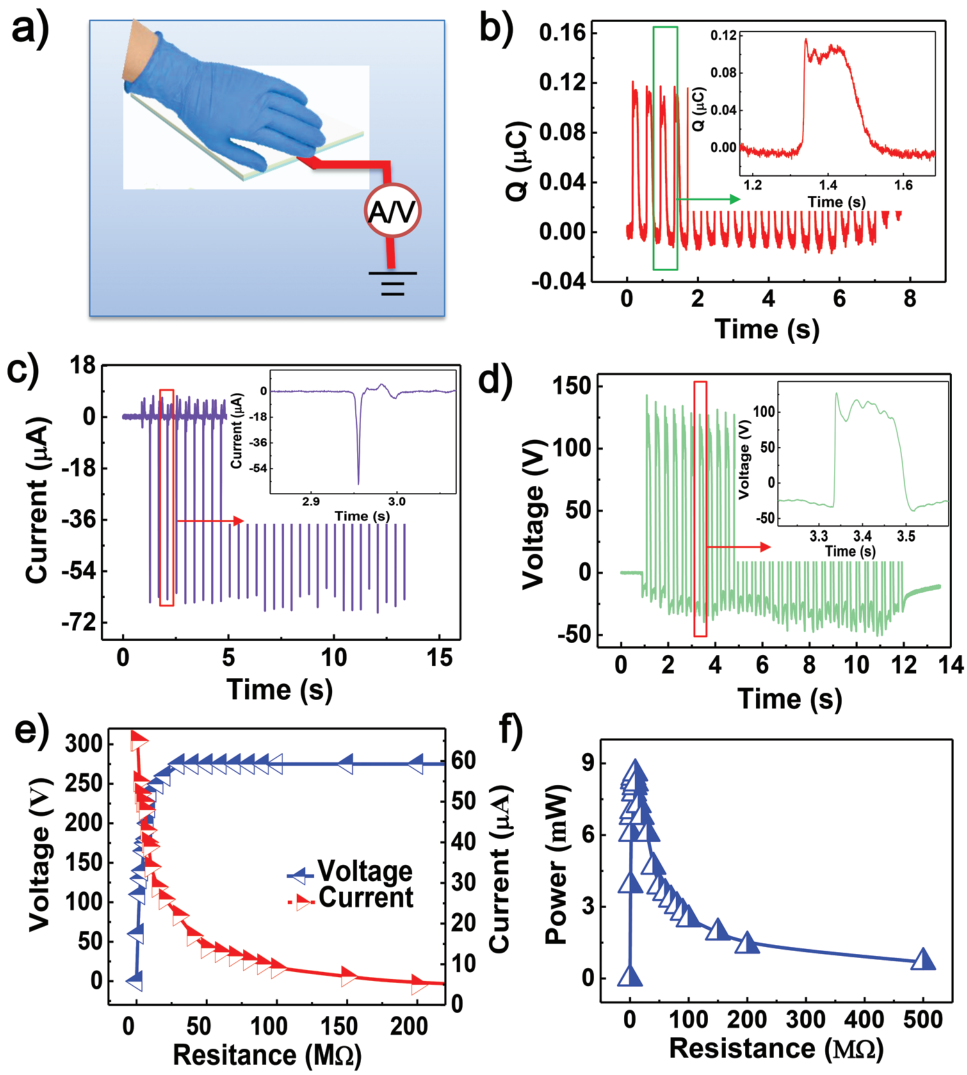

Figure 4. Demonstration of the nontransparent S-TENG harvesting energy from human motions. a) Diagram of the testing mode where human palm covered with latex glove presses the S-TENG periodically. b) Transferred charges between latex surface and PTFE surface. c) Short-circuit current and d) Open-circuit voltage of the S-TENG. Inserts are zoom-in view of a short circuit current and open-circuit voltage during a complete reciprocating movement. e) Maximum output voltage and current versus different load resistances. f) Output power under various load resistances.

the PP based S-TENG is 4.50 and 1.04 μA; when the impact force is 64.20 N, the P–P current of the PTFE based and the PP based S-TENG is 5.60 and 17.20 μA. Thus, it is indicated that the output current of PTFE based S-TENG is higher than PP based S-TENG and that the triboelectric performance of PTFE is better than PP when rubbed with latex material. Moreover, the results also lead to a conclusion that the bigger the impact force is, the higher the current amplitude is. That's because a bigger impact force corresponds to a tighter contact, which means a better triboelectrification.

Figure 6c demonstrates the output current of the PTFE based S-TENG (90 mm × 45 mm) when it rubs with different object surfaces. It infers the output current is evidently higher when the S-TENG is rubbed with latex and Al material than rubbed with textile, while the output current is quite close when the S-TENG is rubbed with latex and Al materials. Precisely speaking, the P–P current (peak to peak current) of S-TENG is 3.16, 5.8 and 7.5 μA respectively when rubbed with textile, Al, and latex (Figure S3, Supporting Information). Therefore, the triboelectric performance of latex is better than Al, while the triboelectric performance of Al is better than textile when rubbed with S-TENG.

The performance of the transparent S-TENG for harvesting energy from object's motions and factors influencing its electric output is also surveyed in the same way. Under the impact force of 52.65 N, the P–P current and P–P voltage is about 20 μA and 230 V respectively (Figure 6d,e). Insertion of Figure 6d shows the current varies in direction and amplitude during a complete motion cycle, which may be due to the complicated charge transfer during the foam based elastic collision and separation. Figure 6f shows the output current is different when the transparent S-TENG is rubbed with textile, Al, and latex. Precisely,

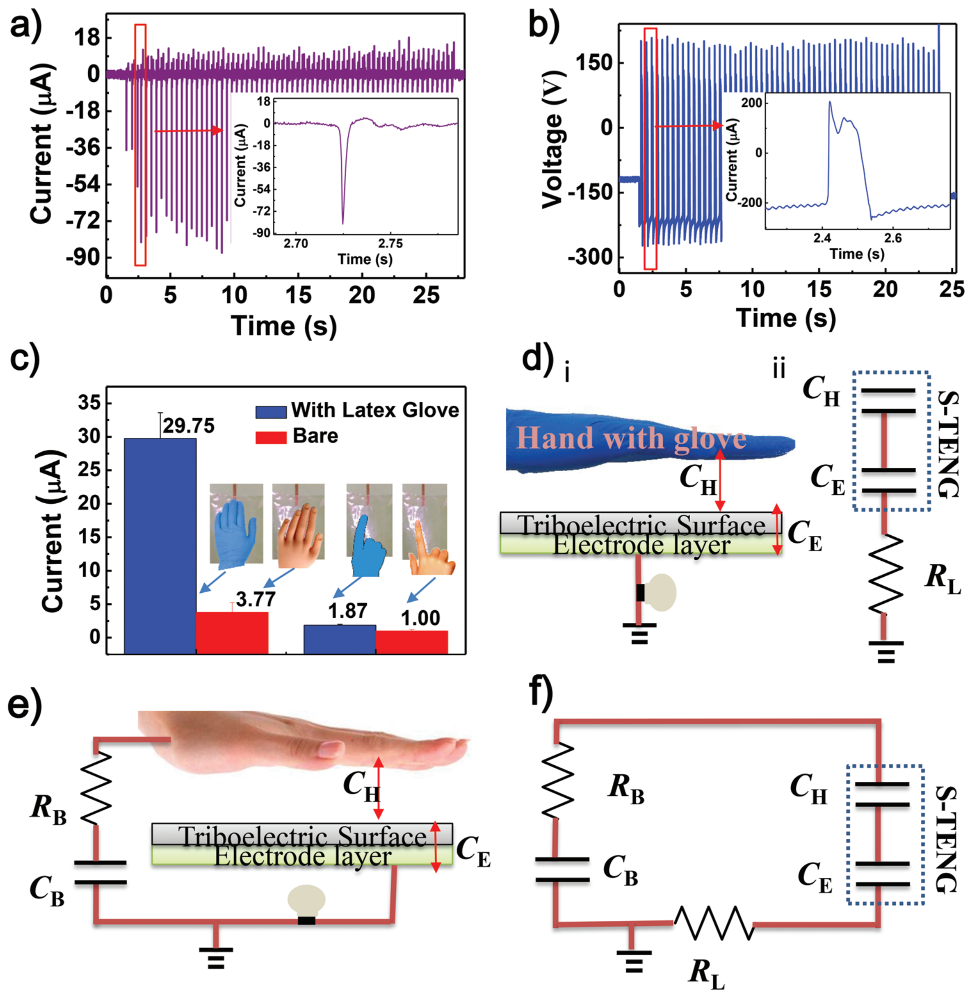

Figure 5. Demonstration of the transparent S-TENG harvesting energy from human motions. a) The short circuit current and b) open circuit voltage when the S-TENG is pressed by palm covered by latex under the force of 140 N. c) The current comparison of S-TENG when pressed by palm covered by latex, by bare palm, by finger covered by latex, and by bare finger. The press force for palm is about 60 N and the press force for finger is about 8 N. Schematic and equivalent electric circuit when the S-TENG is pressed d) by bare palm and e,f) by palm covered by latex.

the corresponding P–P current is about 10.3, 15, and 20.4 μA respectively (Figure S4, Supporting Information). It infers that latex is a better triboelectric material for S-TENG. Moreover, the output current of 10.3 μA with triboelectric material of textile implies a very promising application of fabricating wearable devices.

To demonstrate the S-TENG could act as a sustainable power source and help fabricating self-powered sensing systems, we connect it with LEDs under various conditions and test its capacity for sensing instantaneous press force. **Figure 7**a shows the nontransparent S-TENG could light up at least 35 LEDs (left in Figure 7a, Video 1, Supporting Information) and the transparent S-TENG could light up at least 70 LEDs when pressed by human palm covered by latex (right in Figure 7a, Video 2, Supporting Information). Inserted pictures are the corresponding S-TENGs and LEDs before triggered by human pressing movement. Even tapped by bare finger, the S-TENG also could light up a LED (Figure S5a, Supporting Information). Figure 7b shows LEDs are lightened up when a person walks wearing a shoe cushioned with S-TENG based insole (insert at the bottom, Video 3, Supporting Information). Thus, it could be used for fabricating self-powered light-up shoes (Figure 7b) based on harvesting energy from human walking or running movement. The S-TENG also could be decorated on clothes for harvesting energy from human movement (Video 4, Supporting Information). Figure 7c shows LEDs could be lightened up when a person runs wearing clothes decorated with S-TENG. To demonstrate the S-TENG could be utilized as an instantaneous force sensor, a circular transparent S-TENG with a radius of 9 mm was surveyed under different instantaneous press force. Figure 7d,e and Figure S5b–f in the Supporting Information show the S-TENG exhibits different output current under different instantaneous pressure. The relationship between forward output current and force is plotted in Figure 7f, revealing a clear linear relationship with a detection sensitivity of 0.947 μA MPa^{-1}, which indicates the S-TENG has great potential for practical application as an instantaneous force sensor.

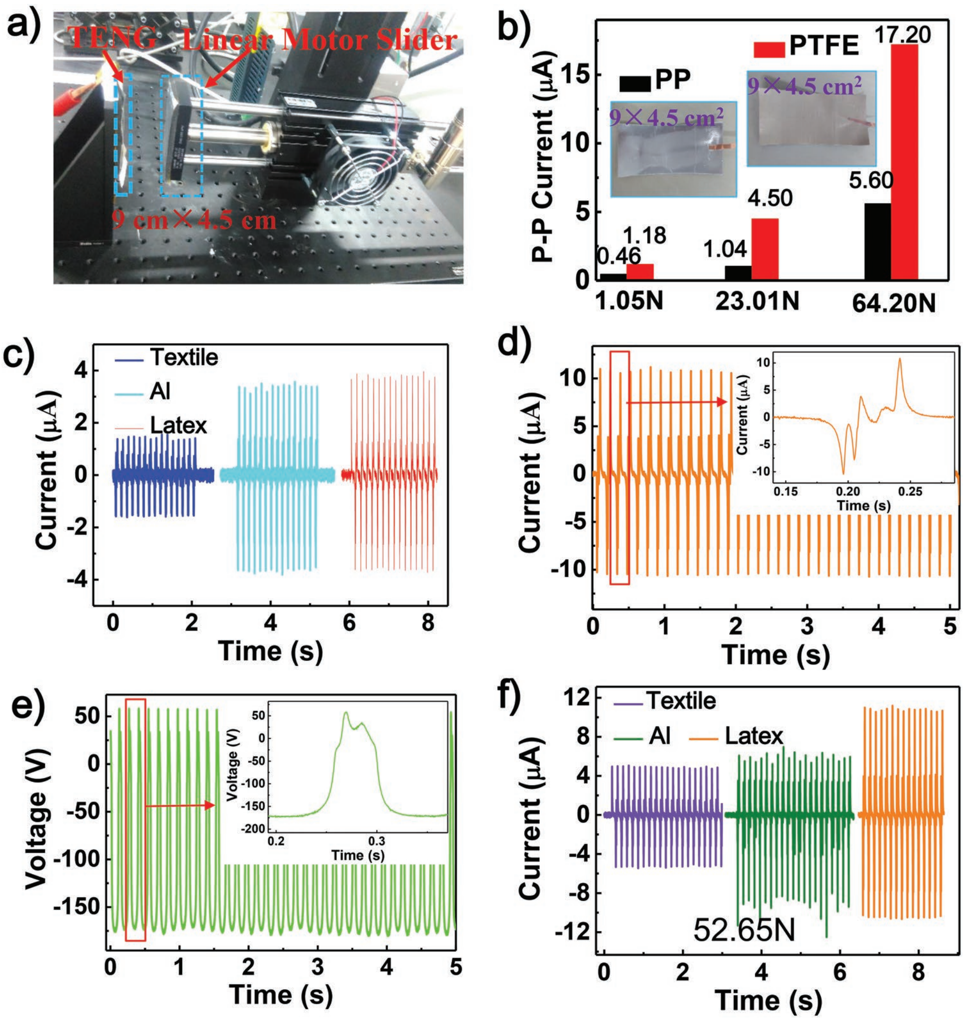

Figure 6. Demonstration of S-TENG harvesting energy from machine's pressing movement. a) Linear motor and testing setup. b) Peak to peak current of PP based and PTFE based opaque S-TENG under different impact force. c) Output current of the PTFE based opaque S-TENG when rubbed with latex, textile, and Al. e) Output current and f) voltage when the transparent S-TENG is rubbed with latex. c) The output current the transparent S-TENG when rubbed with textile, Al, and latex. The impact force for c–f) is 52.65 N.

3. Conclusion

In summary, we have developed a novel flexible, ultrathin, light weighted S-TENG which harvests mechanical energy from human motions and environment and senses instantaneous force without extra power. The S-TENG, either opaque or transparent, incorporates a friction layer, an electrode layer, and a substrate layer into a thin sheet with extremely simple structure. An average output current of 78 μA is obtained when flapped by human palm covered with latex glove. At least 70 LEDs are lightened up. Even tapped by bare finger, it exhibits a current of 1.00 μA. Experimental results show its capacity for practical application as power source for fabricating sustainable wearable devices. The detection sensitivity is about 0.947 μA MPa^{-1} when it acts as an instantaneous force sensor. Because of its flexibility, thinness, light weight, and extremely simple structure, it has great application prospects for fabricating sustainable wearable electronics and smart sensing systems.

4. Experimental Section

Nanopore-Based PTFE Surface Modification: A PTFE (180 μm) thin film was consecutively cleaned with alcohol, deionized water, and then blown dry with nitrogen gas. Then, the surface of PTFE film was deposited with a thin Cu film (about 20 nm) by sputtering as the mask for the following etching to create the nanopore-structure using the ICP reactive ion etching. Specifically, Ar, O_2, and CF_4 gases were introduced into the ICP chamber with the flow rate of 15.0, 10.0, and 30.0 sccm, respectively. One power source of 400 W was used to generate a large density of plasma, and the other power of 100 W was used to accelerate the plasma ions. The etching time was about 20 min, and the diameter of the as-fabricated nanopores ranged from 0.4 to 1.1 μm.

Electrical Measurement of S-TENG: During the electrical measurement of the S-TENG, the red terminal of a measuring system was connected with the output electrode of S-TENG, and the black terminal was connected with the ground. The open-circuit voltage and transferred charge density were measured by a Keithley 6514 System Electrometer, and the short-circuit current was measured by an SR570 Low Noise Current Amplifier (Stanford Research System).

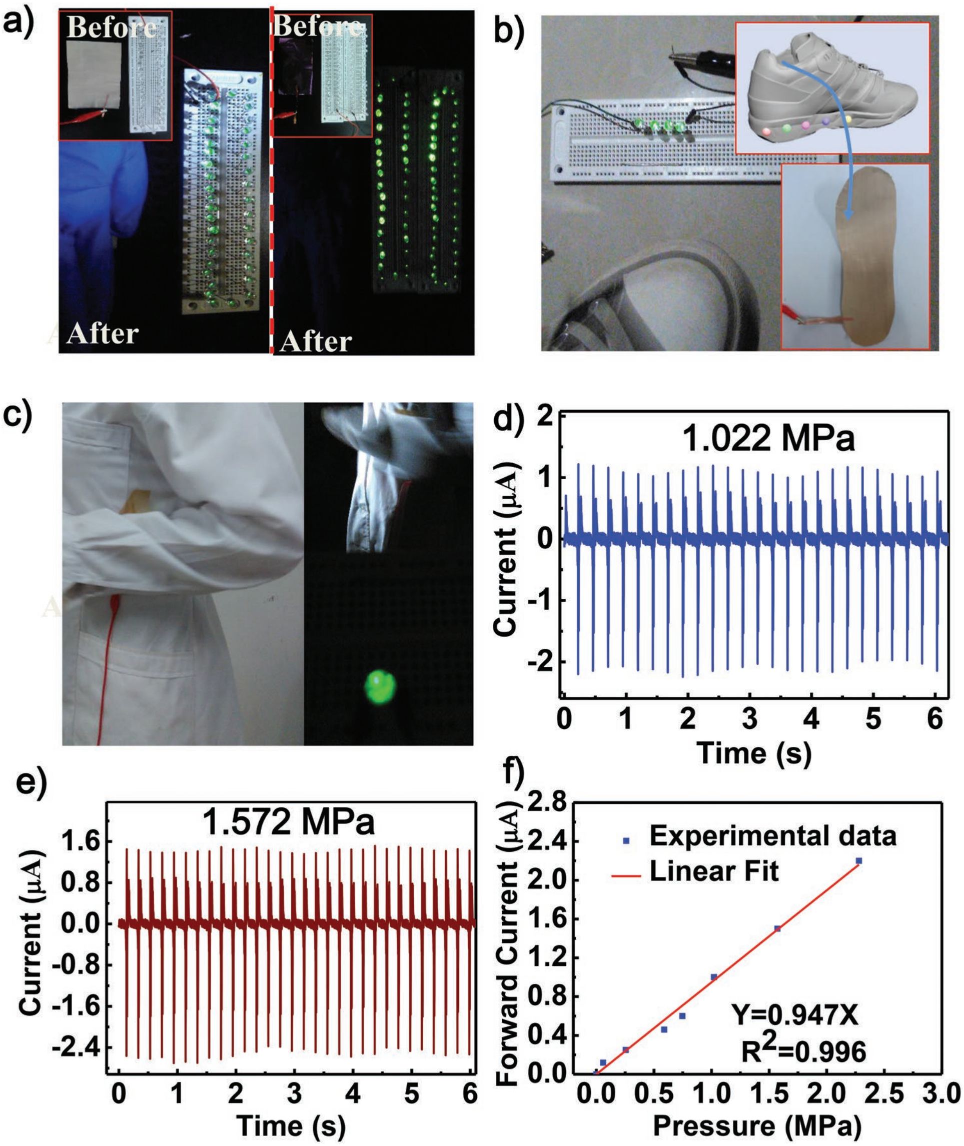

Figure 7. Demonstration of the S-TENG as a sustainable power source and an instantaneous force senor. a) Photograph of an LED lighting panel driven by the nontransparent S-TENG (left) and transparent S-TENG (right) when triggered by human palm. Inserts are the S-TENG and LEDs before triggered. b) Photograph of LEDs driven by an S-TENG based insole when triggered by human walking. Insert is a model of a self-powered light-up shoe. c) Photographs of an S-TENG decorated lab-gown (left) and an LED lightened up by the lab-gown (right) when a person runs with it. d,e) Output current of the transparent S-TENG (circular, radius is 9 mm) under press force of 1.022 and 1.572 MPa. f) Relationship between forward output current and instantaneous press force.

Fabrication of ITO Electrode: An FEP (25 µm) thin film was consecutively cleaned with alcohol, and deionized water, and then blown dry with nitrogen gas. Then, the FEP surface was sputtered with ITO by magnetron sputtering (Discovery 635, Denton Vacuum). Specifically, Ar was introduced into the sputtering chamber with the flow rate of 35 sccm. The sputtering lasted 30 min with DC Power Supplies of 180 W at a substrate temperature of 120 °C. Finally, a transparent FEP based ITO film (370 nm) with an electrical conductivity of 6.76×10^3 S m^{-1} was achieved.

Fabrication of Nontransparent S-TENG: A PTFE (180 µm) coated with adhesive gum on one side, was first modified with nanopore on the other side, then put the modified side of the PTFE sheet opposite to the conductive side of a thin adhesive Al sheet with a copper electrode lead in between, and squeezed them together.

Fabrication of Transparent S-TENG: An FEP (25 µm) thin film was first sputtered with ITO, then adhered a copper electrode lead to the ITO layer. Lastly, A PET substrate was adhered onto the ITO layer with copper electrode lead in between.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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