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3D printed noise-cancelling triboelectric nanogenerator

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ABSTRACT

Triboelectric nanogenerator (TENG), which converts the ambient mechanical energy to electricity by friction, is one of the most promising methods for powering up portable devices. Despite of the successful development so far, there still remain some issues to be improved. Here, we focus on the generation and maintenance of high output-power under harsh environments, and the noise cancellation of the device to keep a stable operation for a long period of time. The TENG, fabricated using a 3D printer, is a fully-packaged, cylinder-shaped device with polydimethylsiloxane (PDMS) bumpy balls inside and linearly patterned Al film on the inner surface. The new design and optimization remarkably increases the output power up to 45 mW, operable under harsh environments such as water, providing enough DC power for charging a battery of smart watch. The noise occurring during the operation is canceled to the noise level (~50 dB) of a normal conversation, by approximately 20 dB, with no degradation of the output power by using highly compressible, conductive Ag nanowires-embedded polyurethane sponge instead of Al. This helps people around the device feel comfortable during the operation. Finally, as a large-scale power supply, windmill composed of three TENGs, are also developed.

1. Introduction

With an increasing consumption and the fast shortage of fossil fuels, humans may be threatened with serious energy crises. Searching for a new energy source from our ambient environment is so essential for the sustainable development of our society [1]. Recently, various types of energy-harvesting techniques based on classic scientific phenomena such as piezoelectric [2–5], thermoelectric [6–8], electrostatic [9–11], and electromagnetic effects [12,13] have been broadly investigated to generate electricity from the mechanical or thermal energy in our surrounding environment. Among these technologies, the mechanical energy source is so convenient because it exists everywhere and anywhere, appropriate for the realization of self-powered portable electronic devices. Recently, triboelectric energy-harvesting technology in conjunction with triboelectrification and electrostatic induction has recently been suggested [14–21]. It is highly efficient, low-cost, and eco-friendly, and can be widely applicable because it can rely on many semiconductor processing technologies. So far, many energy sources, such as human walking [22], mechanical vibration [23], rotation [24], wind [25–27], water waves [28–30], were applied and proven to be so practical for powering up the portable electronic devices.

Despite of many successful demonstrations of the TENGs, there are still many issues to be solved for the commercialization, such as low energy conversion efficiency, high working frequency, material loss by wear, high sensitivity to humidity, large deviation in output power, etc [31–35]. With the development of the TENGs with high-output power, a unique framework to assure the sustainability and reliability of the power production in a practical system should be suggested and developed. To maintain the performance of the device, the surface of both contacted materials should not be changed by the friction. One of the main influencing factors was water molecules on the surface at a high humidity. These water molecules adsorbed on the surface dissipate the generated charges and discharge ultimately to the ground, thus degrading the charge capturing ability of triboelectric materials during operation. This phenomenon is generally not a favor of TENG [36]. To reduce the effect, there were several attempts such as the production of the super-hydrophobic surfaces and the fabrication of fully-packaged frameworks, etc [37–40]. However, the output performance may be insufficient for generating high sustainable output power and still influenced by the water molecules. In this paper, we

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report a new type of fully-packaged TENGs, from master molds fabricated by 3D printing technology, allowing for the one-step fabrication of the nanogenerator's frameworks very simply and quickly. The key idea is the friction between the PDMS balls, which acts as charge accepting materials, and the Al film on the inner surface of the cylinder-type TENG. The electrical output of the device showed an open-circuit voltage (V_{oc}) as high as 90 V and a short-circuit current (I_{sc}) of 0.9 mA. The electrical output of the device also corresponds to an instantaneous power of 45 mW through the optimization of numerical and structural parameters, which is an enhancement of approximately 70 times comparison with the output power (0.65 mW) of the reference, as shown in Fig. S1 (Supporting information). This output performance was not changed significantly after the device was dipped in the water for several tens of hours, indicating that it is quite stable under harsh environment.

As another important issue, the noise occurring during the friction between two surfaces may make us feel uncomfortable and damage our hearing. Actually, it has been known since the early 1980s that noise from large wind turbines can adversely affect human health. Sound levels from turbines are typically about 55 dB when measured at a distance of about 100 m [41]. The sound level of the noise during scavenging wind power may even harm hearing of a normal resident. In general, the noise level was measured to be approximately 80 dB when it was measured under the input conditions such as external force between 30 and 50 N and frequency between 1 and 10 Hz. In this research, we report that the noise can be reduced by using conductive sponge materials consisting of the polyurethane sponges embedded by the Ag nanowires, instead of the Al film. Under the practical frequency range (< 3 Hz), the noise was reduced approximately 20 dB to the noise level (~ 50 dB) of a normal conversation.

2. Experimental

2.1. Fabrication of cylinder-type TENGs and PDMS balls

Acrylonitrile Butadiene Styrene (ABS) filament (Makerbot Industry, USA) and fused deposition modeling (FDM) based 3D printer (Replicator 2X, Makerbot Industry, USA) were used for the fabrication of various master molds and frameworks such as the base and body parts of the cylinder-type TENG. They were printed at a printing speed of 90 mm/s, a plate temperature of 110 °C, and with the raft to enhance the adhesion property between the printed object sand plate. The area of the base electrode is approximately 8 cm^2 and the height of the cylinder is about 7 cm. On the inner surface of the body, Al films or conductive sponges with linear patterns are coated to enhance the output performance, and the distance between lines and the width of each line were fixed to be 7 mm. Various molds were also made to fabricate PDMS balls with various morphologies such as dimple, and bumpy surfaces by the mold-casting technique. The base monomer (Sylgard 184 A) and curing agent (Sylgard 184B) were mixed with a weight ratio of 10: 1 into a beaker. The PDMS solution was placed into a vacuum process to degas the solution, cast into the various molds and dried in atmosphere at 90 °C to rapidly cure the PDMS solution. After the casted polymer was peeled off from the molds, various PDMS balls were obtained. The PDMS balls were put into the body, fabricating with a fully-packaged cylinder-type TENG.

2.2. Fabrication of highly compressible and conductive sponge

Polyurethane (PU) sponge (Scotch Brite, 3 M) was used for the fabrication of conductive sponges. First, the sponge was transferred to an exposure chamber cleaner (AHTECH LTS, Korea) specified for UV/Ozone treatment, and exposed for 10 min to make the surface hydrophilic. It was then dipped into the Ag nanowires solution (K35GNAMI, Nanopyxis) for 5 min, degassed and dried under vacuum at 90 °C for 2 h to evaporate the remaining solvents. The conductive sponges were then coated onto the inner surface of the body and base.

2.3. Characterization and measurements

The morphologies of conductive sponges were characterized by a Nano 230 field-emission scanning electron microscope (FE-SEM). A Tektronix DPO 3052 Digital Phosphor Oscilloscope and a low-noise current preamplifier (model no. SR570, Stanford Research Systems, Inc.) were used to measure the electrical output signals. The charge density from the electrical outputs was measured using a Keithley 6514

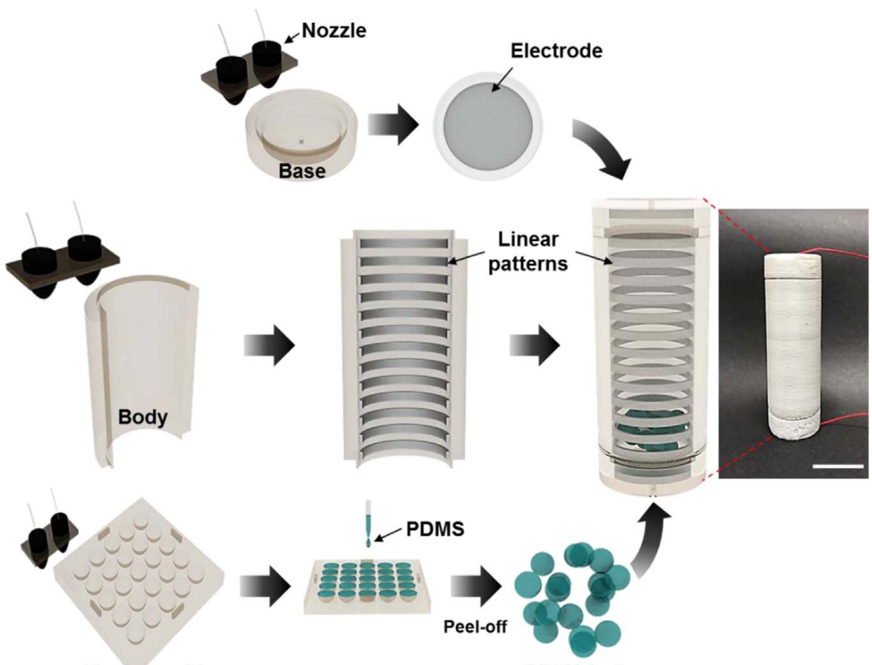

Fig. 1. Schematic diagrams of the fabrication process for the cylinder-shaped TENG, consisting of body and base parts, and PDMS balls. On the inner surface of the body, a conductive material with linear patterns is coated to enhance the density of charges donated. The photo image of the device is also shown in the inset. Scale bar: 3 cm.