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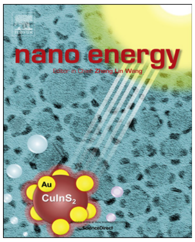

RAPID COMMUNICATION

A multi-layered interdigitative-electrodes-based triboelectric nanogenerator for harvesting hydropower

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Water wave;
Water drop

Abstract

Hydropower is the most important and wildly-used renewable energy source in the environment. In this paper, we demonstrate a multi-layered triboelectric nanogenerator (TENG) to effectively harvest the water wave energy. For a single-layered TENG, interdigitive electrodes are incorporated in order to generate multiple electric outputs under water wave or water drop impact. For the collection of water wave energy, a polyurethane (PU) coated copper rod is used to roll back and forth and contact with the polytetrafluoroethylene (PTFE) film covered interdigitative electrodes. The surfaces of the PU and PTFE films are fabricated as porous structures and nanowire arrays, which provide an advantages of large contact area and efficient separation. Under one wave impact, the single-layered TENG composed of nine pairs of interdigitative electrodes can provide nine pulses of electric outputs (each pulsed output voltage is 52 V and output current density is 13.8 mA m^{-2}). The instantaneous output power density of a five-layered TENG is 1.1 W m^{-2}. In addition, the PTFE film covered interdigitative electrodes has been successfully used to harvest water drop energy, whcih can also generate 9 pulses of electric outputs upon one water drop falling. All these results show the developed TENG has a potential to harvest the hydropower of ocean wave and raindrop in the near future.

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Introduction

Over the past decades, climate change has been recognized as the most serious environmental issue affecting our world. Therefore, a great effort has been devoted to discover renewable energy sources with minimized carbon emissions. In addition, less dependence on fossil fuel is mandatory for the sustainable development of the world. In 2012, the first prototype triboelectric nanogenerator (TENG) based on the contact electrification of solid materials was invented to harvest mechanical energy from different sources in the environment, such as wind [1,2], water [3], and human motions [4,5]. And four different operation modes have been proposed and demonstrated to show the massive potential of solid-solid TENG, which including vertical contact-separation mode [6,7], lateral sliding mode [8,9], single-electrode mode [10,11], and freestanding triboelectric-layer mode [12]. Unlimited to energy harvesting application, TENG can further function as self-powered nanosensors by modifying the surfaces of contact materials. The major advantage of self-powered nanosensors is that they can work without external power supply, which have attracted increasing attention in recent years. For examples, self-powered nanosensors based on TENG structure toward catechin molecule [13], temperature [14], humidity [15], metal ion [16], and light [17] have been widely researched and successfully developed.

Alternatively, scientists also utilized water-solid contact electrification to fabricate a new prototype water-TENG in 2013 [18]. The working mechanism of water-TENG is similar to the first prototype TENG based on solid-solid contact electrification, which is a coupling of triboelectric effect and electrostatic induction. The major difference is that in this water-TENG, water itself is one of the contact materials to cause the triboelectric charges and generate electric outputs. For example, the contact electrification between polydimethylsiloxane (PDMS)-patterned pyramid arrays and difference sources of water (deionized, tap, and salt water) has been studied and demonstrated with the capability to either collect water wave energy or function as self-powered temperature and ethanol sensors. Recently, another water-TENG was developed to collect the water drop energy based on single-electrode operation mode [19]. This water-TENG successfully showed the potential to harvest the water drop energy under both conditions that the water drop is precharged during the traveling process or the triboelectric charges are generated when the water drop is contacted with the superhydrophobic polytetrafluoroethylene (PTFE) film. Scientists have also showed that by changing the superhydrophobic material composition of PTFE to TiO_2 nanomaterials, the water-TENG can provide photocatalytic and antibacterial functions when harvesting hydropower [20]. A new active transducer without using any external bias voltage has been sucessfully demonstrated to collect the hydropower from various water motions [21], which is also based on water-solid contact electrification. These results about water-TENG are important because hydroelectric power is unlimited and could be good alternative to solar energy [22,23].

Different from those previous studies, in this paper we design a multi-layered TENG to effectively harvest the hydropower. For a single-layered TENG, interdigitative electrodes are incorporated in order to generate multiple electric outputs under one water wave or water drop impact. For the collection of water wave energy, a polyurethane (PU) coated copper rod is used to roll back and forth and contact with the PTFE film covered interdigitative electrodes. The working principle is based on solid-solid contact electrification, which is different from that of water-TENG in the previous studies [18-21]. In order to enhance the electric output of TENG, the surfaces of the PU and PTFE films are fabricated as porous structures and nanowire arrays, which provide the advantages of large contact area to generate more triboelectric charges on the surfaces and efficient separation after contact. Under one water wave impact, the single-layered TENG composed of 9 pairs of interdigitative electrodes can provide 9 pulses of electric outputs (each pulsed output voltage and current density can reach 52 V and 13.8 mA m^{-2}, respectively). The instantaneous output power density of a five-layered TENG is 1.1 W m^{-2}. The rectified electric outputs have been demonstrated to power light emitting diodes (LEDs). Besides, the part of the PTFE film covered interdigitative electrodes also show the potential to harvest raindrop energy based on water-solid contact electrification, whcih can also generate 9 pulses of electric outputs upon one water drop.

Experimental section

Preparation of PU and PTFE thin films with nanostructures

For the polytetrafluoroethylene (PTFE) thin film with nanowire arrays on the surface were synthesized by using a ordered anodic aluminum oxide (AAO) foil as the template and a PTFE solution as the precursor. The AAO template was prepared through a two-step anodization approach. The high-purity aluminum foil (99.99%) was cleaned, degreased, and annealed at 500 °C for 3 h. Then the aluminum foil was electropolished in a perchloric acid solution (2.0 M in ethanol) at a 4 °C for 2 min. In the first anodization step, the electropolished aluminum foil was anodized in a oxalic acid solution (0.3 M) at a constant voltage of 40 V for 40 h. The anodization layer was removed through the wet chemical etching with a solution containing phosphorus acid (0.9 M) and chromium (VI) oxide (0.2 M). Subsequently, a second anodization was carried out under the same condition as the first anodizaion step for 1 h. The AAO template was finally immersed into another phosphoric acid solution to widen the pores. A commercial PTFE precursor was poured into the AAO template and a vacuum process was applied to remove the air remaining in the holes. After curing at ambient temperature for one day, the solvent was evaporated and a PTFE film with nanowire arrays on the surface formed. Alternatively, the polyurethane (PU) film surface were fabricated with porous structures. The commercial PU film were etched with a sulfuric acid solution (3.0 M) for 2 min and then cleaned with water.

Fabrication of TENG with interdigitative electrodes

In this part, a poly(methyl methacrylate) (PMMA) mask was curved first by a laser cutter. Then the mask was attached on another PMMA substrate for the deposition of aluminum interdigitative electrodes. Aluminum (thickness around 100 nm) was