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Full paper

Painting a high-output triboelectric nanogenerator on paper for harvesting energy from human body motion

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ABSTRACT

Paper-based triboelectric nanogenerators (TENGs) represent an affordable, green, and eco-friendly energy harvesting methodology. In this work, we propose a novel X-shaped paper TENG (XP-TENG) formed from a ballpoint ink layer coated by painting with a commercial brush pen. The paper and Teflon tape serve as the triboelectric pairs, with the paper serving as the supporting component. Moreover, the XP-TENG is capable of providing two working patterns that can yield an expanded scope of practical applications. A stacked XP-TENG was proposed for increasing the output performance and harvesting the mechanical energy generated by motion of the human body. This staked XP-TENG can directly light up 101 blue high-power LEDs with working voltage of 3.4 V. The fabricated XP-TENG can be used for harvesting mechanical energy from human walking.

1. Introduction

In the last few decades, rapid dissemination of portable electronic devices has facilitated our everyday life [1–4]. Portable electronic devices (for example, mobile phones, laptops, sports bracelets) have emerged as essential tools for many people, and efficient, renewable, and eco-friendly batteries are required for powering these devices. Moreover, the conventional rechargeable chemical batteries are detrimental to people's health and the environment [5–9]. In addition, the limited power supply of the rechargeable batteries is inadequate for continuous operation of portable mobile electronic devices. Therefore, a wearable, sustainable and pollution-free power source is required for sustaining these devices.

Triboelectric nanogenerators (TENGs) are smart devices that are capable of harvesting the low-frequency energy from our environment [10–16]. TENGs have significant potential for the realization of numerous self-powered systems, for example, power generation systems, storage systems, and sensing systems [17–26]. Many methodologies have been proposed for improving the output performance of TENGs, but most of these methods are both cost-prohibitive and complex [27–30]. However, in 2013, paper (a commonly available material) was used for the first-time ever as a supporting component for paper-based TENG [31]. This served as the motivation for investigating low-cost TENG. Nowadays, different types of paper-based structures have been designed and fabricated for enhancing the output performance of TENGs, with paper serving as both the supporting component and the functional component [32–36]. Zhang et al. have recently proposed a paper TENG formed from graphite layer coated by drawing with a graphite pencil [37], and employed as a conductive electrode. Nonetheless, the reliability of this graphite layer, which is adhered to the paper substrate, is expected to be negatively impacted by the deformation of the paper substrate.

One of the most attractive features of TENGs is the ability to harvest energy from various mechanical sources, such as human walking [37,38], human eye movement [39], and vehicular motion associated with encountering road potholes [40]. Identifying accessible low-cost commercial substances for reliable and high-output paper TENGs with a broad range of applications is essential for realization of this harvesting. In this work, we propose a novel X-shaped paper TENG (XP-TENG), based on a ballpoint ink layer coated by painting with a brush pen, which could effectively harvest mechanical energy from human body motion. The major innovations of this study are summarized as follows:

(A) The ballpoint ink layer formed by painting with a brush pen is used as conductive electrodes for the paper TENG. We demonstrate that the sheet resistance of the ballpoint ink layer is more stable than that of the graphite layer when the paper substrate is bent and the surface of the conductive electrodes are scratched. This excellent performance sheds light on the fact that, compared with the graphite layer, the ink layer has a longer service life, and is more suitable for the intricate environment. Maximum values of 326 V, 45 μA, and 542.22 μW/cm^2 are obtained for the open-circuit

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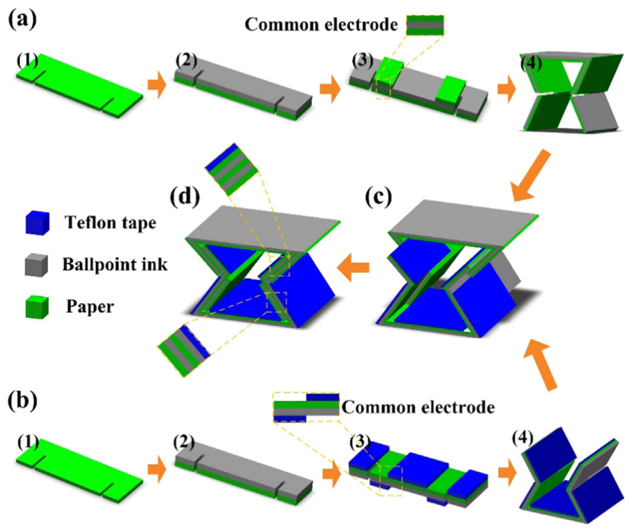

Fig. 1. Preparation mechanism of the fabricated XP-TENG. (a) The fabrication process of the Π-shape device. (b) The fabrication process of the inverted Π-shape device (inset shows a common electrode). (c) The assembly process of the XP-TENG. (d) Schematic illustration of one fabricated XP-TENG unit (inset shows the configuration of the device).

voltage (V_{OC}), short-circuit current (I_{SC}), and maximum power density, respectively, of the XP-TENG. This output performance is far superior to that of the output performance realized for the graphite layer [41].

(B) We propose a novel XP-TENG. Paper and Teflon tape constitute the triboelectric pairs, with the paper serving as a supporting component. Six friction pairs are integrated into one XP-TENG. Compared with other paper-based triboelectric structures, the X-shaped structure is an assembled cut-paper and origami-paper architecture that is capable of providing two working patterns. This can expand the scope of practical applications, for example, a stacked XP-TENG based on a second working pattern could harvest the mechanical energy generated by human elbow motion.

(C) For enhancing output performance, we propose a stacked XP-TENG. Full-wave bridges are independently connected to each working unit. The generated electrical output of the stacked XP-TENG with four working units stimulated by the human hand is capable of directly lighting up 101 high-power blue LEDs with working voltage of 3.4 V.

(D) The fabricated XP-TENG can be placed in a backpack for the purpose of harvesting the mechanical energy produced by the gait of an individual. This simple, affordable, and portable electronic device with two working patterns is expected to promote the realization of a sustainable power supply for wearable flexible electronic systems.

2. Experimental

Various structures, including arch structures, V-shape structures, and diamond structures, have been reported in previous studies [34,37,42,43]. However, most of the triboelectric structures had a single working pattern, thereby limiting the practical application of the TENG and rendering the device inefficient especially at a relatively low volume. Therefore, in this work, we proposed a novel XP-TENG. The design of the presented device is based on a novel X-shape geometry, which is referred to as an assembled cut-paper and origami-paper architecture.

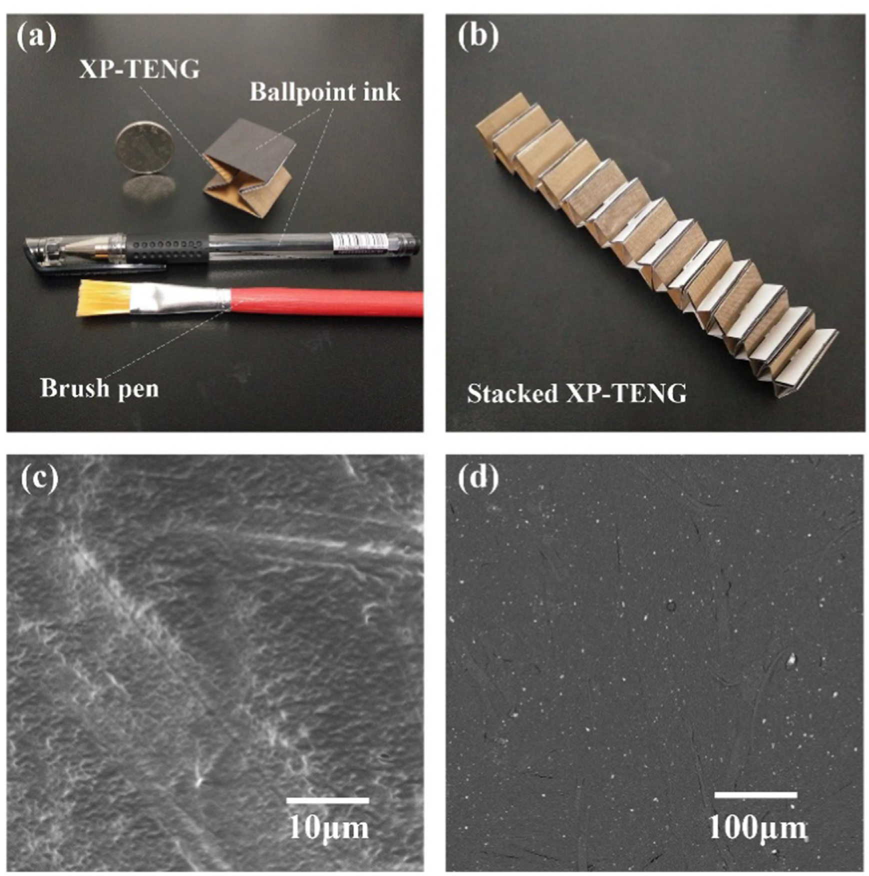

Fig. 2. (a) Photograph of a typical fabricated 3 cm × 3 cm XP-TENG unit. (b) Picture of stacked XP-TENG. SEM image of the (c) Teflon tape and (d) ballpoint ink surface.