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Full paper

Progressive contact-separate triboelectric nanogenerator based on conductive polyurethane foam regulated with a Bennet doubler conditioning circuit

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ABSTRACT

Scavenging the energy of human motions has attracted widespread attentions with the development of wearable electronics. This paper for the first time proposed a progressive triboelectric nanogenerator based on macro-triangle-prism-shaped conductive polyurethane (PU) foam and polytetrafluoroethylene (PTFE) film, which occupy the top and bottom spots of the triboelectric table respectively. The proposed macro-structured conductive PU foam also integrates the functions of spring, spacer and electrode. Thanks to the innovative structures and chosen of the materials, an extended current pulse width is obtained. A maximum RMS power density of 100 nJ/cm^2/tap was obtained with a 60 MΩ resistive load and press force of 10 N@5 Hz. By regulating the TENG with a Bennet doubler conditioning circuit, the ubiquitous voltage saturation phenomenon when charging a storage capacitor using full-wave rectifiers is avoided. Moreover, the energy per cycle, charging efficiency and totally stored energy can be exponentially pumped up. With a Bennet circuit charging a 5 nF capacitor, a harvested energy density of ~ 710 nJ/cm^2/tap was obtained when voltage across the capacitor was 400 V. Putting the device under sole within 25 human steps, the totally stored energy was 0.43 mJ with a Bennet circuit, 3.6 times higher than that using a full-wave rectifier (0.12 mJ). The Bennet was proven better for regulating the triboelectric nanogenerators with long operation-time compared to the classical full-wave rectifier.

1. Introduction

There is a continuously growing demand for new power sources with the rapid development of flexible electronics and wireless sensing nodes for applications in medical and structural health monitoring, internet of things (IoT) and environmental sensing [1–5]. The most commonly used power, i.e. chemical battery, is always accompanied with a limited lifetime and environmental problems [6]. The nanogenerator, which transduces environmentally existing energy including solar, thermal, mechanical and chemical energy to electricity, is a remarkable solution due to its renewable, flexible and sustainable properties [7]. Among different environmental energy sources, mechanical energy from vibrations, body motion, water/acoustic waves and even wind flow, is widely distributed and relatively easy to be harvested for the applications of wearable electronics. Therefore, emerging techniques including piezoelectric [8–10] and triboelectric-electret nanogenerators (TENG) [11–19] attract a wide attention, owing to the possibility of developing high-efficiency, flexible, biocompatible, and environmentally friendly mechanical energy harvesting devices. TENGs are particular electrostatic kinetic energy harvesters (e-KEH) [20] based on the coupling of contact electrification and electrostatic induction. Among four basic working modes [11] of TENG, the contact-separate (CS) mode is mostly concerned because of its high-efficiency and wide range of application [21]. CS-TENG consists in physical contact of two materials with different abilities of attracting electrons. Opposite charges are left on the surfaces of the two friction materials, and a current will take place from one electrode to another to rebalance the electrostatic field when they contact/separate each other with mechanical force, as for any e-KEH.

The output performances of TENG can be improved by enlarging the surface area [22], increasing the surface charge density [23,24], or adding 2-dimensional materials as charge store layers [25]. However, least attentions were paid to the elastic part of the TENG, although it is of great significance for the output performances. The material properties and structural designs of the mechanical springs define the contacting time, the approaching and detaching velocity, and the separating gap of the two electrodes, all these three points being crucial for a TENG. Various spring designs and materials have been tested including

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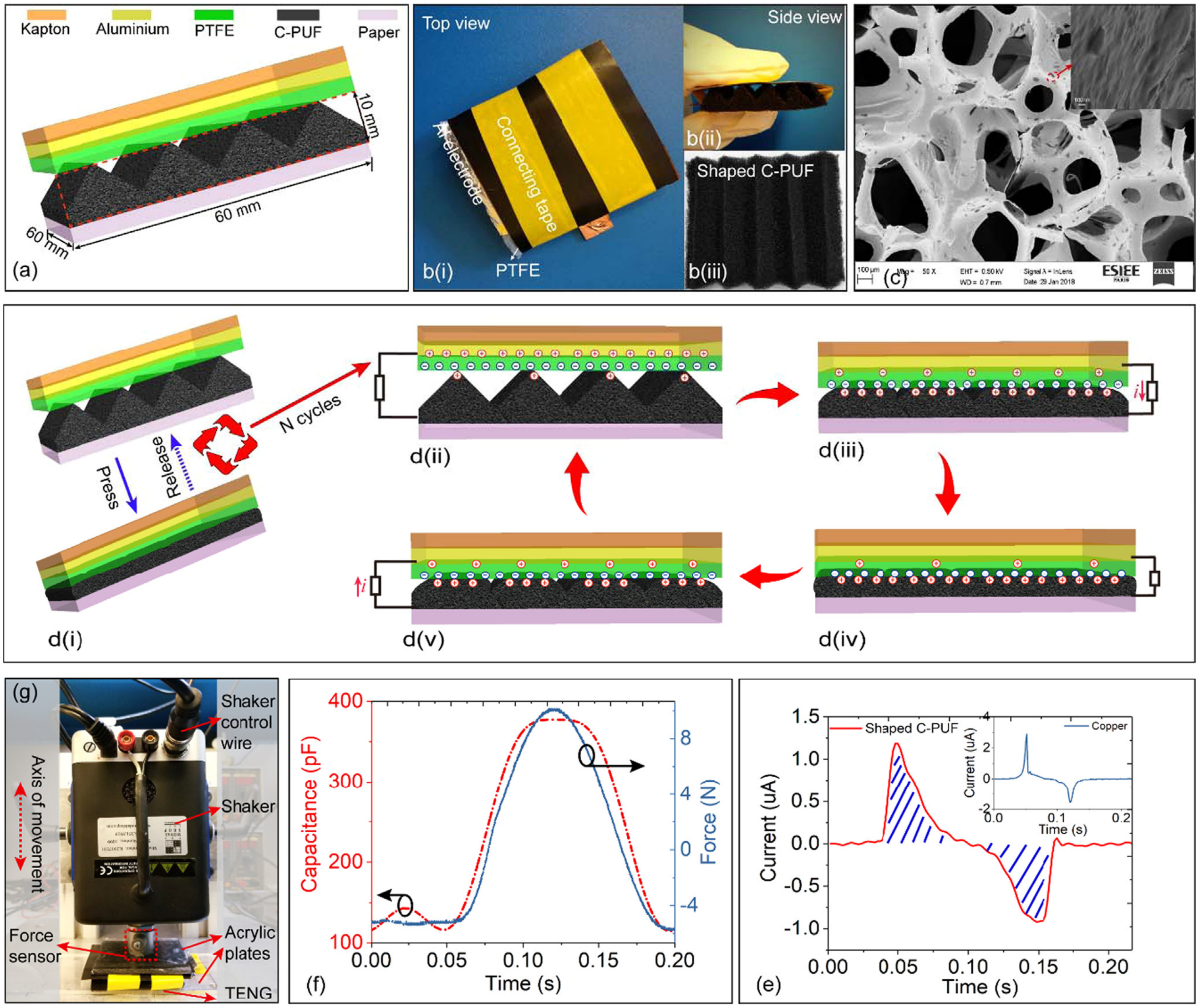

Fig. 1. Illustration and principles of the fabricated TENG. Diagram of the TENG (a). Top view b(i), side view b(ii), and fabricated C-PUF with triangle prisms b(iii). SEM image of the C-PUF (c). Process of the electron transport between different layers during operation (d). Measured transient current of the TENG (e), the inset figure is the current of a TENG using planar copper and PTFE as the friction materials. Capacitance variation of the TENG (e). Measurement setup (g).

classical metal spring [15], flexible polymer such as Kapton [26], arched or wave-shaped structures integrated with electrodes [14,27,28], and flat foam [29] as spacers to separate the two friction layers. However, the above designs have the drawbacks of wasting spaces and/or being sometimes not fully flexible. More advanced structure designs allow to enhance the electrical performances and application practicality of the TENG, for instances the bellows-type [17] that includes the packaging of the TENG, multilayers stacked silicone elastomers [30], and paper-cutting structures [31,32]. Interestingly, we noted that no researchers selected the commercial available low-cost open-cellular polyurethane (PU) foam as the spring materials except [29] utilizing flat PU foam as a spacer. In addition to the high shape recovery property of the PU foam, which gives it the potential to be a good spring, the PU foam is also a good friction layer since it occupies the top spot of positive materials in the triboelectric table [11]. The only time PU foam was used as the friction material was reported in [33].

In this paper, the authors propose a novel TENG based on a macro-structured *conductive PU foam* (C-PUF), which is PU foam doped with conductive carbon black powder, and a polytetrafluoroethylene (PTFE) film that is close to the bottom of the triboelectric table [11]. The C-PUF was shaped into macro scale triangle prisms, while its porous surface has micro/nano 3D structures. At the same time, C-PUF plays the roles of spring, spacer, friction layer and electrode. To the best knowledge of the authors, this is the first time that a conductive foam, and in particular C-PUF, is used for TENG in such a way: thanks to the macro-triangle prism shape, the contact and separation between the two electrodes become progressive. This means that the friction area is gradually growing/decreasing as the external force is applied/released. In this way the device operates as a mix between the contact-separation and the sliding modes. Due to its innovative structures and the chosen materials, the TENG gets the property of self-release without using extra springs. As it will be shown in the next section, the area below the current curve (that is directly related to the width of the current peak and to the harvested energy) is highly extended because the contacting time between the two friction materials are greatly enhanced thanks to the progressive contact and separate actions. The proposed TENG is particularly suitable for practical applications such as energy harvesting and pressure sensing for in/under sole during human walking. In addition, we also experimentally demonstrate that the universal voltage saturation phenomenon when charging a capacitor with a full-wave rectifier within a certain operation cycles can be avoided by using a Bennet doubler conditioning circuit [34–36]. The Bennet doubler