Applied Energy 213 (2018) 353–365

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Harvesting mechanical energy, storage, and lighting using a novel PDMS based triboelectric generator with inclined wall arrays and micro-topping structure

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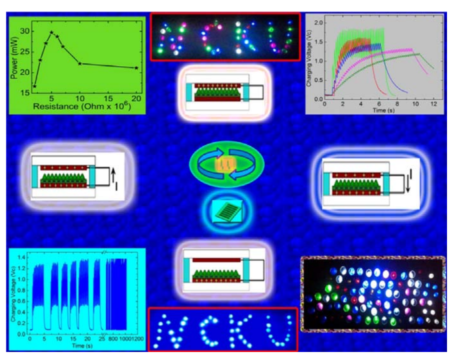
HIGHLIGHTS

- A novel **I**nclined **W**all **A**rrays and **M**icro-**T**opping (IWA-MT) PDMS is for triboelectric generator (TEG).
- IWA-MP-PDMS-TEG can harvest mechanical energy for high electric energy conversion & application.
- The open-circuit voltage is up to 135.8 V and short-circuit current of 109.5 µA i.e. density of 3.53 µA cm^{-2}.
- The maximum power is up to 29.7 mW and a power density of 9.6 W m^{-2}.
- The output energy can be stored in capacitors and light up 83 LEDs under tapping.

GRAPHICAL ABSTRACT

In this work, we describe a novel **I**nclined **W**all **A**rrays and **M**icro-**T**opping (IWA-MT) PDMS based triboelectric generator (TEG) consist of Micro-Particle topping (IWA-MP) and Splayed Micro-Dome topping (IWA-SMD) TEG. The TEG consists of an aluminium foil and an IWA-MT-PDMS film. In the separate-contact working mode, the IWA-MT-TEG shows good characteristics of **sustainable** mechanical–electrical energy conversion, energy storage, brightly colored LED emission, advertising board display, and high output performance. The fabricated method is a **green**, low-cost, easy-fabrication using a CO_2 laser-ablation on a polymethyl methacrylate mold and a polymer casting process.



ARTICLE INFO

Keywords:
Triboelectric generator
Energy harvesting
CO_2 laser
PDMS
Micro-topping

ABSTRACT

The triboelectric generators (TEG) or triboelectric nanogenerators (TENG) are effective devices converting the wasted mechanical energy into electrical one that can be used powerfully in light emission and energy storage for various low-power electronic applications. The TEG/TENG's output performance strongly depends on the surface morphology of the contact tribo-materials. Here, we investigate the morphology effect on the output performance of a **novel** polydimethylsiloxane (PDMS) based TEG with **I**nclined **W**all **A**rrays and **M**icro-**T**opping (IWA-MT) structure concerning mechanical–electrical energy converted electricity, storage, and lighting. The special novel shape of the IWA-MT-PDMS in the contact-separating mode with aluminum (Al) caused the increased contact area and friction of the two tribo-surfaces for enhancing the power and performance of TEG device. The **sustainable** IWA-MT TEG was fabricated using a green, low-cost, flexible CO_2 laser-ablation on the polymethyl methacrylate mold and a polymer casting process. Two IWA-MT types were designed to study the power enhancement and mechanical–electrical energy conversion of TEG including an **I**nclined **W**all **A**rrays with **M**icro-**P**article topping (IWA-MP) and with **S**players **M**icro-**D**ome topping (IWA-SMD). In comparison, the IWA-MP-PDMS-TEG significantly exceeds the IWA-SMD-PDMS-TEG with a maximum open-circuit voltage of 135.8 V,

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https://doi.org/10.1016/j.apenergy.2018.01.039
Received 16 June 2017; Received in revised form 11 January 2018; Accepted 13 January 2018
0306-2619/

a short-circuit current of 109.5 μA, a current density of 3.5 μA cm^{-2}, a maximum power of 29.7 mW corresponding to a power density of 9.6 W m^{-2}. The energy storage ability of IWA-MP-PDMS-TEG is characterized by a charged voltage of 1.74 V at 0.76 s into a 0.22 μF capacitorand, and stable charging with thousands of times into a 0.1 μF capacitor. The IWA-MP-PDMS-TEG can directly light on 83 colored LEDs wired in series, and power to the advertising boards.

1. Introduction

It is crucial nowadays to harvest or convert the wasted energy like solar, windy, waterway, or mechanical motion into useful energy for daily human need. Accompanying with the issue, many effective energy converting methods have been recently introduced to harvest wasted energy into electrical energy for real applications like: pyroelectric for self-powered photodetector system, nanodevices, or photosensing [1–3], piezoelectric [4,5], mechanical vibration [6], electromagnetic energy [7,8]. Triboelectric generators (TEG) and triboelectric nanogenerators (TENG), based on triboelectric effect and electrostatic induction, have been known as a friendly-environment, effective mechanical-electrical energy conversion devices [9–13]. They can be used for lots of our daily living practical applications like the acceleration sensor [14], force sensor [15,16], self-powered sensor [11], portable electronics [17], and sustainably powering biomedical microsystems [18]. Many research groups recently have paid much attention to the TEG/TENG for the electrical energy supplies [19–21], high endurability for severe environment [19], self-power biomedical systems [22], self-powered electronics [23], and blue energy [24]. While battery construction and wasted batteries including harmful chemicals are one of the results of living environment pollution, the TEG/TENG devices are potentially effective stable green powers for lighting emission, charging, or standing in place of batteries [25]. However, to find a technical solution based on cost-effective, rapid machining, friendly environment, and a high-performance criterion is a big issue for the TEG/TENG devices. Besides, the mechanisms, structures, or compound materials of the TEG/TENG technology are important factors to harvest mechanical wasted energy for power generation applications. They include harvesting airflow energy [26], waterway energy [27], self-powered smart seat [12], water flow [28], or human motion [29]. The PDMS (polydimethylsiloxane) is the effective triboelectric, non-toxic material, and easily formed by a casting process in micro-molds. The PDMS surface morphology could strongly affect the TEG/TENG's output performance, like microwire [30], wrinkle structure [31], nano-pattern [32], and micro-pyramid [33]. On the morphology characterization, introducing a structure onto the polymer surface will increase its surface roughness leading to increasing the friction and contact area of the tribo-materials as it is faced to push and rub with other tribo-materials. The role criteria of characterizing TEG/TENG's electrical performances include the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), current density (J_{SC}), power, energy storage, and lighting emission to assess for the real power generation applications. Some examples of lighting emission are to drive 20 LEDs by a nanostructure with a maximum power of 11 μW, V_{OC} of 60 V, I_{SC} of 10 μA [34]; 10 LEDs by the **silver** nanoparticles morphology with a power of 178 nW, V_{OC} of 6.3 V, I_{SC} of 0.635 μA [35]; 70 LEDs [36] by the triangular line PDMS/gold nanoflower structure with a power of 540 μW. Besides, some fabrications used **expensive** and **rare materials like silver** [35] and **gold** [36] and lots of **toxic chemicals** like $HAuCl_4$, polyvinylpyrrolidone, and KOH solutions in the electrodeposition, photolithography and KOH etching process. It reveals that the TEG/TENG with a higher power can light more bright LEDs. Some successful applications of TEG/TENG power sources are listed in the Table S1 supporting information. For examples, they include the self-powered sensors by a 2 mW power [11]; the self-powered wearable sensors by a 12 μW power [37]; a self-powered wireless body sensor network system for heart-rate monitoring by a 2.28 mW power [38]; a self-powered locomotion detector for security applications by a 576 μW power [39]; a humidity sensor for effective moisture detection by a 52.3 μW power, V_{OC} of 33.7 V, and I_{SC} of 1.86 μA [40]; a self-powered wireless remote system by a 2.5 μW cm^{-2} power density, and J_{SC} of 1.35 μA cm^{-2} [41]; the autonomous power MEMS application by a 39.8 μW/cm^2 power density [42]; the biomedical applications and driven 18 LEDs by V_{OC} of 245 V and I_{SC} of 50 μA [43]; a touch sensor by V_{OC} of 50 V [44], a self-powered communication system by V_{OC} of 750 mV [45]; and forecasting potential sensor through tech mining [46]. In brief, the real applications can be realized by TEG/TENGs with the power range from 12 μW to 2.28 mW, or even 750 mV. It is noted that a TENG/TEG with higher power output can enlarge more applications for devices using low-power electricity.

In this work, we have demonstrated the morphology effect on sustainable mechanical-electrical energy conversion, energy storage, lighting emission, and output performance of a **novel** TEG structure formed of the inclined wall arrays with micro-topping (IWA-MT) PDMS structure based triboelectric generator (IWA-MT-PDMS-TEG). Moreover, they are fabricated using a green, low-cost, easy-fabrication CO_2 laser-ablation method on the polymethyl methacrylate (PMMA) mold and a polymer casting process. The sustainable IWA-MT-PDMS-TEG consists of easy-finding materials of IWA-MT-PDMS film and aluminum (Al) foil, in that, Al plays two core roles as electrode and tribo-material. Two special kinds of IWA-MTs were introduced to enhance the power output: the inclined wall arrays with a micro-particle topping PDMS film based triboelectric generator (**IWA-MP-PDMS-TEG**) and the inclined wall arrays with a splayed micro-dome topping PDMS film based triboelectric generator (**IWA-SMD-PDMS-TEG**). The advantages of IWA-MT-PDMS films transferred from the female PMMA mold by CO_2 laser ablation are the green process and more quick-manufacturing, low-cost than other traditional methods using photolithography [47], reactive ion etching [34], 3D printing technique [48], or complicated processes. The traditionally complicated methods include using the expensive gold electrodeposition/silicon lithography/KOH etching processes [36], silver particle by chemical reduction [35], or **expensive gold material** and ZnO nanorods by chemical etching [49]. Table 1 lists the comparison of surface structure, materials, fabrication methods, applied force and electrical characteristics between the traditional TENG and our IWA-MT-PDMS-TEG.

In the same working condition and simply external force by hand tapping with low frequency, the IWA-MP-PDMS-TEG transcends with the maximum V_{OC} of 135.8 V, I_{SC} of 109.5 μA, J_{SC} of 3.5 μA cm^{-2}, the power of 29.7 mW at a 5 MΩ external resistance, and the power density of 9.6 W m^{-2}. In contrast, the lower electrical values generated by the IWA-SMD-PDMS-TEG comprising the maximum V_{OC} of 112.6 V, I_{SC} of 83.5 μA, J_{SC} of 2.7 μA cm^{-2}, the power of 13.8 mW, and the power density of 4.4 W m^{-2}. The both IWA-MT-PDMS-TEGs also showed the good energy storage ability and emission applications. In details, the IWA-MP-PDMS-TEG can charge into a 0.22 μF capacitor with the maximum charged voltage (V_C) of 1.74 V at 0.76 s, stable charging with thousands of times into a 0.1 μF capacitor, and drive 83 LEDs connected in series lighting brightly on by the hand pressing. In contrast, the IWA-SMD-PDMS-TEG can only charge V_C of 1.04 V into the same capacitor at 4.5 s and light 65 LEDs. The IWA-MTs can enhance the output performance of the TEG because of increase in the contact area and friction between the IWA-MT-PDMS and Al in the contact-separate working cycle. Moreover, the IWA-MP has more sharpness micro-topping shape and denser micro-topping than that of the IWA-SMD. By introducing the IWA-MT-PDMS into the TEG, the IWA-MP-PDMS-TEG has the V_{OC} and