FABRICATION OF PORTABLE TRIBOELECTRIC NANOGENERATOR BASED ON NATURAL LEAVES

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Abstract

Recently, green triboelectric nanogenerators (TENG) have emerged as an alternative adequate power supply to solid-state chemical batteries to overcome certain drawbacks, including toxic materials, limited lifetime, or recharged requirement. In this article, we demonstrated the fabrication of the natural and common leaf-based triboelectric nanogenerator (NF-TENG), which uses jackfruit, banana, and bamboo leaves as positive triboelectric layers. Among some fabricated NF-TENGs, the bamboo leaf-based TENG presents novel output characteristics, including the maximum output power density of 7 $mW.m^{-2}$, the short-circuit current of 6 μA under the excitation power and the frequency supplied to the mechanical oscillator of 33.6 mW and 30 Hz. This NF-TENG can light up 18 green commercial LEDs simultaneously, which promises to be a novel solution for powering low-power electronic devices using different vibration energy sources.

Keywords: *Triboelectric nanogenerator; bamboo leaf; energy haversting.*

1. Introduction

Recently, triboelectric nanogenerator (TENG) has been developing explosively as an effective solution to power hundreds of billions of Internet of Things (IoT) devices in the future [1-5]. The operating principle of TENG is based on the triboelectrification effect and electrostatic induction [6, 7] that can convert flexibly environment mechanical vibrations such as wind [8], rain drops [9], and even the movement of the human body [3, 10] into electrical energy. TENG owns outstanding advantages compared to other nanogenerators, such as simple configuration and fabrication process, diverse material selection, and low-cost but high-output voltage characteristics [11].

TENG configuration generally includes the electrodes and the triboelectric layers [12]. The contact or sliding friction of the triboelectric layers will generate oppositely charges on their surface so that the characteristic of triboelectric layers decisively affects the output characteristic of the TENG. Triboelectric layers can be divided into two main groups: (1) positive triboelectric one that donates electrons and (2) negative triboelectric one that accepts electrons during frictional contact or sliding process [13, 14]. Group (2) usually limits the choice of material to polymer films such as Polytetrafluoroethylene

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(PTFE), Polydimethylsiloxane (PDMS), Polyvinylidene fluoride (PVDF), Polyvinylchloride (PVC), etc. In contrast, group (1) has more diverse choices of material such as metal films (Gold, Copper, Aluminium), organic material films (Poly vinyl alcohol, Polyethylene terephthalate (PET), Nylon, etc. Recently, Cellulose ($(C_6H_{10}O_5)_n$) materials have gained increasing attention for positive triboelectric layer due to their own many hydroxyl groups in the molecule [5]. Fortunately, these materials are low-cost and readily available in nature because of a parts of various plants. Some previous works have used them in the fabrication of TENG, such as husks [15], peanut shells [2], powdered leaves [16], and natural leaves [17].

Among some types of rich Cellulose materials, leaves present the high-performance positive triboelectric layer with a large surface area, low-cost, easy replacement, and film configuration for mass production of TENGs [16-21]. In this study, we demonstrated the use of common leaves in tropical climates, which are easily collected and have large surface areas as positive triboelectric layers in fabricated TENG, including jackfruit, banana, and bamboo leaves. Those materials have not been used for TENG in previous works. The results show that the bamboo leaf-based TENG has outstanding output characteristics which promise powering applications for low-power electronic components such as LEDs, microsensors, and microelectromechanical systems.

2. Experiment

2.1. Fabrication of triboelectric nanogenerator based on natural leaves

Figure 1(a-f) illustrate the fabrication process and the fabricated NF-TENG. Materials used for the fabrication procedure include four groups: (1) sheets of acrylic (2 mm thick), transparent double-sided tape (30 mm wide, 1mm thick), copper tape (single-sided adhesive, 50 mm wide, 0.05 mm thick), two signal wires (the core of aluminium fibres, with the diameter being about 1 mm and 100 mm length) and PET film (0.5 mm thick, commonly used as a protective cover for A4 paper). These materials were all commercial products and could be easily purchased; (2) PTFE film (50 mm wide, 0.03 mm thick, purchased from Taizhou Guangming Electronic Materials); and (3) three types of leaves from jackfruit, banana, and bamboo collected in Hanoi, Vietnam. They were washed in deionized water, dried at 40°C for 24 hours, and then cut into 50 × 50 mm sheets.

The fabrication process includes four main steps as follows: First, 02 acrylic sheets were cut into squares with dimensions of 50 × 50 mm, cleaned, and removed the surface protective paper (Fig. 1a). They play the role of the top and bottom flat substrates of the NF-TENG for mounting the electrodes and triboelectric layers (PTFE and leaf). Next, they were covered with a layer of double-sided adhesive tape (Fig. 1b) and attached copper electrodes (adhesive side facing up) and two signal wires as shown in Fig. 1(c-d). Then, attach the PTFE film and sheet of leaf on top of two electrodes. Finally, a PET film (5 × 11 mm) and double-sided tape create a sandwich structure with two triboelectric layers facing each other at a distance of about 2 mm (Fig. 1f).

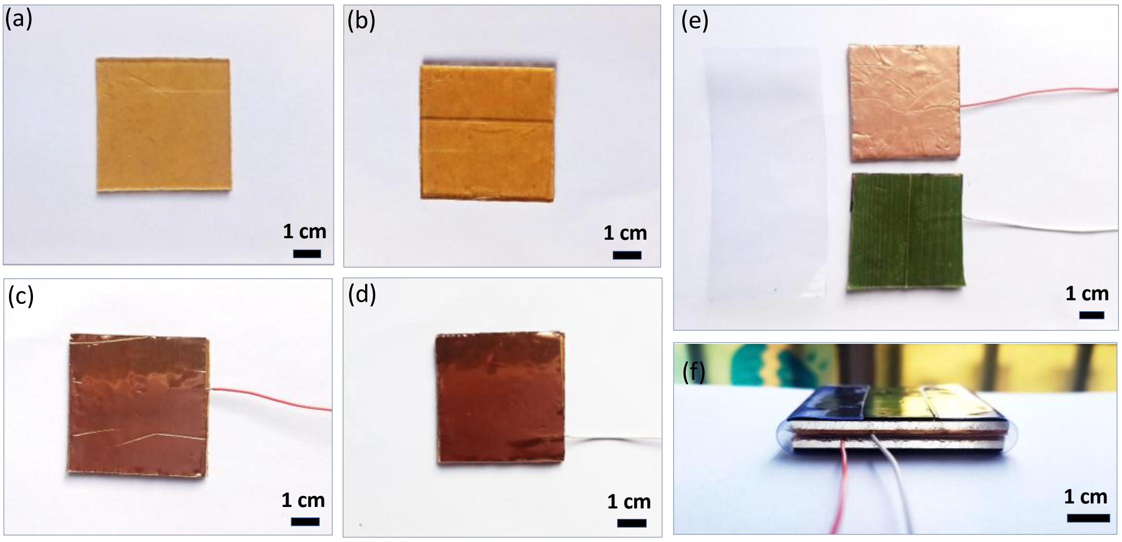

Fig. 1. (a-e) The fabrication process of the NF-TENG and (f) The fabricated NF-TENG.

2.2. Investigating the characteristics of NF-TENG

Figure 2 shows the measuring system used for characteristics of the fabricated NF-TENG, including (1) A function generator (GF 597A, Vietnam, frequency range: 20 Hz - 30 MHz, 0.1 Hz resolution, max Vp-p ~ 20 V; 50 Ω internal impedance, Sinewave form); (2) A mechanical oscillator (A dynamic speaker, 25 W maximum power, 4 Ω impedance, speaker's diaphragm is mounted a ABS plastic rod (weight 40 grams, diameter 20 mm, 80 mm length); (3) The fabricated NF-TENG is mounted on a mini scissor lift table (4); (5) A test board for mounting electronic components; (6) A digital oscilloscope (GW Instek GDS-1102B, China) and (7) A digital multimeter (GW Instek GDM-8342, China).

The generator can control the power and excitation frequency of the mechanical oscillator. The lower side of the TENG is mounted on the mini scissor lifting table, while the upper side contacts with the oscillating rod (from the oscillator). The real-time AC open-circuit voltage (V_{OC}) characteristic was investigated by connecting the two leads from the TENG to the digital oscilloscope. We use the AC current measurement mode in the digital multimeter GDM-8342 to measure the open-circuit current (Root-mean-square current (I_{RMS})) value. The measurement parameters set up as follows: (1) Measured value: root-mean-square current; (2) Sampling rate: 10 readings/second; (3) Current measuring range:

500 µA, and resolution: 10 nA. The excitation power supplied to the oscillator is calculated by measuring the voltage and current supplied to the oscillator.

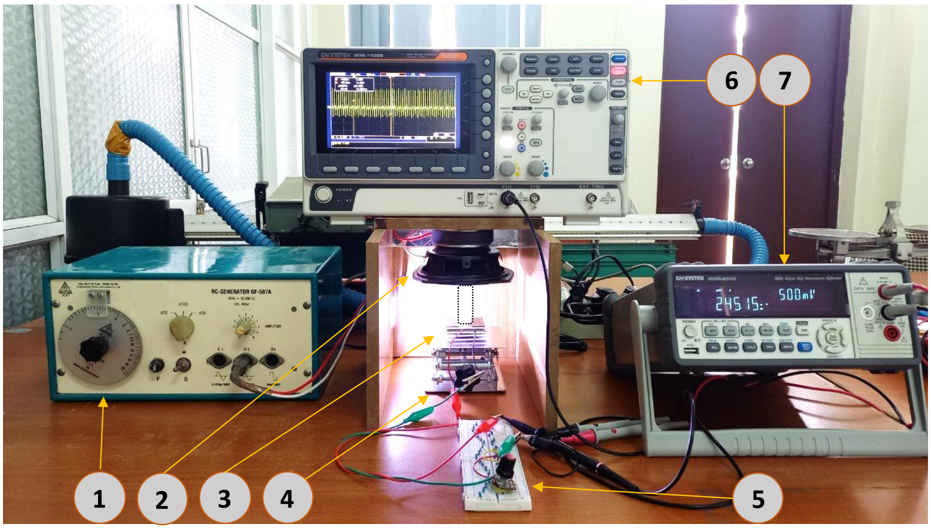

Fig. 2. The characteristic measurement diagram of NF-TENG.

The surface of triboelectric layers (leaves and PTFE film) was studied by using Scanning Electron Microscope (SEM-TM4000plus, HITACHI, Japan) after they were coated with a thin gold layer of about 10 nm thickness by sputtering.

3. Results and discussion

3.1. Working principle of NF-TENG

The principle operation of NF-TENG is based on the triboelectrification and electrostatic induction [6, 7, 22] as illustrated in Fig. 3. At the initial state (Fig. 3a), the two triboelectric layers are in the electrical equilibrium, and the current in the circuit is equal to zero. Under excitation from the mechanical oscillator, two triboelectric layers come into contact and friction with each other. As the results, electrons transfer from the surface of the leaf to the surface of the PTFE film due to the stronger ability of PTFE film to gain electrons, creating equal positive charges and negative charges on the surface of two triboelectric layers (Fig. 3b). When stopping the mechanical excitation, the elastic force from the PET film causes the two triboelectric layers above separate from each other and a potential difference between the two electrodes due to the electrostatic induction the mechanical excitation stops, the elastic force from the PET film causes the two triboelectric layers above separate from each other (Fig. 3c). Then a potential difference between two electrodes is established due to the electrostatic induction [18]. This potential value drives current through the external load, from the top electrode to the bottom one. The current flow leads to a redistribution of charges on the two electrodes and restores the electrical equilibrium state when two triboelectric layers are maximally separated (Fig. 3d). When the excitation mechanical oscillation continues, this electrical equilibrium once again is broken, causing the current which flows through the load in the opposite direction from the bottom electrode to the top one as in Fig. 3e. If the above excitation is repeated and maintained, the NF-TENG will operate as an AC power supply for the load in the external circuit.

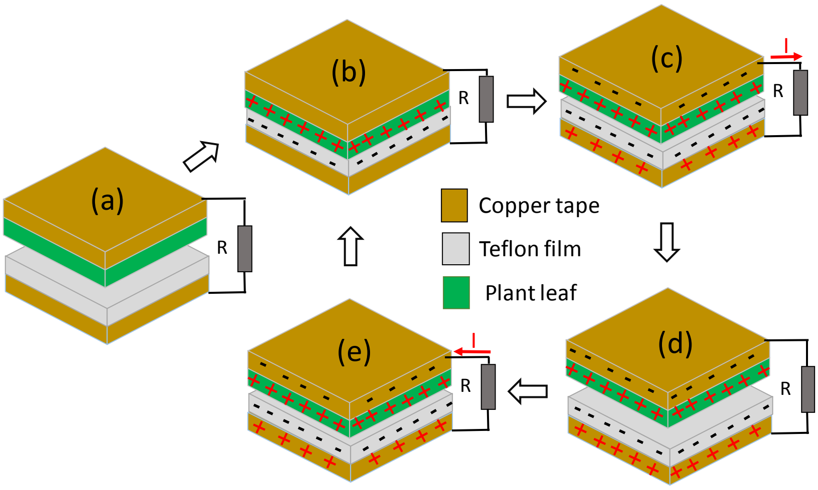

Fig. 3. a-e) Illustrating the operating principle of the NF-TENG.

3.2. Characteristics of NF-TENG

Figure 4 presents the SEM images of the triboelectric layers' surface. The PTFE film shows a uniform and smooth surface (Fig. 4a), while the surface of the jackfruit leaf has prominent, distributed small round nodules (their diameter is about 8 - 10 µm) scattered (Fig. 4b). The surface of the banana leaf has small raised ridges with a dense distribution while the surface of the bamboo leaf has a sparse and flat ridge. The thickness of jackfruit, banana, and bamboo leaves are approximately 200 µm, 400 µm and 80 µm, respectively (Fig. 4e-g). Based on the same structure of NF-TENG, the specific surface characteristics, thickness, and chemical composition of the leaves can affect the friction process between them and the PTEF film, thereby affecting the output characteristics of the NF-TENG.

Figure 5 shows the open-circuit voltage (V_{OC}) characteristics of the NF-TENGs fabricated from the three types of leaves above. At the same excitation frequency value of 30 Hz and the power supplied to the mechanical oscillator of 33.6 mW, the results show that the V_{OC} of the bamboo leaf-based TENG has a maximum value of ~ 9 V, compared to ~ 4 V for banana leaf and about 3.2 V for jackfruit leaf. Their average V_{P-P} is about 14 V; 5.2 V, and 3.8 V, respectively. Those results prove bamboo leaf is a novel natural material for fabricating TENG with prominent electrical friction performance. The obtained results can be explained by the following reasons: (1) The surface of the bamboo leaf has few burrs, which increases the frictional contact area with the PTFE film. Meanwhile, the surface with many high ridges of the banana leaf and the small round nodules scattered on the jackfruit leaves can create gaps and reduce the contact area between them and the PTFE film; (2) The thickness of the bamboo leaf is only ~1/2.5 and ~1/5 compared to jackfruit leaf and banana leaf, respectively, making the electrostatic induction effect more effective (normally the distance between two layers of electrical friction needs to be at least about 10 times their thickness [7]); (3) The composition of cellulose and other chemical compounds in the above leaves can also affect the output characteristics of TENG. However, due to the biological diversity (plant varieties, regions, weather, soil characteristics, etc.), the chemical composition of leaves is complicatedly affected, needing further research.

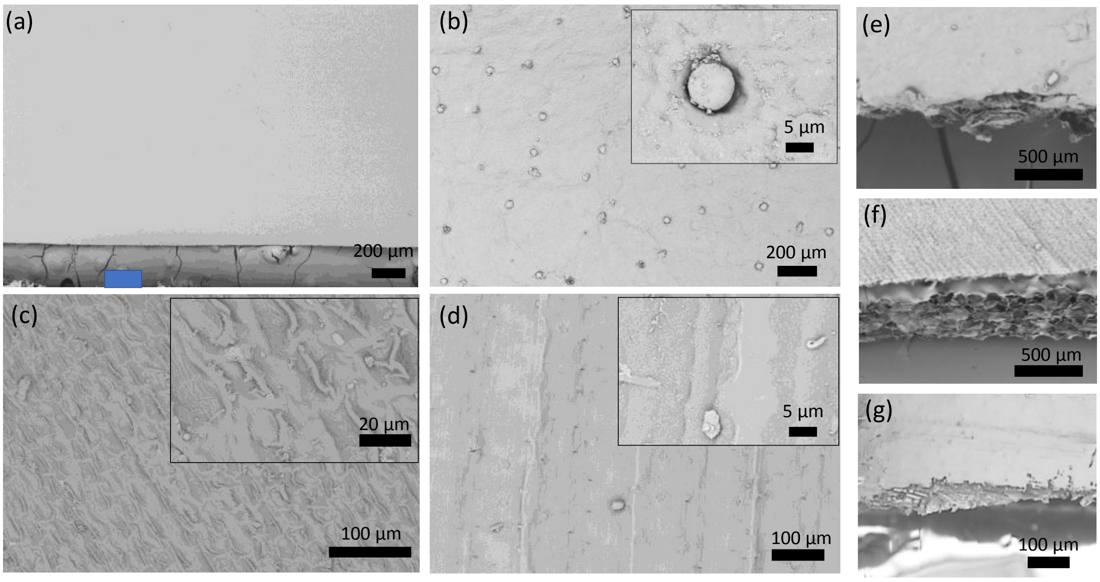

Fig. 4. a-d) SEM images of PTFE film, jackfruit leaf, banana leaf and bamboo leaf; e-g) Cross-sectional SEM image of jackfruit leaf, banana leaf and bamboo leaf.

The dependence of the V_{OC} and short-circuit current (I_{SC}) of bamboo leaf-based TENG on the excitation power supplied to the mechanical oscillator is shown in Fig. 6. The maximum of V_{OC} tends to increase with increasing excitation power as demonstrated in Fig. 6(a-d), reaching values of 2.5 V, 5.1 V, 7.5 V, and 15 V when the excitation powers are 24.7 mW, 29 mW, 33.6 mW, and 38.6 mW, respectively. At the above excitation powers, the I_{SC} maintains values of 3 µA, 4 µA, 6 µA, and 9.1 µA, respectively (Fig. 6e). The fabricated NF-TENG is present as a stable current source, with a response time when varying excitation power of only about 0.4 ms (Fig. 6f).

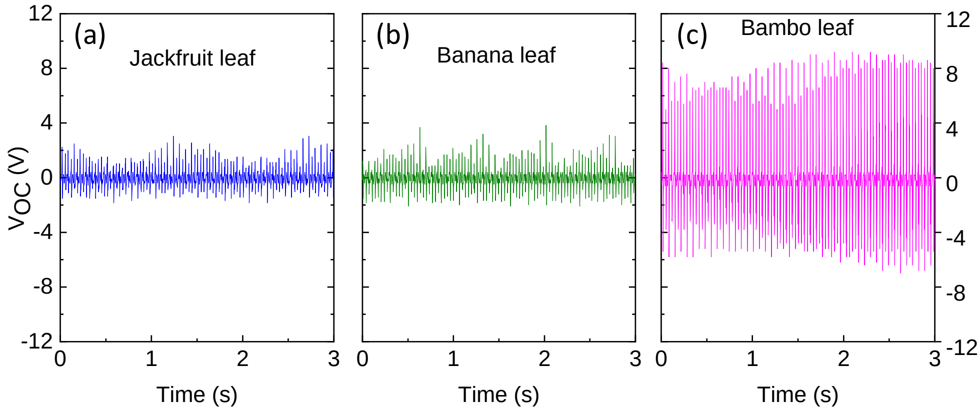

Fig. 5. a-c) The open-circuit voltage characteristics of the fabricated NF-TENGs.

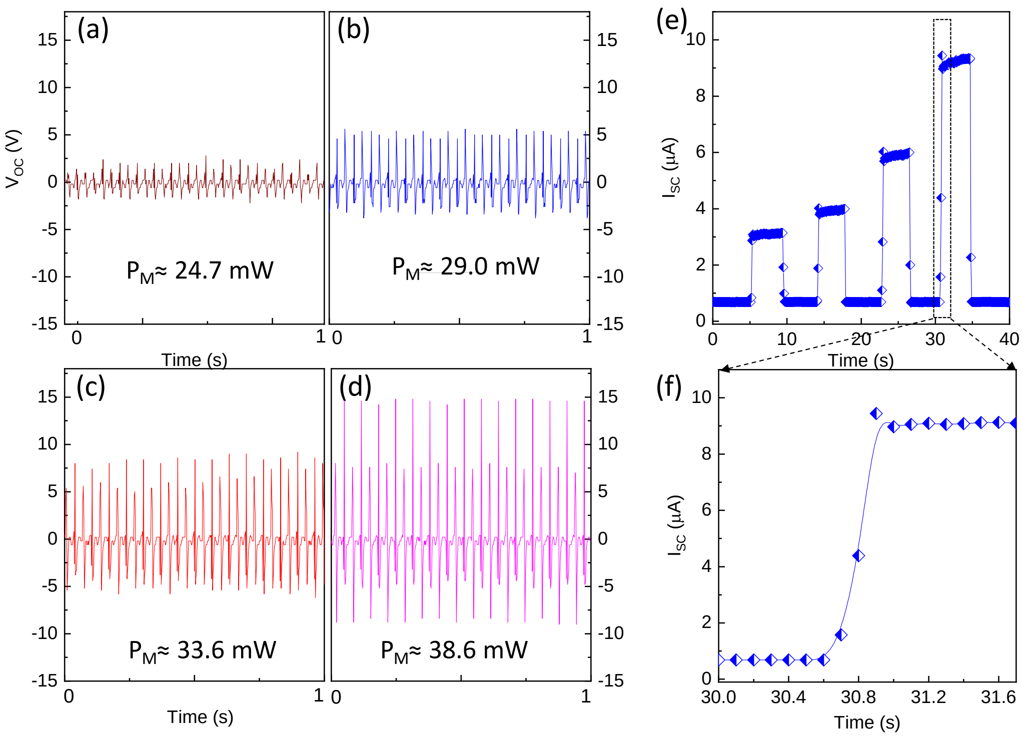

Fig. 6. a-f) The dependence of the V_{OC} and short-circuit current (I_{SC}) of bamboo leaf-based TENG on the excitation power supplied to the mechanical oscillator.

Figure 7 shows the voltage, current, and power characteristics when the NF-TENG supplied to different external pure resistors. Under 33.6 mW excitation power, when the value of the resistor < 10^5 Ω, the current value in the external circuit maintains a constant of approximately 6 µA, drops to 2.8 µA at $2{\cdot}10^6$ Ω, and down to nearly 1.0 µA at 10^7 Ω (red line). Besides, the voltage value gradually increases from 0.5 V at the resistor value is

10^5 Ω to 5.5 V when the resistor value is 10^7 Ω and reaches the highest value of about 12 V when the resistance is 10^8 Ω (blue line). The power density characteristic present as a function of the external circuit resistors is shown in Fig. 7b, with a maximum power density of 7 mW/m^2, similar to other works [17, 18, 24, 25]. The peak power of NF-TENG is linearly dependent on the excitation power as shown in the insert image in Fig. 7b, indicating that it is possible to control the power of NF-TENG flexibly by varying the excitation power.

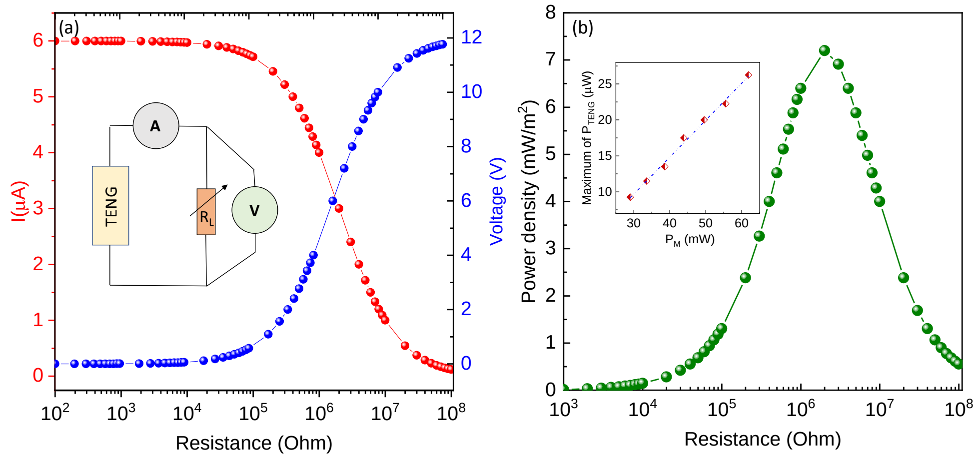

Fig. 7. a-b) The voltage, current, and power characteristics of the NF-TENG with different resistors.

Figure 8 illustrates the practical power supply application of the NF-TENG. The fabricated bamboo leaf-based NF-TENG is connected to a 4-diode rectifier bridge circuit and directly supplies to 18 green commercial LEDs in series (Diagram illustration as shown in Fig. 8a). Under mechanical excitation power and frequency of 33.6 mW and 30 Hz, the NF-TENG is capable of light up 18 green LEDs continuously (Fig. 8c), compared to when they are not powered (Fig. 8b). The results show the potential application of NF-TENG in powering low-power electronic devices.

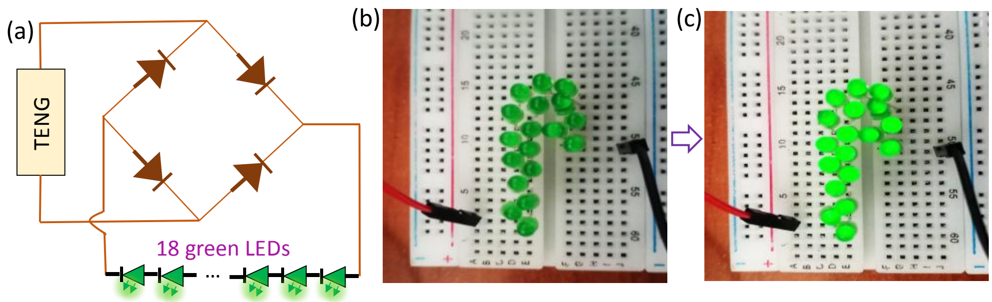

Fig. 8. a) Diagram illustrating the connection of NF-TENG to 18 green commercial LEDs; b-c) Before and after powering the LEDs by the fabricated NF-TENG.

4. Conclusion

This article demonstrates the fabrication of novel triboelectric nanogenerators based on natural leaves, including jackfruit, banana, and bamboo leaves. The bamboo leaf-based TENG shows prominent output characteristics, which have a maximum output power density of 7 $mW.m^{-2}$ and 6 µA of the short-circuit current under the excitation power, and the frequency supplied to the mechanical oscillator of 33.6 mW and 30 Hz. This NF-TENG can light up 18 green commercial LEDs and promises a potential novel solution for powering low-power electronic devices.

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CHẾ TẠO MÁY PHÁT ĐIỆN NANO MA SÁT CẦM TAY TỪ CÁC LOẠI LÁ TỰ NHIÊN

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Tóm tắt: Gần đây, sự phát triển nhanh chóng của các thiết bị Internet of Things (IoT) dẫn tới nhu cầu ngày càng lớn của việc cung ứng các nguồn cấp điện công suất thấp có khả năng hoạt động bền bỉ và thân thiện với môi trường. Máy phát điện nano điện ma sát (TENG) được coi là giải pháp cung cấp điện hiệu quả thay thế cho các loại pin hóa học thể rắn có chứa vật liệu độc hại gây ô nhiễm môi trường, tuổi thọ hạn chế và cần được sạc lại sau một thời gian sử dụng nhất định. Trong nghiên cứu này, các tác giả đã mô tả việc chế tạo máy phát điện nano ma sát dựa trên một số loại lá tự nhiên và phổ biến (NF-TENG) ở các quốc gia có khí hậu nhiệt đới, bao gồm lá mít, lá chuối và lá tre. Trong các NF-TENG dựa trên lá tự nhiên đã chế tạo, TENG dựa trên lá tre thể hiện các đặc tính đầu ra tốt với mật độ công suất đầu ra tối đa đạt tới 7 $mW.m^{-2}$ và dòng điện ngắn mạch đạt giá trị 6 µA dưới công suất kích thích và tần số cung cấp cho bộ tạo dao động cơ lần lượt là 33,6 mW và 30 Hz. Thiết bị TENG này có khả năng thắp sáng 18 đèn LED thương mại màu xanh lá cây và hứa hẹn sẽ là một giải pháp phù hợp để cung cấp năng lượng cho các thiết bị điện tử công suất thấp bằng cách chuyển đổi các nguồn năng lượng dao động cơ học khác nhau từ môi trường xung quanh hoặc từ các chuyển động của bộ phận cơ thể con người.

Từ khóa: *Máy phát điện nano ma sát; lá tre; thu năng lượng từ môi trường.*

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