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Article

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Energy Reports

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Suggested Citation: Zhu, Zhiyuan et al. (2019) : Paper-based methodology for investigation of triboelectric nanogenerators, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 5, pp. 393-397,
<https://doi.org/10.1016/j.egyr.2019.03.007>

This Version is available at:

<https://hdl.handle.net/10419/243594>

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Research paper

Paper-based methodology for investigation of triboelectric nanogenerators



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ARTICLE INFO

Article history:

Received 16 December 2018

Received in revised form 19 February 2019

Accepted 19 March 2019

Available online xxxx

Keywords:

Triboelectric nanogenerator (TENG)

Matching impedance

ABSTRACT

Triboelectric nanogenerators (TENGs) have been investigated as a promising methodology to harvest mechanical energy into electricity. The matching impedance and the transient property of TENGs are important for their practical application. In this work, we proposed novel paper-based methodology for investigation of TENGs. First, we propose a novel method for triggering transience of pencil-on-paper (POP)-TENGs using household microwave oven and commercial graphite pencil. Moreover, a fast, simple and cost-effective approach for measuring the matching impedance of TENG based on paper variable resistor is proposed. The results of this work are beneficial for simple, fast and cost-effective functionalization of TENGs.

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1. Introduction

Triboelectric nanogenerators (TENGs), proposed by Prof. Zhong Lin Wang in 2012, have been investigated as an efficient methodology to harvest mechanical energy into electricity (Wei et al., 2018a; Tang et al., 2015; Li et al., 2016a; Guo et al., 2016). TENGs are developing rapidly for different sensing and energy harvesting applications (Xu et al., 2019; Wu et al., 2019; Askari et al., 2018b; Li et al., 2017; Askari et al., 2018a,c; Kim et al., 2014; Askari et al., 2017; Kim et al., 2015). The measurement of matching impedance of TENGs is important in order to tune their output performance (Li et al., 2016b, 2014; Wu et al., 2018; Wang et al., 2017). Currently, an external variable resistor is connected to TENG, and the electronic performance on the resistor is measured versus various loading resistance (Tang et al., 2014; Zhang et al., 2016; Li et al., 2015). The matching impedance of TENG is determined when the output power on variable resistor reaches its peak. In most cases, the variable resistor is provided by apparatus such as rotating resistance box, which is expensive and time consuming when adjusting resistance. Moreover, the resistance changes are represented by typical resistance points (difficult to cover every value in resistance changing region), which affect the accuracy of the matching impedance measurement.

On the other hand, the electronic waste (e-waste) of power source is one of the fastest growing problems of modern society. Transient electronics refer to fully functional and complete electronic systems that can be made non-functional or physically destroyed on demand (Hwang et al., 2012; Yin et al., 2014; Song et al., 2014; Chang et al., 2017). Ultimately, transient electronics offers solution for disposing of electronics in a safe and easy form. The external trigger stimulus is the key point that influence the transient performance of electronics. Different triggers, such as water (Brenckle et al., 2015), light (Hernandez et al., 2014), and temperature (Park et al., 2015) have been used to make materials transient. Soluble transient electronics, which utilize water as a trigger, take a considerable amount of time for complete destruction. Other types of triggers (light, temperature, and others) require other specialized and expensive equipment (microfluidic, UV radiation, precise heating instrument, etc.) with complicated triggering process. Therefore, it is important to develop a direct and cost-effective triggering method for rapid destruction of TENGs.

Paper TENGs are proposed with the advantages of low cost, flexibility and ease of disposal (Wu et al., 2016a; Zhang et al., 2018). Especially, Xiaosheng Zhang et al. invented a paper TENG based on pencil-drawn electrode using cost efficient, commercially available commodity materials and single-step processes (Zhang et al., 2017). Along with the inherent advantages of TENG for harvesting mechanical energy (Wu et al., 2016b; Meng et al., 2013a; Wei et al., 2018b; Zhao et al., 2017; Meng et al., 2013b;

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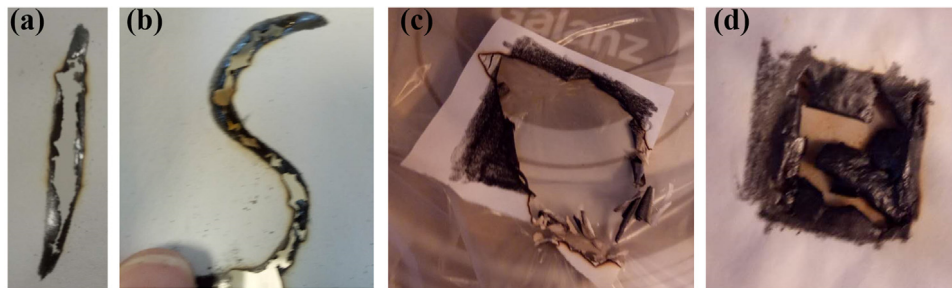


Fig. 1. Destruction of typical (a) straight pattern, (b) S pattern, (c) dry square pattern, and (d) wet square pattern.

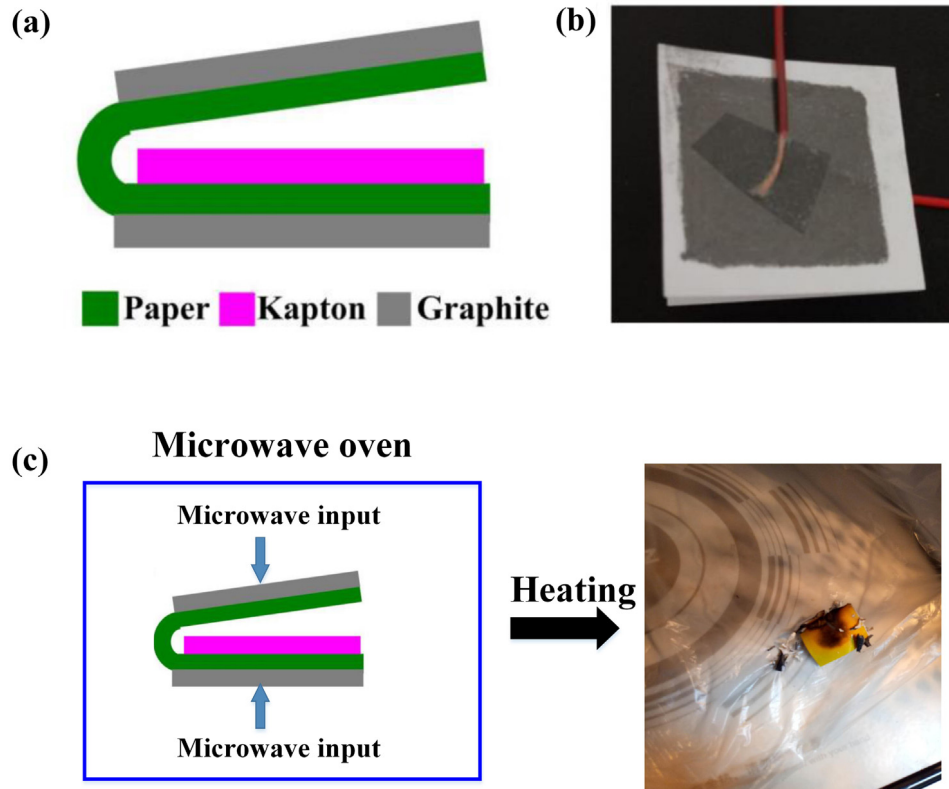


Fig. 2. (a–b) Schematic and photograph of the paper TENG, (c) Destruction of the paper TENG.

Luo et al., 2018; Wei et al., 2018c; Luo et al., 2015), this kind of paper TENG is promising candidate for transient electronics considering that the paper substrate can be easily destroyed. It is noted that the commonly used triggering method for paper is simple fire burning, which is rapid and cost-effective. However, because electronics are often packaged with glass or polymer encapsulation, simple fire burning may not guarantee complete destruction. Furthermore, it is difficult to control the destruction profile for the fire burning of paper substrate.

In this work, we present a novel method for direct and rapid TENG transience-triggering based on commercially available microwave oven, paper and a graphite pencil. The transience of paper substrate can be triggered even when the paper substrate is coated with polymer clay, indicating potential application in polymer packaged paper electronics. Further, a fast, simple and cost-effective approach for measuring the matching impedance of TENG based on paper variable resistor is proposed. The results of this work are beneficial for simple, fast and cost-effective functionalization of TENGs.

2. Results and discussions

Compared with conventional batteries, transient power devices have been demonstrated to have the advantages of controllable termination of functionality (Fu et al., 2015). However, most of these devices are expensive and need external power sources for operation, which limit their scope of application. The development of simple and cost-effective TENGs is of great importance for transient electronics applications.

Microwave is a form of electromagnetic energy, and microwave irradiation can be applied to preparing graphite-based material. For instance, reduced graphite oxide materials can be readily obtained in a commercial microwave oven (Zhu et al., 2010). However, little research has been carried out using commercial pencils as graphite supplies for transience of paper substrate in a commercial microwave oven. Moreover, the application range of pencil/graphite should be extended further to cover more fields and show its beneficial features in multidisciplinary domains.

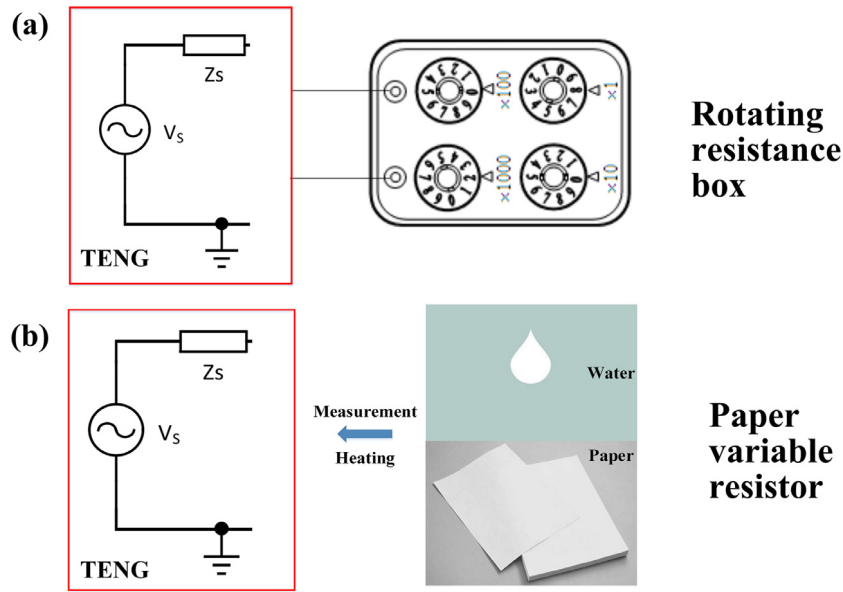


Fig. 3. Schematic of matching impedance measurement based on (a) rotating resistance box, and (b) paper variable resistor.

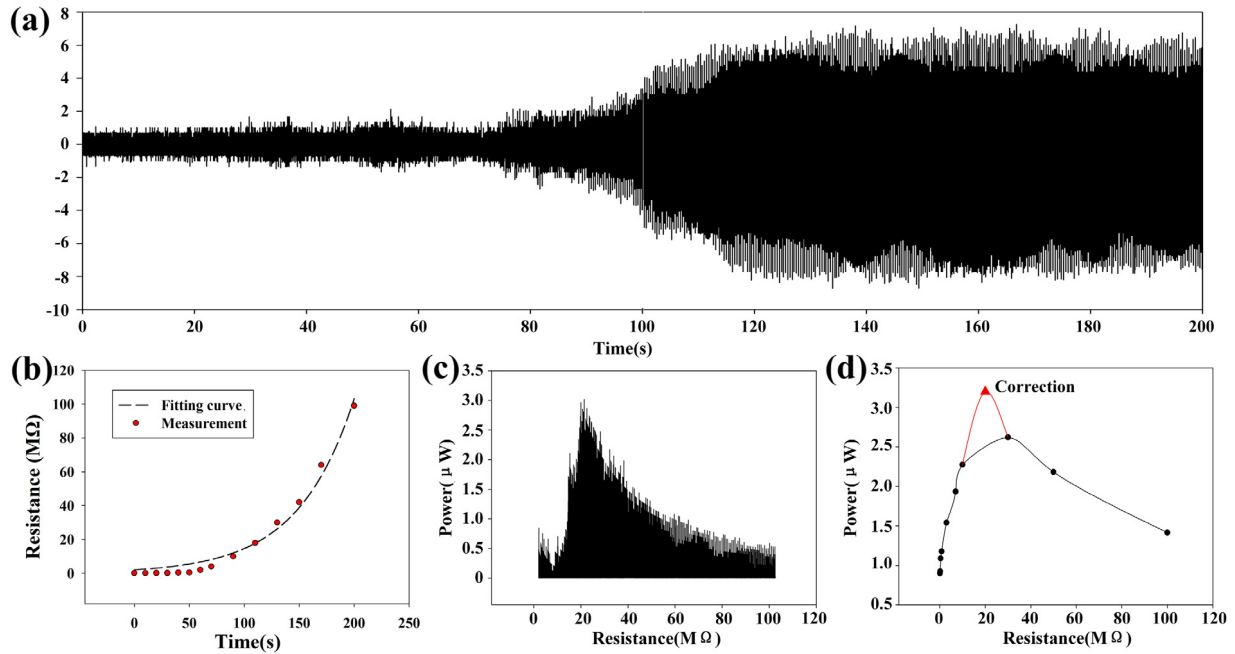


Fig. 4. (a) Output voltage versus time measured by paper variable resistor, (b) the measured resistance and fitting curve of paper variable resistor versus time, (c) dependence of output power on loading resistance of paper variable resistor, and (d) dependence of output power on loading resistance of rotating resistance box.

The critical point for the destruction of paper substrate is the selection of the pencil/graphite material. A regular graphite pencil (inorganic clay binder), a flexible graphite pencil (organic and polymeric binder) and a water-soluble graphite pencil (water-soluble binder) were prepared to draw a pattern on paper for transience triggering. A commercial microwave oven (manufactured by Galanz Electrical Appliances Ltd, 1000 W) was used for transience triggering. After heating for 30 s, the graphite pattern made by the water-soluble graphite pencil and the paper substrate beneath were destroyed, as shown in Fig. 1. In contrast, there was no obvious destruction for the regular graphite pencil and the flexible graphite pencil patterns. Therefore, the water-soluble graphite pencil was selected for forming the graphite patterns in this work.

The microwave heating (Fig. 2(c)) is calculated as follows. The microwave power absorbed per unit volume (P_{av}) can be defined as follows (Chambers et al., 2012):

$$P_{av} = 2\pi f \epsilon_0 \epsilon_r'' |E|^2 \tag{1}$$

Where f is the frequency of the microwave field, in this work, we used 2.45 GHz microwave frequency; ϵ_0 is the permittivity of free space or in vacuum, ϵ_r'' is the relative imaginary permittivity or (relative dielectric loss) and $|E|$ is the absolute value of the induced electric field strength. The approximate values of ϵ_r'' and $|E|$ can be obtained from reference (Hotta et al., 2011; Santos et al., 2010).

Eq. (2) is absorption heat formula, where C stands for specific heat capacity of graphite (710 J/(kg·K)), m stands for the

quality of graphite, which can be calculate by graphite density and volume.

$$\Delta T = \frac{P_{av} V t}{C m} \quad (2)$$

Therefore, the temperature dependence of graphite with time can be calculated. After 30 s of heating, the temperature of graphite increased by 191 K, making the paper burned out.

In this study, a cost-effective transient paper TENG is fabricated. During contact between triboelectric pair, the electrification will produce positive charges on the paper surface and negative charges on the Kapton tape surface. Charge transfer is induced when electrical equilibrium disappears. A reverse potential difference occurs for the initial approach of the paper substrate and Kapton tape. This difference will induce reverse flow of the inductive charges.

Fig. 2(a) and (b) show the schematic and photograph of the device, respectively. A conductive graphite square pattern (painted by water-soluble graphite pencil) serves as the electrodes. Kapton tape and paper are taken as triboelectric pair. Fig. 2(c) illustrates the destruction of the paper TENG subject to microwave heating. The transience of paper substrate can be triggered even when the paper substrate is coated with polymer clay, indicating potential application in polymer packaged paper electronics.

Another batch of pencil-on-paper TENGs are fabricated for investigation of matching impedance, which is defined as the resistance where the maximum output power occurred. The mechanical triggering input of the TENG is provided by vibration exciter. The triggering frequency is approximately 5.3 Hz. Fig. 3(a) sketches the schematic of matching impedance measurement based on rotating resistance box. A rotating resistance box was utilized as variable resistor load for fabricated TENGs, and the output signal was recorded by an oscilloscope. Although the above measurement method is widely applied, it has the following limitations: the variable resistor is provided by apparatus such as rotating resistance box, which is expensive and time consuming when adjusting resistance. Moreover, the resistance changes is represented by typical resistance points (difficult to cover every value in resistance changing region), which affect the accuracy of the matching impedance measurement.

In order to overcome the above limitation, we propose paper variable resistor-based measurement method, as shown in Fig. 3(b). The fabricated TENG is connected to blank paper, which is sprayed with tap water. A hotplate is used to evaporate the water, thus, the resistance of paper resistor is controlled.

The output voltage of the paper variable resistor is shown in Fig. 4(a). The tuning of the paper variable resistor is illustrated in Fig. 4(b). The resistance of the paper resistor can be fitted to the function of $y = \exp(0.0195^*(x+37.4949))$ (Eq. (3)) with a correlation coefficient of 0.9919, where x and y are the time and the resistance, respectively, as shown in Fig. 4(b). We assume that the resistance of the paper resistor satisfies Eq. (3), thus, the output power vs loading resistance is illustrated in Fig. 4(c). Comparing Fig. 4(c) and Fig. 4(d) (before correction), we observe different matching impedance, which is attributed to not enough selected measurement points of conventional method (based on rotating resistance box). According to Fig. 4(c), we remeasured the power and voltage and made corresponding revisions (shown as added point in Fig. 4(d)). It is obtained that the two method can complement with each other, and make accurate measurement of the matching impedance.

3. Conclusion

A novel method for triggering transience of paper TENG using a household microwave oven and a commercial graphite pencil is proposed. After heating for 30 s, the graphite pattern made by the

water-soluble graphite pencil and the paper substrate beneath were destroyed. Furthermore, a fast, simple and cost-effective approach for measuring the matching impedance of TENG based on paper variable resistor is proposed. The measurement results show that the proposed method can make accurate measurement of the matching impedance. This work has great potentials for simple, fast and cost-effective functionalization of TENGs.

Acknowledgments

This work was supported by National Natural Science Foundation of China (Grant No. 61804132, Grant No. 61674128, Grant No. 61731019) and Aerospace Science Foundation, China (Grant No. ASFC-2017ZC76002). The author would also like to thank the anonymous reviewer for the valuable judgment of this paper.

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