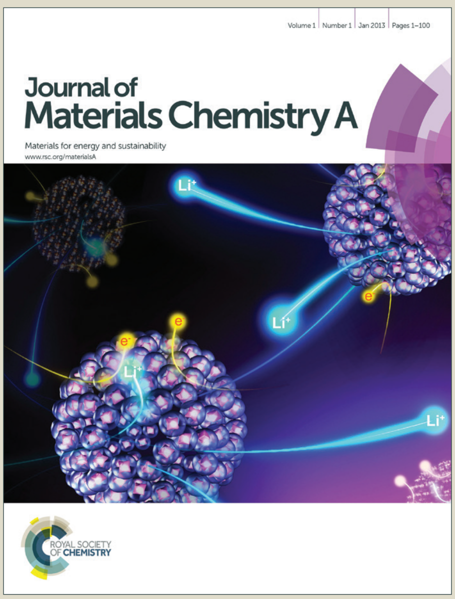
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Newton's Cradle Motion-like Triboelectric Nanogenerator to Enhance Energy Recycle Efficiency by Utilizing Elastic Deformation

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Abstract

Triboelectric nanogenerators (TENG) that harvest energy from ambient environment have been paid great attention to since it was first reported. However, structures of TENGs working in vertical contact-separation mode are somewhat monotonous and energy loss cannot be avoided during the working process. In this paper, we design a novel TENG based on three elastic plates, one acryl board in center with two identical steel plates on both sides, by which periodic contact/separation of the friction layers proceeds like Newton's Cradle except the intermittent input of mechanical energy to overcome the electrostatic interaction on the charged friction layers. Such a lamination structure in original contact mode can provide much higher energy conversion efficiency than that of the friction layers in the original separation mode. With this new design, the output current of the TENG is 5.7 times as much as that of the common contact/separation TENG and 2.3 times as much as that of the similar structure TENG without using elasticity. The maximum short-circuit current, open-circuit voltage and output power are 114 μA, 428 V, 4.32W m^{-2} respectively, which is strong enough to light more than one hundred of commercial LED lights. In addition, the TENG is applied to a self-powered flashing clapping palm decorated by 29 LEDs which might replace the fluorescence palm powered by chemical reactions of a dye mixed solution in the future.

Keywords: triboelectric nanogenerators; Newton's cradle; self-powered; clapping palm; elastic deformation

1. INTRODUCTION

It has been a great dream of people to invent a device that could harvest energy from the ambient environment to be used in our daily life and reduce environmental pressure from the fossil energy consumption. To realize this dream, people have tried many ways to convert environmental energy into electric energy, including the technology based on electromagnetic induction,[1, 2] thermoelectric effects,[3, 4] electrochemical reactions,[5, 6] photoelectric effects,[7, 8] and piezoelectric effects,[9, 10] etc. In recent years, nanogenerators that utilize piezoelectric effect, pyroelectric effect[11, 12] and triboelectric effect[13, 14] have been developing very fast. Among all these nanogenerators, triboelectric nanogenerators (TENG) based on the combination of triboelectric effect and electrostatic induction has attracted more attention, which has successfully harvested various kinds of mechanical energy, such as airflow,[15, 16] waterflow,[17-20] vibration,[21-23] sliding,[24, 25] rotation motions[26, 27] and biological energy.[28, 29] TENGs mainly have two working modes, the vertical contact-separation mode[30] and sliding mode[31] (including rotation). Although the TENG working in vertical contact-separation mode has a simple structure and is easy to be fabricated, energy loss in such monotonous structures cannot be avoided during the working process.

However, for most of TENGs working in the vertical contact-separation mode, their friction layers (electrode and electret films) separate in initial state. An external force is applied to the device to make the friction layers contact and to deform inside, while the device restores its shape by separating the friction layers when the external force is gone. As this process goes periodically, current is generated in the external circuit due to the transfer of electrons between the electrodes. Although part of the elastic potential energy is used to separate the friction layers to overcome the Coulomb interaction, most of it disappears without being used according to the small effective range of Coulomb interaction, which hinders high conversion efficiency achieved by the TENGs. Therefore, a new type of TENG with efficient energy utilization should be developed.

In this paper, we innovatively design a novel TENG based on three elastic plates, one acrylic board in center with two identical steel plates on both sides, by which periodic contact/separation of the friction layers proceeds like Newton's Cradle except the intermittent input of mechanical energy to overcome the electrostatic interaction on the charged friction layers. We call it Newton's Cradle motion-like triboelectric nanogenerator (NC-TENG). The elastic acryl board in the center acts as an energy transmission medium to transfer kinetic energy from one side to the other side. The steel plate moves at a relative velocity and obtains the kinetic energy and external energy supply, and then stores the excess kinetic energy as an elastic potential energy by its elastic deformation. Besides, we design a so-called half-contact structure, by which the separation of friction layers is much easier due to the elasticity and flexibility of the steel plates. Meanwhile, with the subsequent vibration brought by spring laminations, the NC-TENG working in half-contact mode generates larger current output. Such a lamination structure in the original half-contact mode can provide much higher energy conversion efficiency than that of the friction layers in the original separation mode. The output of NC-TENG is 470% higher than that of the common contact-separation TENG and 130% higher than that of a similar structure TENG without using elasticity. The maximum short-circuit current, open-circuit voltage and output power are 114 μA, 428 V, 4.32 W m^{-2} respectively, which is strong enough to light more than one hundred of commercial LED lights and to charge commercial capacitors. In addition, the NC-TENG is successfully applied to a self-powered flashing clapping palm decorated by 29 LEDs which might replace the fluorescence palm powered by chemical reactions of a dye mixed solution in the future. The electricity generation mechanism by alternate conversion between kinetic energy and elastic potential energy, and some factors that influence the output of NC-TENG are discussed in details. The creative idea to bring Newton's Cradle energy transmission mode to the vertical contact/separation TENG would lead to new structure/material design for TENGs and greatly improve their energy conversion efficiency.

2. EXPERIMENTAL SECTION

2.1 Fabrication of NC-TENG: The structure of NC-TENG is shown in Figure 1, which illustrates that it is composed of one aluminum electrode adhered on an acryl board in the middle and two steel electrode plates symmetrically located on both sides with PTFE thin film on the one surface and acryl sheet on the other surface of the steel plates. Two steel electrodes are connected by copper wires to form one electrode (steel electrode). In order to obtain a rough structure on the surface of the friction layer, PTFE film have been etched by surface inductively coupled plasma reactive ion.

The surface morphology is shown in the inset of Figure 1c. Aluminum electrode is also connected with copper wires serving as the other electrode (Al electrode). In addition, to ensure that the charged electrets could separate from aluminum electrode effectively, two PVC spacers (5 cm×0.35 cm×0.1 cm) are pasted on the middle acryl plate in the two sides 1 cm to aluminum electrode (see Figure 2). Therefore, when the generator is in static state, the PTFE films do not fully contact Al electrode, which are in half-contact state.

The aluminum foil covered three surfaces of the acryl board (22 cm×5 cm×0.4 cm) serving as Al electrode (Figure 2). The steel electrode is composed of two identical spring steel plates, which has good flatness, good elasticity, a well polished surface, and fatigue-resistance. In the experiment, a spring steel plate (500 cm×5 cm×0.01 cm) are cut into two pieces of 14 cm long, and are dried at 40 °C after ethanol spray treatment. Both steel plates are covered with double-side adhesive tape and then PTFE films (5 cm×5 cm) are pasted on the sides facing to Al electrode and acryl sheets (5 cm×5 cm) are pasted on other sides (Figure 1).

2.2 Characterization of NC-TENG: The output performance of the NC-TENG is measured using a Stanford low-noise current preamplifier (Model I SR570) and a Data Acquisition Card (NI PCI-6259). Figure S1 schematically shows the measuring system. In the experiment, we fix the acryl board onto the motion module of the linear motor (WMU1536075-090-D). Through a computer controlled modular experiment system, we could enables the module to do periodically straight reciprocating motion with period of T and amplitude of A.

3. RESULTS AND DISCUSSION

3.1 Working mechanism of NC-TENG

The electricity of the TENG comes from the mechanical motion on the basis of triboelectrification[22-34] and electrostatic induction. Figure 3 presents the charge distribution in electricity generation process. The purple arrow and the circled black arrow stand for the velocity direction of linear motor and the current direction between the electrodes, respectively. Before the experiment, we have vibrated the NC-TENG for some time to ensure the charge distribution on the surfaces of PTFE and electrode as is shown in Figure 3a. The more detailed charge distribution in electricity generation process is shown in Figure S2. The NC-TENG is driven by the linear motor to do periodically straight reciprocating motion. When the NC-TENG moves right (Figure 3b), the PTFE film separates from the Al electrode due to the inertia of the steel plate on the left. Electrons move from the steel electrode to Al electrode and produces current flowing from aluminum electrode to steel electrode in external circuit. During this process the spring steel plate deforms with storage of the elastic potential energy until the NC-TENG moves left after it reaches the most right point. Then, the deformed steel plate restores its shape and releases the stored potential energy into kinetic energy to the steel plate on the left, and then passes the energy to the steel plate on the right through the elastic Al-acryl board in the center, while the PTFE film on the left steel plate contacts the Al electrode to generate a current flowing from the steel electrode to Al electrode in the external circuit (Figure 3c). Almost at the same time the PTFE film on the right steel plate is pushed away from the Al electrode by obtaining the kinetic energy and its inertia, where the current is produced from Al electrode to the steel electrode (Figure 3d). When the NC-TENG moves to right after reaching the most left point, the right steel plate restores its shape and contact with Al film to generate a current flowing from steel electrode to Al electrode (Figure 3a), and meanwhile the right steel plate releases the deformed potential energy to the left steel plate through the Al-acryl-board to push it away from the Al electrode and to produce a current from Al electrode to steel electrode (Figure 2a). The whole period is from the state in Figure 3a to the state in Figure 3d. The most important point is that separation comes right after the contact of friction layers, just like Newton' Cradle motion process, therefore the states in Figure 3c and Figure 3d are very close in time, which is identified by the alternate backward and forward currents in the later measurement. The amount of the transferred charges of every separation and contact could be given by:

$$Q = \sigma ab \qquad (1)$$

Where *σ, a* and *b* represent the surface triboelectric charge density on the surface of PTFE, the length and width of the friction area respectively. Here, a=b=5 cm. The generated current could be given by:

$$I = \frac{dQ}{dt} = \frac{\sigma ab}{d/v} = \frac{v\sigma ab}{d} \qquad (2)$$

To simplify the charge induction process of separation and contact, two approximations are proposed[35] (Figure S3). One is that the Al electrode and PTFE are separated and contacted in parallel mode. The other one is that the effective range of the charge induction is a constant of d. Thus, we get formula 2, where υ represents the relative speed of separation and contact of the friction layers. As the relative speed of contact is always faster than that of separation, the forward current (Steel→Al) is much higher than that of backward current (Al→Steel). The spring steel plate can store the energy in separation process as elastic potential energy, and convert the potential energy into the kinetic energy to accelerate the steel plate going forward to the Al electrode. Thus, higher current output is achieved.

To better understand the role of the spring steel plate in the NC-TENG, we fabricate another two devices with similar friction layers to the NC-TENG to compare their output performance (Figure 3). The first type is a common TENG in which two PTFE films are fixed on opposite acryl plates and the Al electrode on an acryl plate moves between them to contact/separate the PTFE films alternately driven by linear motor (Figure 4a1, Figure S4a and Video 1). The second type is a TENG in which the steel plate is cut in two pieces to eliminate the elasticity. The periodic contact/separation between the PTFE plates and Al electrode is driven by linear motor and these plates are taped to limit the motion amplitude of the PTFE plates by using PVC belt as are shown in Figure 4b1, Figure S4b and Video 2. With the light weight and excellent flexibility, PVC belt can hardly bring any resistance to the motion of PTFE plates. The third type is the NC-TENG as is described above (Video 3). All the three TENGs do periodically straight reciprocating motion driven by a linear motor in a period of 400 s and amplitude of 4 cm, 5 cm, 6 cm, 7 cm, and 8 cm. The output currents of these TENGs are shown in Figure 4 a2-c2. From these plots, we can see that the positive and negative output currents of the first type TENG are almost the same, an approximate 20 μA without obvious amplitude change, because the speeds are the same in separation and contact process (Figure 4a2 and a3) in different displacement amplitudes. The output current of the second type TENG without using elasticity of the spring steel plate slowly increases from 40 μA to 49 μA with an increase in displacement amplitude (Figure 3b2). However, the output current of the NC-TENG has better response (from 66 μA to 114 μA) to the increase in displacement amplitude, because the NC-TENG can efficiently utilize the energy through the storage and conversion by the spring steel plates. Both the second type and third type of TENG generate asymmetrically positive and negative currents due to the different contact and separation speeds of friction layers. From the analysis above, we know that the average output current of the NC-TENG is 5.7 times and 2.3 times as much as that of the first type TENG and the second type TENG. Moreover, the output voltage and power under different external loads of three types of TENGs are shown in Figure S4-S6, from which we can see that the NC-TENG has much higher output performance than that of two others either in voltage or power. The experiment demonstrates that the spring steel plates used in the NC-TENG can increase the relative speed of contact and separation of friction layers through storage and release of elastic potential energy. As is shown in Figure 4c3, we could see four pulses, in which pulse 1 and pulse 2 are respectively generated in contact and separation process, which is much higher than that of other two TENGs. The small pulse 3 and pulse 4 are caused by the subsequent vibration due to the half contact-separation of PTFE and Al electrode, as are shown in Figure 4 and Figure S7. Thereby, the charge transfer in unit time increases by adding these small pulses. This indicates that half-contact design with spring steel plate can enhance TENG's charge transfer in unit time to some extent. Meanwhile, the release of the stored elastic potential energy in one steel plate is used to push the opposite side steel plate away from the center Al electrode through energy transmission of the acryl board. The opposite steel plate moves away at a higher relative velocity by obtaining the potential energy and external energy supply, and then stores excess kinetic energy as an elastic potential energy by its deformation again.

3.2 Influence factors

To compare the NC-TENG's output performance in different conditions, the experiments in different periods and amplitudes are conducted and the results are shown in Figure 5, where the 3D graphs are all smoothened by bilinear difference arithmetic (Figure a and d). To better illustrate the shaded part, the contour map is added to the X−Y plane. Four 2D graphs derived from these two 3D graphs by projecting are depicted in Figure 5b, c, e, and f, revealing the output current and the quantity of the transferred charges in a half period in different periods and with different amplitudes, respectively. In Figure 5a-c we can see that with an increase in amplitude and a decrease in period, the output current increases very sharply. The quantity of transferred charge in half a period in different periods and with different amplitudes is shown in Figure 5d-f. Under the same motion period, the quantity of transferred charge increases with an increase in amplitude and reaches largest when moving period is 500 ms.

The output current, voltage and power of the NC-TENG driven by the linear motor in a motion period of 400 ms and amplitude of 8 cm with different load resistance in external circuit are measured and the results are shown in Figure 6a-b. The current decreases and voltage increases with increase in load resistance, and tends to be constant in a large resistance. The output power reaches the maximum of 10.8 mW at load of 3 MΩ, corresponding to power density of 4.32 W m^{-2}. Compared with other TENG, the output performance of the NC-TENG is greatly enhanced.[16, 36, 37]

3.3 Practical Applications

As the alternating current generated by the NC-TENG cannot be directly used by electronic devices, we need a bridge circuit and capacitor to convert it. Therefore, the capacitance (47 μF) is charged by the NC-TENG at frequency of 2 Hz and amplitude varying from 4 cm, 5 cm, 6 cm. The voltage-time plot is shown in Figure 6c, which illustrates that the capacitor charges fastest with amplitude of 6 cm, and the capacitor is charged to 4 V within 65 s. The faster charging process corresponds to the larger amplitude due to the larger current generated. This result accords with the data in Figure 5d.

It has always been our goal of developing nanogenerator to harvest energy from daily life and apply it to electronic devices. A self-powered flashing clapping palm decorated by 29 LEDs which might replace a fluorescence palm powered by chemical reactions of a dye mixed solution in the future. Fluorescence sticks and clapping palms are often used in an open concert at night for audience interaction. However, fluorescence sticks cannot be recycled and causes pollution. In order to cut down pollution and waste, we apply the NC-TENG to self-powered clapping palms. The structure of the clapping palm is similar to that of the NC-TENG (Figure S8). LEDs are connected in series at the finger part of the palm, and spring steel plate is used at the wrist part. Consequently, we have lit up 29 LEDs simultaneously by shaking the palm without external power (Figure 6d and Video 4).

4. CONCLUSIONS

In this paper, the Newton's Cradle motion-like triboelectric nanogenerator that utilizes elastic deformation to recycle energy is designed and fabricated. On the basis of the previous nanogenerators of vertical contact-separation mode, we bring in spring steel plate to store elastic potential energy and then convert it to kinetic energy to accelerate the contact/separation process, by which high output current is obtained. Moreover, the design of half-contact makes the two electrodes separate more easily. The output current of NC-TENG is 130% higher than that of a similar one without elasticity, and 470% higher than that of TENG with simple contact-separation structure. The largest short-circuit current, open-circuit voltage and output power are 114 μA, 428 V, 4.32 W m^{-2} respectively. Besides, the NC-TENG could not only be applied to commercial capacitor charging, but also to self-powered fluorescence clapping palm, which might replace fluorescence sticks in future. It shows the essential role of nanogenerators in the field of self-power and device energy supply. The NC-TENG is an innovative nanogenerator different from the previous ones of vertical contact-separation mode and presents a great leap forward in the design, fabrication and application of nanogenerators.

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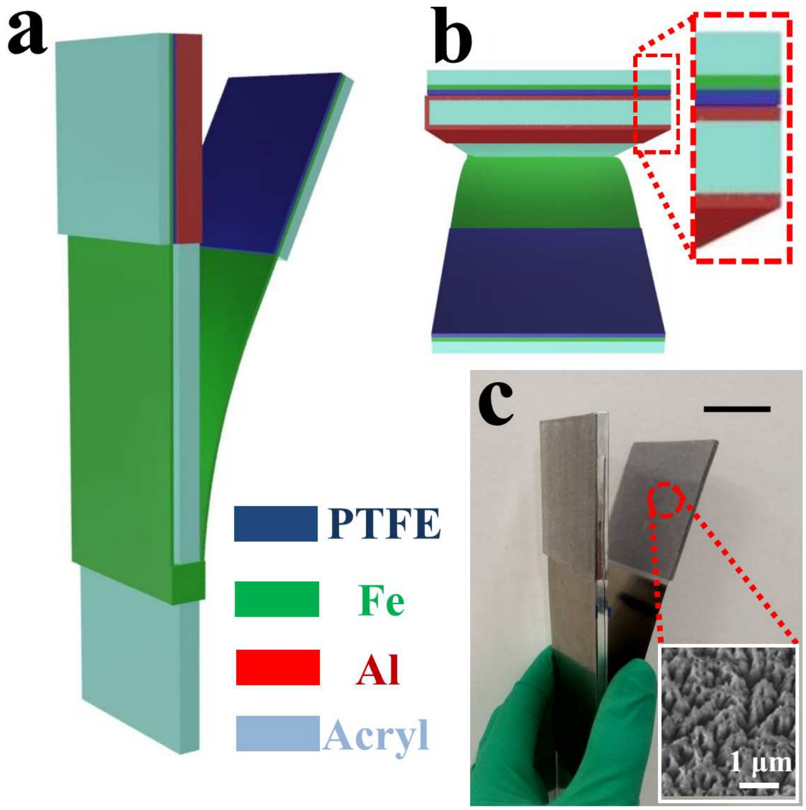

Fig. 1 (a) Schematic diagram of the Newton's cradle motion-like triboelectric nanogenerator (NC-TENG) and (b) top view of the NC-TENG. (c) Digital photograph of the NC-TENG. The scale bar is 2 cm. The inset is SEM image of the PTFE surface.

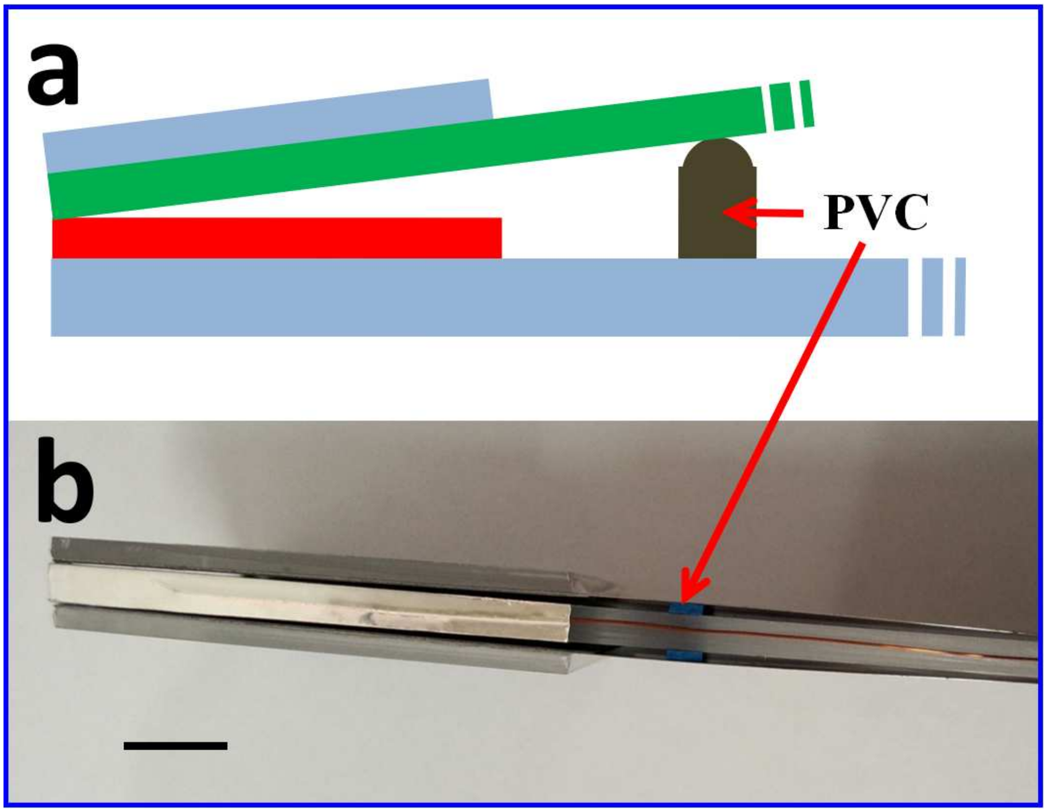

Fig. 2 Schematic diagram of the PVC spacer of the NC-TENG and (b) digital photograph of the NC-TENG. The scale bar is 1 cm.

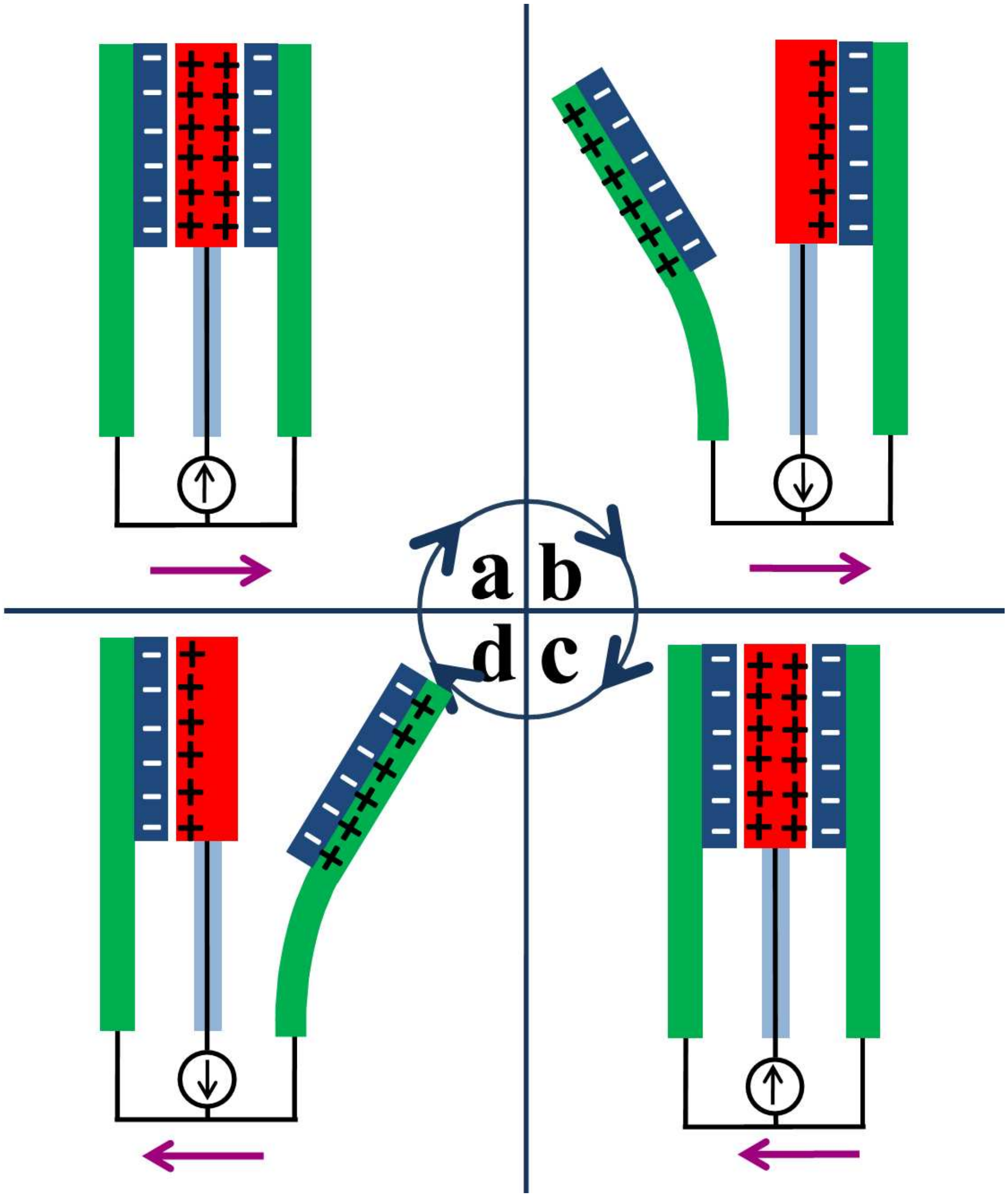

Fig. 3 Working principle of the NC-TENG. (a-d) Schematic diagrams of the charge distributions and current direction when linear motor move in one period. The purple arrow and the circled black arrow stand for the velocity direction of linear motor and the current direction between the electrodes, respectively.

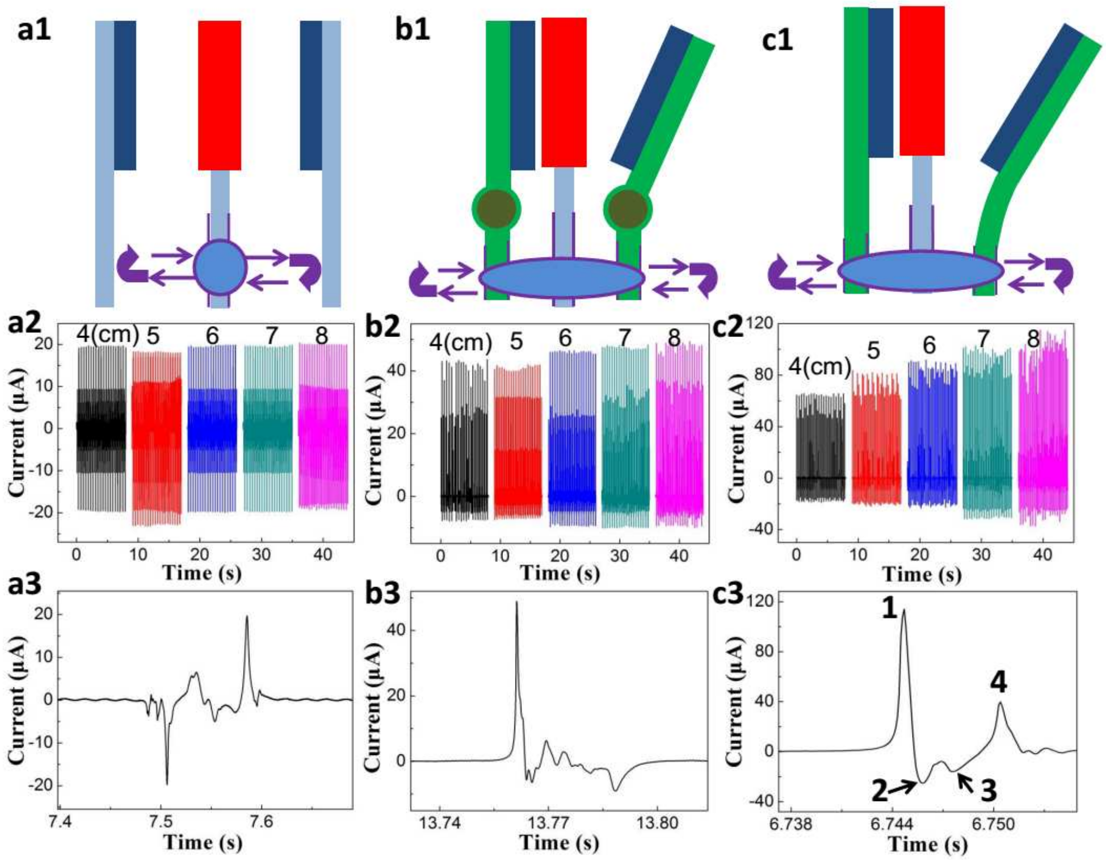

Fig. 4 The comparison of three different TENGs with similar structure. Structure diagrams of (a1) the common contact/separation structure TENG, (b1) the NC-TENG with steel plate cut and (c1) the NC-TENG. (a2-c2) Corresponding output current of three TENGs under different working amplitudes. (a3-c3) Corresponding enlarged output current of three TENGs.

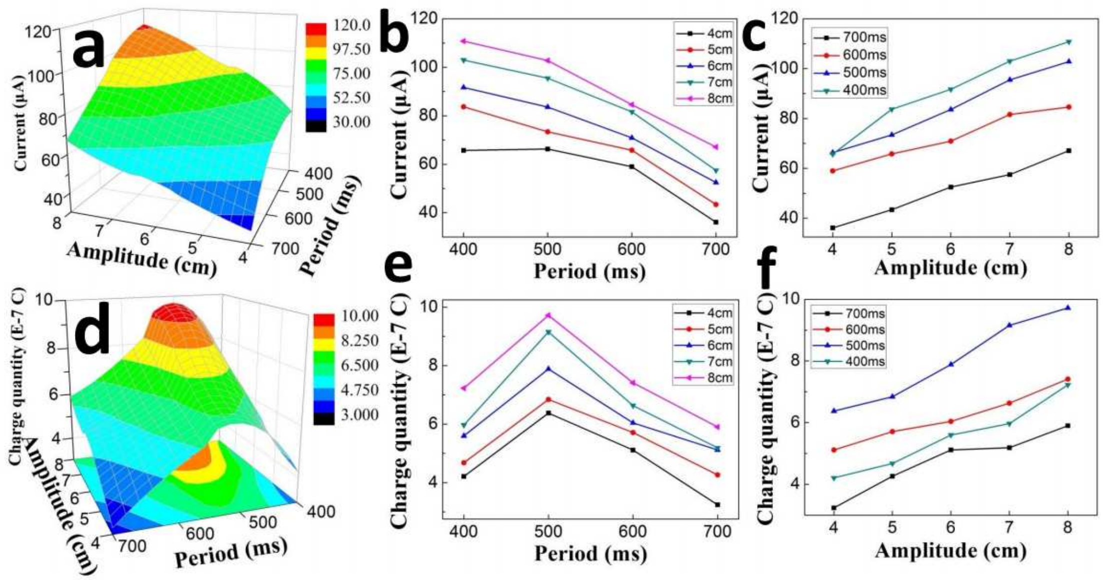

Fig. 5 Performance of the NC-TENG. (a) 3D surface graph of the varied output current on changing both the amplitude and period. (b and c) Corresponding 2D graphs derived from the 3D surface graph. (d) 3D surface graph of the varied charge quantity on changing the amplitude and period. (e and f) Corresponding 2D graphs derived from the 3D surface graph.

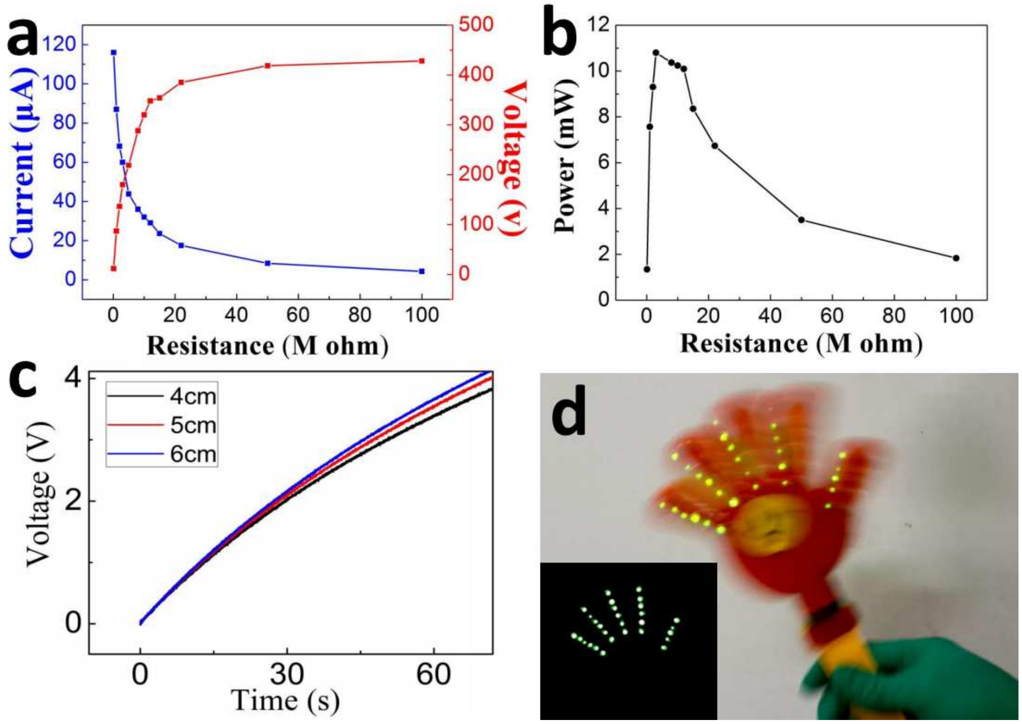

Fig. 6. (a) Output current and voltage and (b) the output power under different external loads. (c) Voltage curve of the capacitor charged by the NC-TENG under different working amplitudes. (d) Digital photographs of the self-powered flashing clapping palm by using the same mechanism of the NC-TENG.

Graphical abstract

The Newton's Cradle motion-like triboelectric nanogenerator (NC-TENG) that utilizes elastic deformation to recycle energy is designed and fabricated. With this new design, the output current of this TENG is 5.7 times as much as that of the common contact-separation TENG and 2.3 times as much as that of similar structure TENG without using elasticity.