A coplanar-electrode direct-current triboelectric nanogenerator with facile fabrication and stable output

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Abstract
Recently, the direct-current (DC) TENG based on triboelectrification and discharge has been reported, which can not only generate a DC power, but also provide a higher charge density compared to traditional TENG. Here, we report a novel coplanar-electrode DC TENG (CDC-TENG) design which can be easily fabricated by two electrodes, and then a theoretical model is built to illustrate its principle and optimize its output performance. Both theoretical and experimental studies show that the designed device can enhance the energy output, and then the output power is optimized. Furthermore, we develop a three-electrode CDC-TENG to output DC during the reciprocating motion. We apply this CDC-TENG design for rotational energy harvesting and produce a stable constant DC output. This represents an important progress to effectively store the energy harvested by the CDC-TENG with the aim to drive portable/wearable/implantable electronics with the stable output.

KEYWORDS
direct current, electrostatic discharge, mechanical energy harvesting, triboelectric nanogenerator

1 | INTRODUCTION

With the rapid development of the sensor network for big data and the Internet of Things (IoTs), more and more efforts have been focused on looking for sustainable mobile energy source at the power levels of micro-to-milli watts for microelectronics.¹³ Among various energy-harvesting devices, triboelectric nanogenerators (TENGs) are...
considered as the most effective way to convert various types of mechanical energy in the natural environment with huge advantages, such as simple structure, low cost, and light weight. The fundamental mechanism of TENG is based on the coupling of triboelectrification and electrostatic induction, which can provide periodical alternating-current (AC) output. However, for powering most of the microelectronics, a direct and stable current is necessary. The major limitation of traditional TENG is that they generate instantaneous peak AC output and thus are not able to be used as a direct power source.

To address this issue, direct current (DC) TENGs without unnecessary circuits have been developed, which will have great potentials on multiple applications. Up to now, there are mainly two methods to implement the conversion from AC power to DC power. The first method is based on power management units to regulate current, such as the full-wave rectifier, a rotary rectifier bridge, a double-wheel design, or a multiphase rotation-type structure. However, these attempts take away TENG’s portability advantage, and the output performance is limited by air breakdown. Hence, some researchers explored methods to achieve DC output through alternative designs. 

Here, we have designed a coplanar-electrode DC TENG (CDC-TENG) with two electrodes in the same plane, which greatly simplified the fabrication process. Based on this CDC-TENG, we raised a theoretical model to illustrate the operation mechanism. Furthermore, this CDC-TENG is optimized based on the theoretical model. Both theoretical and experimental studies show that the coplanar-electrode design can output stable energy as continuously harvested from the environment. Finally, a rotating CDC-TENG is demonstrated, which can provide a constant high-current output. This study represents a progress to effectively harvest the energy with the aim to directly output stable DC power to drive microelectronics.

2 | RESULTS AND DISCUSSION

2.1 | Theoretical mode of the CDC-TENG

For a long time of period, the discharge effect is usually considered as a negative effect in previous research about TENG, which dissipates energy without going through external circuit. However, the DC-TENGs usually utilized the discharge effect to achieve the unidirectional charge transfer cycle. Our design was originally raised based on the analysis on a metal piece sliding on the dielectric substrate (usually insulating negative material). As shown in Figure 1A, when the metal piece contacted the dielectric substrate, charge transfer occurred between them due to the different electronegativity. While the metal piece slightly slides on the substrate, the charge distribution on the metal piece will be changed due to electrostatic induction, and more positive charges will move to the rear side of the electrode to balance electrostatic status, generating a unidirectional current from the front side to the rear side of the metal piece (Figure 1B and Video S1), which can be simulated by commercial software COMSOL as shown in Figure 1C, most of charge is accumulated at both ends of the electrode. In the simulation, we assume that the charge density on dielectric is evenly distributed, and the metal electrode has an equal amount of positive charges. When the electrode slides a little to the rightward, the potential difference between two sides of the electrode will induce the redistribution of the electric charge and generate the current flow. To harvest the energy of this current flow, we can divide the metal piece to be two coplanar parts with a very small gap, as shown in Figure 1D, making a new coplanar-electrode DC-TENG (CDC-TENG) design. When it slides on the dielectric substrate, the positive charge will transfer from the front electrode to the rear electrode to balance the potential difference. The positive charge accumulates at the rear electrode until the discharge happens between the electrode and the substrate, completing one charge transfer cycle (Figure 1D), (Figures S1 and S2). Figure 1F-H shows the output performance of a fabricated CDC-TENG, when it slides on the same direction, which can generate continues DC. Once we change the sliding direction, the electrical output direction is also reversed. Figure 1I shows the equivalent circuit model, which consists of two key capacitances for the sliding mode CDC-TENG, in which $C_1$ is the capacitance between the rear electrode (node A) and the substrate (node C), and $C_2$ is the capacitance between two electrodes (nodes A and B). At the short-circuit condition, as charge accumulates, the electric field in the rear corner of the rear electrode as indicated by the arrow is usually the highest, making it prone to discharge (Figure 1J).
shown in Figure 2. The size of electrodes usually has a large effect on its performance. To find out the specific relationship between these parameters and electrical characterizations of the CDC-TENG, we designed following experiments, focusing on the gap $g$ between two electrodes, and the length $l$ of each electrode, and for the sliding velocity and displacement is constant in the following experiment (Figure S3). Figure 2A shows the test bench of our experiment, and the device as attached on the cantilever is driven by a linear motor. Here, in the first experiment, we varied the length $l$ ranging from 12 to 0.15 mm, while fixing the width $w$ and gap $g$ of two electrodes as 20 and 2 mm and the sliding displacement is 2 cm, as shown in Figure 2B-D. And for the second experiment, we changed $g$ from 5 to 0.15 mm, with the constant electrode dimensions ($w = 20$ mm, $l = 5$ mm and sliding displacement is 2 cm), as shown in Figure 2B-D (Figure S4). From the experiments above, we found that increasing the area of two electrodes will increase the output of TENG, due to the increased total triboelectric charge. In addition, making $g$ smaller also helps to increase the output performance,
possibly because that the device can be more firmly in contact with the substrate, enhancing the surface charge density. In short, by adjusting the area and gap, we can optimize the output power of the CDC-TENG.

2.3 The CDC-TENG with three electrodes

According to the studies above, we noticed that in the CDC-TENG, the current direction is from the front electrode to the rear one. Therefore, in the process of reciprocating motion, the alternating electrical output is generated. To ensure the DC output at any direction of the motion, we designed a new CDC-TENG with three electrodes, as shown in Figure 3A. Through analyzing the working mechanism of this TENG theoretically, as Figure 3B, at the initial state, all electrodes will get positive charges and the dielectric obtain the same amount negative charges, as shown in Figure 3B(i). And during the moving progress, the front electrode always accumulated the highest potential compared to the other two electrodes and this difference will drive the current moving from the front electrode to the latter two electrodes through the external circuit. Therefore, for the medium electrode, no matter forward or backward direction the device moves in, there will always be current flowing into this electrode, as shown in Figure 3B(ii) and (iii), making a DC output (Video S2 and Figure S5). In order to verify our analysis, we conducted the experiments as shown in...
Figure 3A. The output kept unidirectional during the repeated forward and backward motions, as shown in Figure 3C,F. For structural parameters, we investigated the relationship between the electric output performance of this CDC-TENG and the structural parameters, shown in Figure 3C-H. We mainly emphasized two aspects: the length \( l \) of electrodes and the gap \( g \) between two electrodes. Similarly, a large \( l \) and a smaller \( g \) improved the output performance. This study demonstrates a potential method to ensure the DC output for TENGs under any arbitrary motions.

### 2.4 Demonstration of the output performance

To demonstrate the potential application of this TENG, we designed a rotational structure that can be used to
collect rotational energy, which can be driven by the wind cups, as shown in Figure 4A. Figure 4B shows the schematic diagram and the photo showing the distribution of electrodes in the rotator. The gap distance between electrodes is designed wide and narrow intermittently, allowing adjacent two electrodes with the narrow gap to form a CDC-TENG set. Compared with previous designs, this structure can be easily fabricated by attaching patterned electrodes on the rotator, sliding against the stator which is a pristine dielectric substrate. As compared with previous rotational DC-TENGs, this simple structure is much easier to be minimized through printed circuit board (PCB) or optical lithography technologies. The fabricated rotational CDC-TENG was with an active diameter of 70 mm and FEP as the dielectric material. Under different rotation speeds, the output performance is always very stable, as shown in Figure 4C. To demonstrate the ability of the TENG as a DC power source to power electronics, a total of 50 commercial light-emitting diodes (LEDs) were used as the external load. The LEDs were

**FIGURE 4** Demonstration of the Rotational DC-TENG. A, Schematic rotational CDC-TENG. B, Schematic diagram and photograph of the fabricated CDC-TENG. C, Output performance to charge a capacitance under different speeds. D, Schematic diagram of the connection between the CDC-TENG and the yellow and blue LEDs. E, Photograph of the CDC-TENG driving the yellow LEDs. F, Schematic diagram of the reversed connection between the CDC-TENG and the LEDs. G, Photograph of the blue LEDs lighted up by the reversely connected CDC-TENG. H and I, Open circuit voltage and short-circuit current outputs under different rotation speeds. J, current and power output of the rotational CDC-TENG at 400 r/min.
divided into two groups with yellow and blue light, and connected to the device with forward and reverse connections, respectively (Figure 4D). As illustrated in Figure 4E, the 25 yellow LEDs were lighted up by the TENG in rotation, while no light emission can be observed from the blue LEDs, indicating the DC output. Moreover, when the connection direction between the TENG and the LEDs was reversed (Figure 4F), only the 25 blue LEDs can be lighted up, as displayed in Figure 4G and Video S3 in Supporting Information. The results indicate that the CDC-TENG can be used as an efficient power source for directly and continuously driving electronic devices. Figure 4H,I illustrates the voltage and current outputs of the modified structure at different speeds. The small graphs in Figure 4D,E show the current and voltage curves under 400 rpm. When the motor speed reaches a preset value, the current and voltage also begin to stabilize. Figure 4J shows the power output under different loads at 400 rpm, with the optimized power output of ~160 mW achieved at resistance load of 50 MΩ.

3 | CONCLUSIONS

In this paper, a newly designed CDC-TENG is proposed and investigated comprehensively, which can convert both the reciprocating and rotational mechanical energy into DC electricity without using any power-management circuit. The charges transferred from the front to rear electrodes through the external circuit due to the potential difference, then released via the discharge. Under the continuous unidirectional movement, DC output can be produced in the external circuit. The output performance of CDC-TENG was studied under different structural parameters, including the electrode gap and length. A three-electrode CDC-TENG and a rotational CDC-TENG were demonstrated to continuously output DC power by collecting energy from the ambient environment. Compared with previous designs, this CDC-TENG demonstrates advantages of stable output and facile fabrication, especially toward miniaturization of the device. This work may open new avenues for further fundamental research and experimental development of DC-output energy harvesting systems used in various scenes including large-scale energy harvesting and flexible electronics. equal amount of positive charge on the metal. After a little bit of displacement of electrode, we can plot the electric field distribution, and the regime whose electric field over than 3 × 10^6 V/m is the breakdown area.

4.2 | Fabrication device and measurement experiment

For the two-electrode and three-electrode CDC-TENG, we deposit copper on PCB Board. The substrate film we used is FEP. Besides, Keithley 6514 electrometer is used to measure voltage and current in this paper.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section at the end of this article.

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