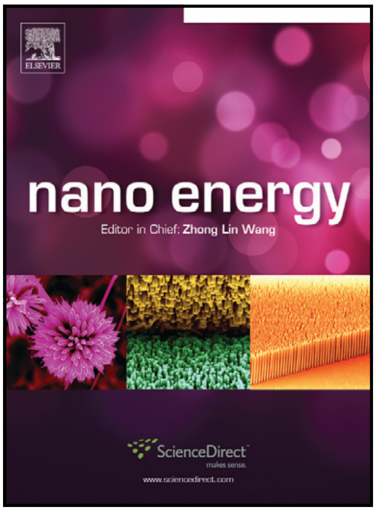

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Cover-sheet-based nanogenerator for charging mobile electronics using low-frequency body motion/vibration

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Abstract:

Effectively harvesting ambient energy is a key approach for realizing self-powered systems for portable electronics, wireless sensing, implanted devices, security and so on. It is generally desired that adding a power harvester should not add much weight, volume or additional components to the electronics. In this work, a cover-sheet-based (CS) triboelectric nanogenerator (TENG) is developed based on the protection structure of an electronics, such as a smart phone, for generating power for mobile electronics through conversion of mechanical energy. It consists of a slider and two stators. Each stator comprises of two complementary micro-grating electrodes. At a sliding velocity 1 m s^{-1}, the CS-TENG produces an output current of 88.8 μA, and a voltage of 2372 V. As a thin cover for mobile electronics, under the hand motions, the CS-TENG can light up household light bulbs or directly driving a mobile temperature meter without the use of a battery. In addition, springs are added to make the CS-TENG suitable for scavenging vibration energy from body motion. This study immediately opens the applications of TENG for conventional sensor systems.

1. Introduction:

As driven by the rapid development of portable electronics and with considering the limitations of the traditional power supplies, harvesting energy from ambient environment is attracting a lot of attention [1, 2] for applications in wireless sensing, implanted devices, and portable/wearable electronics [3, 4]. Mechanical energy, due to its universal availability, is of major interest. Well-developed conversion mechanisms for mechanical energy mainly rely on electrostatic [5, 6], electromagnetic [7, 8], and piezoelectric [9-12] effects, which have been extensively researched for decades. Recently, triboelectric nanogenerators (TENGs) have been invented as an unprecedented technology, featuring advantages such as high efficiency, low fabrication cost, reliable robustness and environmentally friendly [13-23]. In order for practical applications of the TENG as a power source for portable electronics, the output power still needs to be substantially enhanced and the generator construction needs to be optimized. As for a mobile electronics, it is generally desired that adding a power harvester should not add much weight, volume or additional components to the electronics, and the general requirement is to build the energy harvester using the available infrastructure as the base.

In this work, we invented a cover-sheet-based TENG (CS-TENG) in sliding mode by using the protection structure of an electronics such as a cover of a smart phone. It consists of two epoxy resin sheets, on which two complementary micro-grating electrodes were placed. Operating at an in-plane sliding velocity of 1 m s^{-1}, the CS-TENG has a contacting area of 18 cm^2 (the cover's total area is 50 cm^2, smaller than the normal size of a smartphone) and a thickness of 3 mm, and could generate an alternative current (AC) around 88.8 μA, with an average effective power density of 29.3 W m^{-2} and 9.77 kW m^{-3}. It successfully powered up household light bulbs, demonstrating the capability of the CS-TENG as a power supply for regular electronics. Due to the cover-shape design, the CS-TENG was integrated with a portable temperature meter, which can be driven by hand motions without any battery, opening a range of applications of TENG in conventional sensor systems. As an approach that is cost-effective, simple-implementing, scalable, and industry available, the CS-TENG can be widely applied for a variety of self-powered portable electronics.

2. Cover-sheet-based triboelectric nanogenerator (CS-TENG)

2.1 Structural Design

The CS-TENG has a multilayered structure, which mainly consists of two parts, that is, a slider and two stators (Figure 1a).

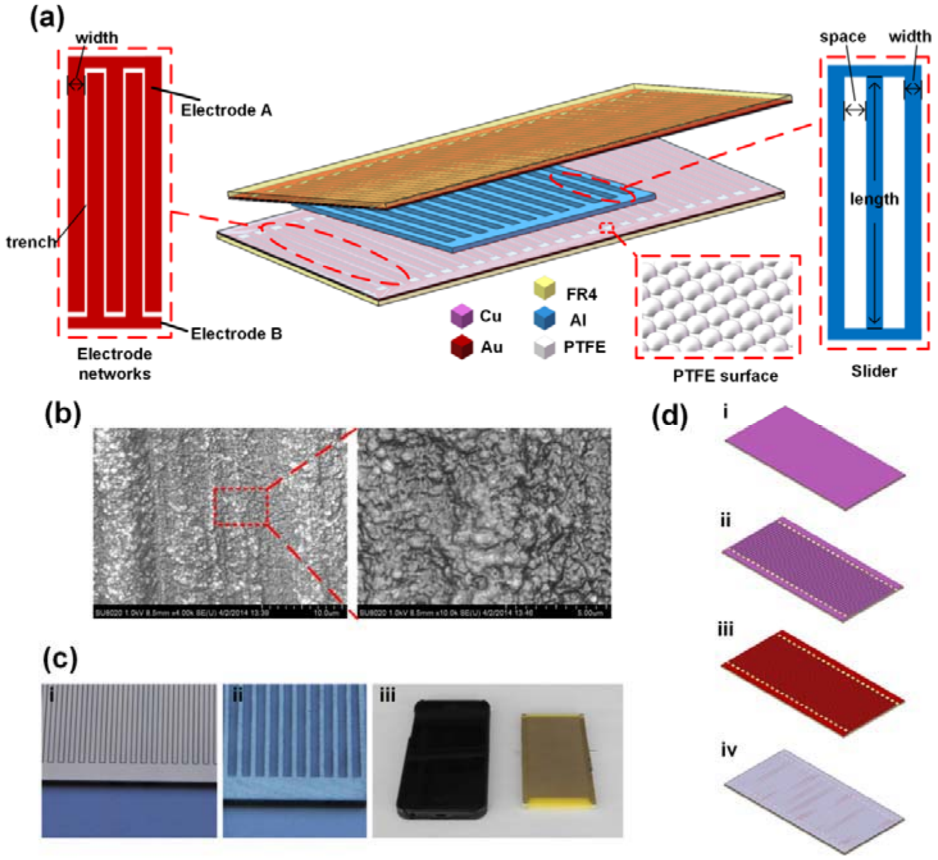

Figure 1. Structural design of the CS-TENG. (a) Schematic illustrations of the CS-TENG. (b) Scanning electron microscopy (SEM) images of the pre-treated PTFE's surface. (c) Photographs of the stator, the slider and the packaged devices (compared to the size of an iphone 5 at left). (d) Fabrication sketches of the stator by printing circuit technology.

The slider is an aluminum grating with a width of 900 μm at a period of 2000 μm in between. The stators are composed of two mirror-symmetry sheets. Each sheet includes three layers: a layer of polytetrafluoroethylene (PTFE) as an electrification material with a thickness of 30 μm, a layer of electrodes and a glass-reinforced epoxy laminate sheet (FR4) as the substrate. In order to further increase the electrification effect, the surface of the PTFE was treated by plasma of oxygen (O_2) and argon (Ar) to create a nano semi-sphere array (Figure 1 a and b) [21, 26, 27]. The underlying electrode is composed of two complementary-patterned electrode networks that are disconnected by fine trenches (100 μm wide) in between, as sketched in Figure 1 a and c. Each network is a collection of metal strips with a width of 900 μm at a period of 2000 μm (same as the slider's pattern) that are electrically connected by a bus at one end. The fabrication of the electrode networks is a well-known high-throughput printing electronics technology (Figure 1d). As exhibited in Figure 1a, both the slider and the stators have two-dimensional planar structures, respectively, resulting in a small volume for the CS-TENG.

2.2 Operating Principle:

The operation of the CS-TENG relies on the relative sliding between the slider and the stator, in which a unique coupling between triboelectrification and electrostatic induction gives rise to the alternating flow of electrons between two electrodes. The electricity-generating process is illustrated in Figure 2.

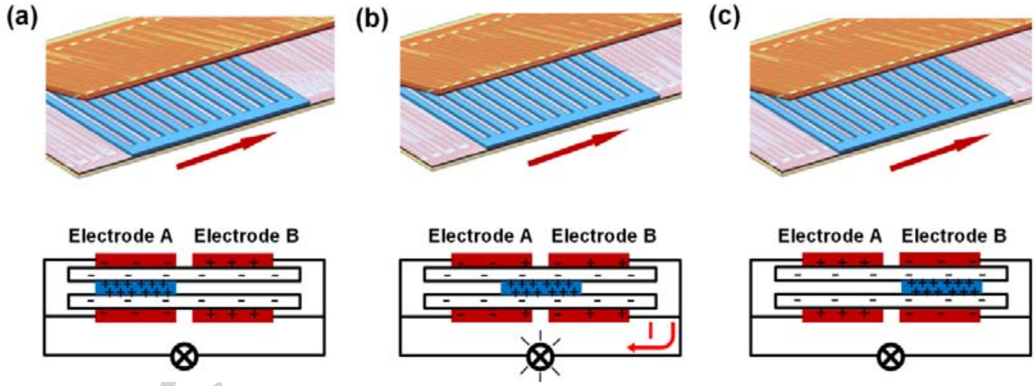

Figure 2. Schematics of operating principle of the CS-TENG. (a) Initial state in which the slider is in alignment with electrode A. The two sections from top to bottom illustrate the three-dimensional schematic and charge distribution in short-circuit condition, respectively. (b) Intermediate state in which the slider is sliding away from the initial position. (c) Final state in which the slider is in alignment with electrode B.

We define the initial state (Figure 2a) and the final state (Figure 2c) as the states when the slider is aligned with electrode A and electrode B, respectively. The middle state (Figure 2b) represents the transitional process in which the slider slides from the initial position to the final position. Since the slider and the stators are in direct contact, triboelectrification creates charge transfer on contacting surfaces, with negative charges generated on the PTFE and positive ones on the aluminum [24], as illustrated in the cross-sectional view in Figure 2. Due to the law of charge conservation, the charge density on the slider is about 4 times of the negative charge density on the PTFE after several round of sliding due to contract electrification process if the spacing between the grating metal strips is much smaller than the width of the metal strip [18].

The working principle of such structure was previously presented in details [20]. If the two sets of electrodes are connected through the external circuit, free charges can redistribute between electrodes due to the electrostatic induction. In the initial state, induced charges accumulate on electrode A and electrode B with charge density of -σ and σ, respectively. As the slider slides, free electrons keep flowing from electrode A to electrode B until the slider reaches the final state where the charge density on both electrodes is reversed in polarity compared with the initial state, as the electrons flow is driven by electrostatic force in order to reach an equilibrium. The amount of charges in this transport process can be expressed by the following equation

$$Q = n\sigma l w_{slider} \tag{1}$$

where n is the number of the strips in the slider, l, w_{slider} are the length and the width of the slider's strip, respectively. Consequently, the output current can be calculated by

$$I = \frac{\Delta Q}{\Delta t} = n\sigma l v \tag{2}$$

Further sliding beyond the final state results in a current in the opposite direction. Therefore, AC current is generated as a result of the periodically changing current direction, which has a frequency f given by

$$f = \frac{v}{2(w_{ele} + s)} \tag{3}$$

where v is the sliding velocity, w_{ele} is the width of the electrode's strip (equals to w_{slider} in our work) and s is the width of the trench between the two electrodes network.

2.3 Characterization of the CS-TENG

2.3.1 Electric Output Measurement

To quantitatively characterize the output of the CS-TENG, a linear motor was connected to the slider to provide mechanical motions. Driven by the linear motor that controls the sliding velocity, the slider makes reciprocating linear motion in a direction perpendicular to the metal strips. At a sliding velocity of 0.3 m s^{-1}, short-circuit current (I_{sc}) has continuous AC output at an average amplitude of 33 μA.

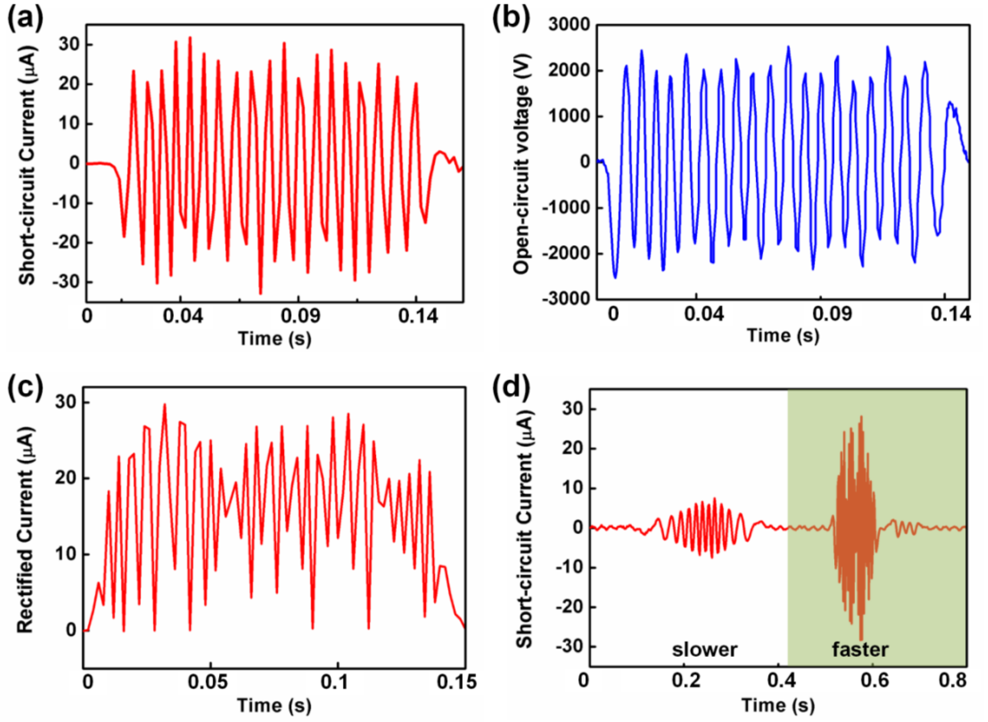

Figure 3. Results of electric measurements for the CS-TENG having a total area of 50 cm^2 and an effective contact area of 18 cm^2. (a) Short-circuit current (I_{sc}) at a sliding velocity of 0.3 m s^{-1}. (b) Open-circuit voltage (V_{oc}) at a sliding velocity of 0.3 m s^{-1}. (c) Rectified current at a sliding velocity of 0.3 m s^{-1}. (d) Current output under varying sliding velocity of 0.08 m s^{-1} and 0.3 m s^{-1}.

The constant frequency of 150 Hz (Figure 3a) is consistent with the result calculated from equation (3). As for the open-circuit voltage (V_{oc}), it oscillates between -2400 and 2400 V at the same frequency as I_{sc} (Figure 3b). Related principle analysis about the open-circuit voltage can be found in the previous work [20]. With a bridge rectifier, the negative output current was reversed, as shown in Figure 3c. Additionally, Figure 3d shows the influence of sliding velocity on the output current: when the slider moves faster, the current becomes larger.

Once an external load is applied, it brings up resistance and thus reduces the amount of electrons that can transport between electrodes. This is revealed by the reduced current with the increasing load resistance, as shown in Figure 4a.

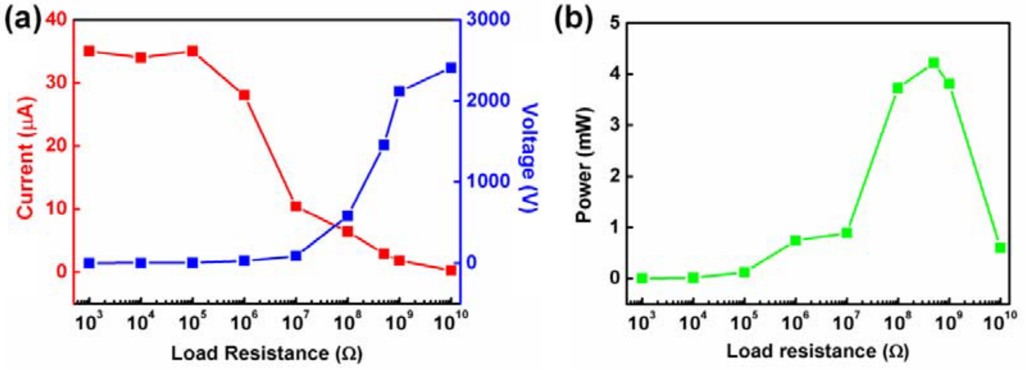

Figure 4. Load matching test at a sliding velocity of 0.3 m s^{-1}.

At the matched load of 500 MΩ, effective power ($P_{effective} = I^2R$, where R is the load resistance) reaches the optimum value of 4.3 mW at a sliding velocity of 0.3 m s^{-1}.

2.3.2 Factors Determining the Electric Output

Sliding velocity is a major determining factor in electric output of the CS-TENG. A nearly linear relationship between the amplitude of I_{sc} and the sliding velocity can be obtained, consistent well with equation (2), while the amplitude of V_{oc} and the amount of the total output charge are independent of the sliding velocity (Figure 5a-c).

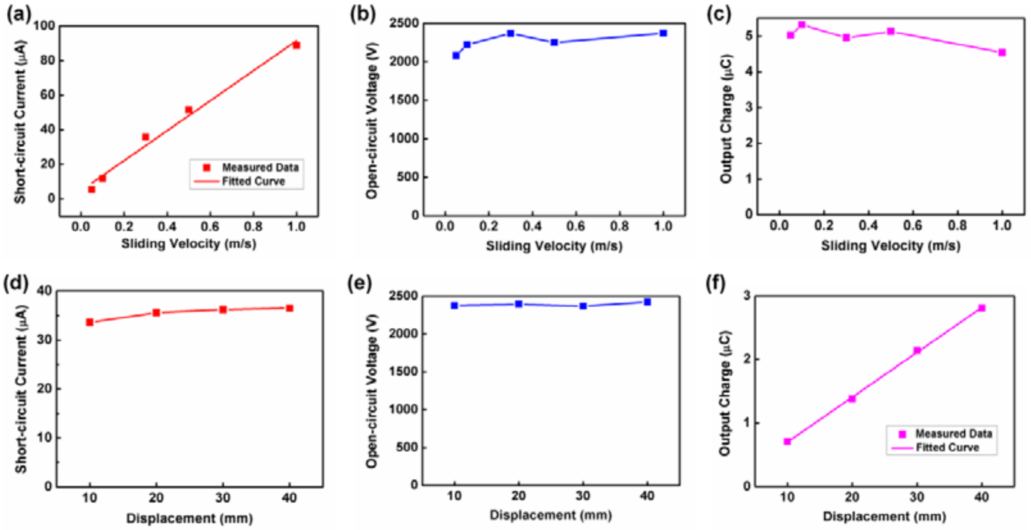

Figure 5. The effect of sliding velocity on the electric output of the CS-TENG. (a)(b)(c) Amplitude of I_{sc}, V_{oc} and output charges with varying sliding velocity. (d)(e)(f) Amplitude of I_{sc}, V_{oc} and output charges with varying sliding displacement.

Since the triboelectric effect is a surface charging effect, the total output charge of the CS-TENG is expected to linearly scale with the relative sliding displacement between the slider and the stators, as demonstrated experimentally in Figure 5f. As for the output current and voltage, they stayed constant, independent of the displacement.

3. CS-TENG as a Power Supply for Regular and Portable Electronics

To demonstrate the ability of the CS-TENG's as a power source, it was connected to a 10 μF capacitor. Under the linear motor's periodic reciprocating sliding, the capacitor was charged to 10 V in several seconds (Figure 6a). Apparently, as the sliding frequency increased, the charging time decreased (Figure 6b). As a power source, the CS-TENG was directly connected to regular light bulbs without using a storage or power management unit. Driven by the human hands' motion at a sliding velocity around 0.1~0.3 m s^{-1}, two white global lights (3W, E27) were powered up (Figure 6c, Supporting Movie s1).

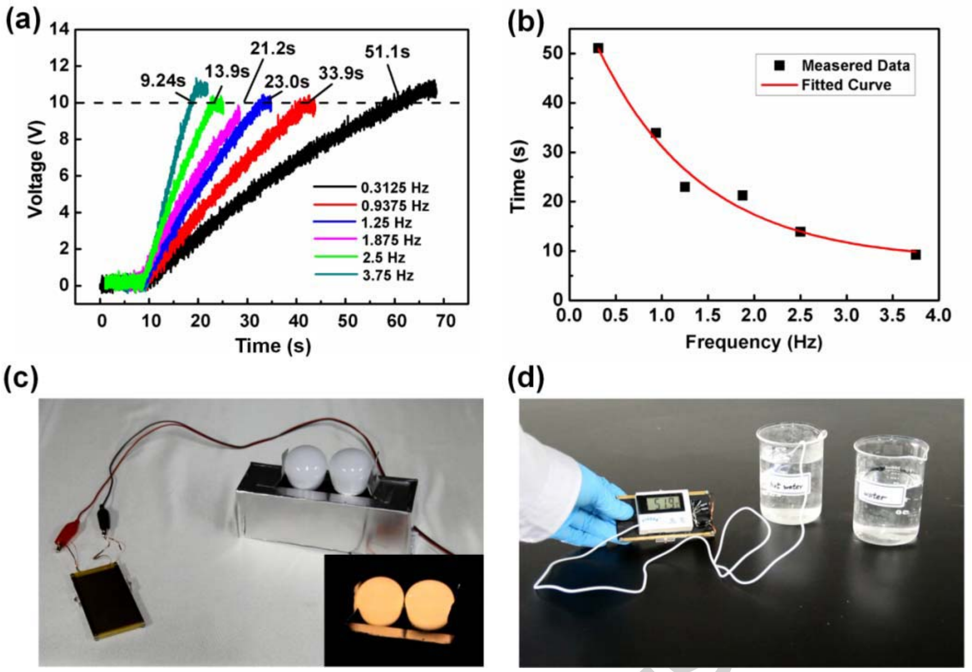

Figure 6. (a)(b) The CS-TENG charged a 10 μF capacitor to 10 V under varying sliding frequency. Demonstrations of the CS-TENG as a direct power source for (c) regular light bulbs and (d) a portable temperature meter.

Due to the small thickness and the planar shape, the CS-TENG was further integrated with a portable temperature meter as a back cover. Without any battery, the temperature meter can perform the measurements after reciprocating sliding the slider for several seconds (Figure 6d, Supporting Movie s2). This is a great demonstration of its application for immediacy applications for small and conventional senor system.

4. Performance as driven by vibrations

Besides the contact sliding working condition as discussed above, the CS-TENG can also be operated in non-contact situation with an air gap existing between the slider and the stators, which is reported to possess a high conversion efficiency [25]. As shown in Figure 7a, four identical extension springs are used to position the Al slider within the parallel plane to the surfaces of the stators with a distance around 1 mm (this configuration of TENG is defined here as the CSS-TENG).

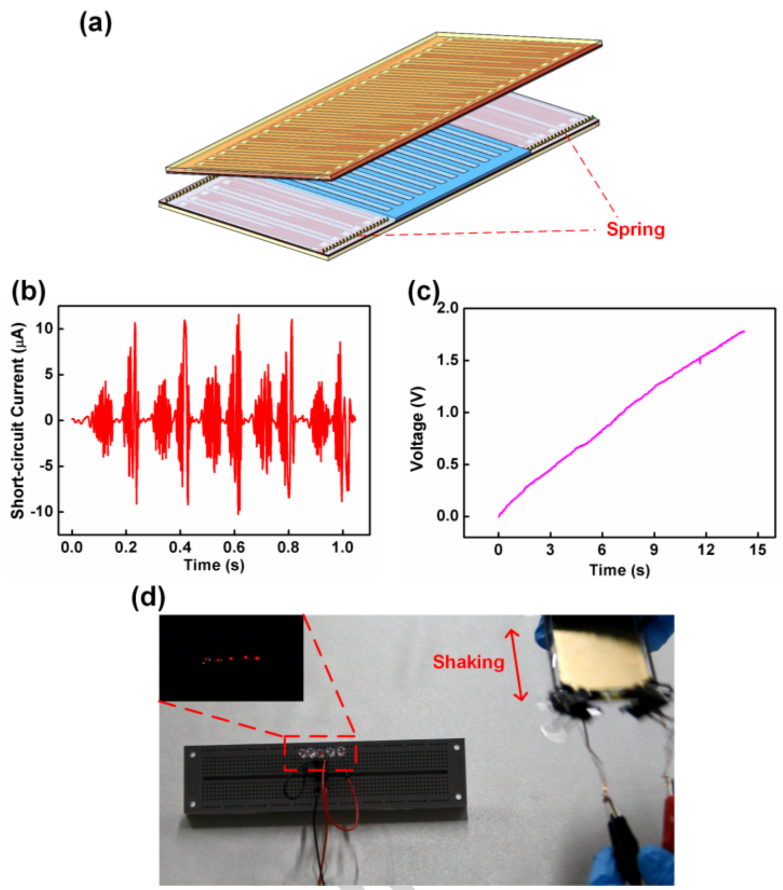

Figure 7. Characterizations and applications of CSS-TENG. (a) Schematic illustrations of the CSS-TENG. (b) Short-circuit current of the CSS-TENG under hand shaking. (c) Charging a 10 μF capacitor under hand shaking. (d) Powering up light-emitting diodes under hand shaking.

When the external mechanical motion applies onto the CSS-TENG along the spring direction, the slider will oscillate around the equilibrium position for multiple cycles, converting the residual vibration energy into electricity. Figure 7b shows the CSS-TENG's output current under the human hand shaking, with the current peak around 10 μA. It was found to charge up a 10 μF capacitor to 1.5 V in 12 s. Additionally, as shown in Figure 7d and supporting movie s3, the CSS-TENG can scavenge mechanical energy from shaking motions to power up five light-emitting diodes when bonded to human hands.

5. Conclusions

In summary, we have developed a cover-sheet-based triboelectric nanogenerator, with a thickness of 3 mm, similar to a protection structure of a mobile electronics. By employing a micro-sized electrode grating and in the sliding working mode, the CS-TENG produces an output current of 88.8 μA and a voltage of 2372 V at a sliding velocity 1 m s^{-1}. As a portable power source, it effectively produces electricity sufficient for powering regular household light bulbs as driven by human hands. Since the cover-shape design is of low weight and volume, and compatible with electronics' package, it is then integrated with a portable temperature meter as the back cover and successfully drives the meter for temperature measurement without the use of a battery. Furthermore, the

CS-TENG is additionally equipped with springs, exhibiting its usage in harvesting vibration energy from body motions. Therefore, this study immediately opens the applications of TENG for regular electronics in portable measurements and wireless sensing.

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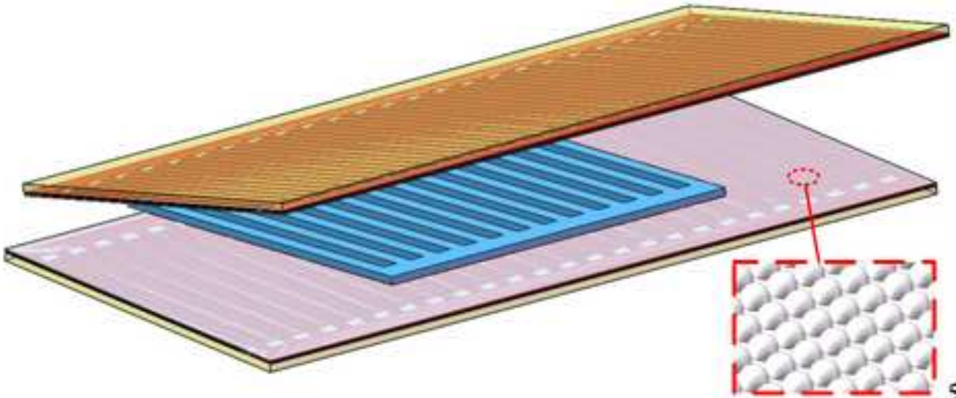
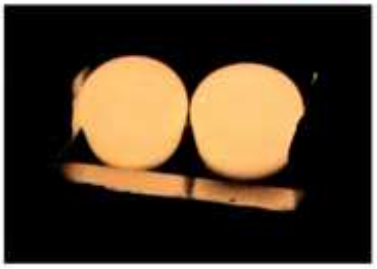
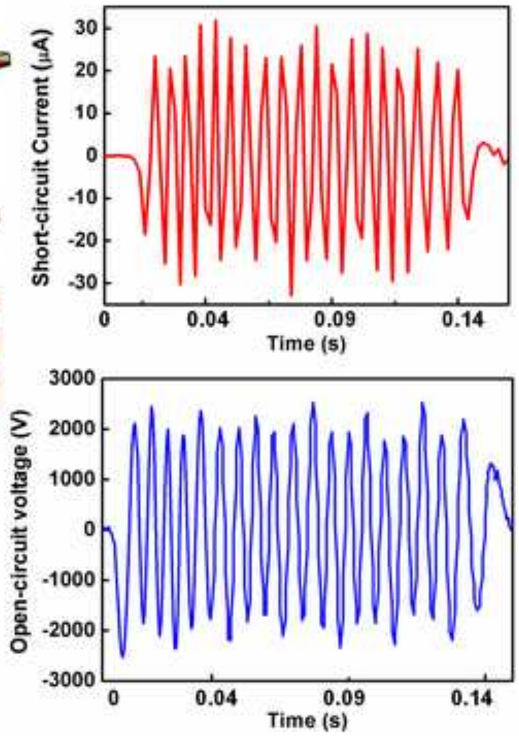
- The cover-sheet-based (CS) triboelectric nanogenerator (TENG) is of low weight and volume, and compatible with electronics' package
- A mobile temperature meter can be driven under the human hands motions without the use of a battery
- The CS-TENG equipped with springs is suitable for scavenging vibration energy from body motion

***Graphical Abstract**







Dr. Wei Tang received his Ph.D. degree from Peking University in 2013. He visited CMI of EPFL to participate in a Swiss-China joint Project in 2012. His research interests are micro/nano-devices, principle investigation of triboelectric nanogenerators, power transformation & management, and self-powered wireless sensing network.

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Dr. Chi Zhang received his Ph.D. degree from Tsinghua University in 2009. After graduation, he worked in Tsinghua University as a postdoc research fellow and NSK Ltd., Japan as a visiting scholar. His research interests are nanogenerator as active micro/nano-sensors, self-powered MEMS/NEMS, flexible electronics, and their applications in sensor networks and human–machine interaction.

Zhong Lin (ZL) Wang received his Ph.D. from Arizona State University in physics. He now is the Hightower Chair in Materials Science and Engineering, Regents' Professor, Engineering Distinguished Professor and Director, Center for Nanostructure Characterization, at Georgia Tech. Dr. Wang has made original and innovative contributions to the synthesis, discovery, characterization and understanding of fundamental physical properties of oxide nanobelts and nanowires, as well as applications of nanowires in energy sciences, electronics, optoelectronics and biological science. His discovery and breakthroughs in developing nanogenerators established the principle and technological roadmap for harvesting mechanical energy from the environment and biological systems for powering a personal electronics. His research on self-powered nanosystems has inspired the worldwide effort in academia and industry for studying energy for micro-nano-systems, which is now a distinct disciplinary in energy research and future sensor networks. He coined and pioneered the field of piezotronics and piezo-phototronics by introducing piezoelectric potential gated charge transport process in fabricating new electronic and optoelectronic devices. Details can be found at: www.nanoscience.gatech.edu.