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# Wearable Triboelectric Generator for Powering the Portable Electronic Devices

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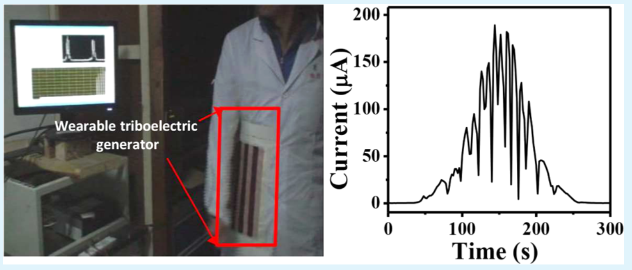
Supporting Information

**ABSTRACT:** A cloth-base wearable triboelectric nanogenerator made of nylon and Dacron fabric was fabricated for harvesting body motion energy. Through the friction between forearm and human body, the generator can turn the mechanical energy of an arm swing into electric energy and power an electroluminescent tubelike lamp easily. The maximum output current and voltage of the generator reach up to 0.2 mA and 2 kV. Furthermore, this generator can be easily folded, kneaded, and cleaned like a common garment.




**KEYWORDS:** *wearable generator, triboelectric generator, body motion energy, energy harvesting*

## INTRODUCTION

With the fast development of portable and mobile electronics, the corresponding convenient and portable power source must be further developed to power them. In recent years, harvesting different kinds of wasted tiny mechanical energies such as small vibration energy,[1−3] sound-wave energy,[4] and body motion energy (BME)[5] has drawn increasing attention because of its huge potential in powering more and more widely used micro/nanodevices. Among all kinds of mechanical energies, BME has the unique advantages and properties. On the one hand , average-sized person stores much energy in fat equivalent to the capacity of 1000 kg battery.[6] And about 25% of these stored chemical energy can be converted into positive mechanical energy.[7] From this, an average mechanical power output of 100 W can be obtained from a pedestrian.[8] Compared to energy in the human body, the power consumption of the portable and mobile electronics is rather weak. Take an iPhone 5S, for example, the output power is about 0.66 W in talking mode and only 0.026 W in standby mode. Even if only a small part of this mechanical energy can be harvested into electricity, it is enough to power most of the portable and personal micro/nanodevices. On the other hand the world population has reached 7 billion today and it continues to increase with a speed of more than 78 million per year. Such a large population provides a rich resource of BME. With these two factors, the BME is expected to be an important mobile energy in the near further. Meanwhile, as the portable and mobile electronics become more and more popular, the demand for mobile power source is consequently growing, which further makes it necessary to develop new techniques to harvest BME into electricity.

For powering some portable function devices,[9−13] a kind of wearable energy-harvesting technology is desirable. Triboelectrification is a common phenomenon in our daily life. Inspired by this, a triboelectric generator that is based on the coupling between the triboelectric effect and the electrostatic effect has been developed for harvesting small mechanical energy. Through the periodic process of contact and separation between two materials with opposite polarized triboelectric charges, electrons can be driven to flow back and forth in the external circuit between the electrodes.[14] By now, the triboelectric generator has made great progress on structure design,[15−21] performance enhancement,[17,22−24] and application.[25−27] Although some researchers have begun to work on how to harvest the BME through piezoelectric/triboelectric generators,[27−30] until now, these triboelectric generators seem more like an accessory of clothing rather than a cloth with the characters of softness, flexibility, foldability, or washability. And their performance needs to be further increased high enough to power portable electronic devices. Therefore, it is highly desirable to develop a truly wearable BME harvesting technique that meets above requirements.

In this work, a novel wearable triboelectric generator with improved performance and the characters of real wearable clothes is developed. Utilizing the friction between clothes of this triboelectric generator, it can convert the mechanical energy of body motion into electrical energy naturally. The short-circuit current and the open-circuit voltage reach a peak value of 0.2 mA and 2 kV, respectively. The charging rate of the device reaches 69 $\mu$C/s. And this wearable generator can easily power an electroluminescent (EL) tubelike lamp.

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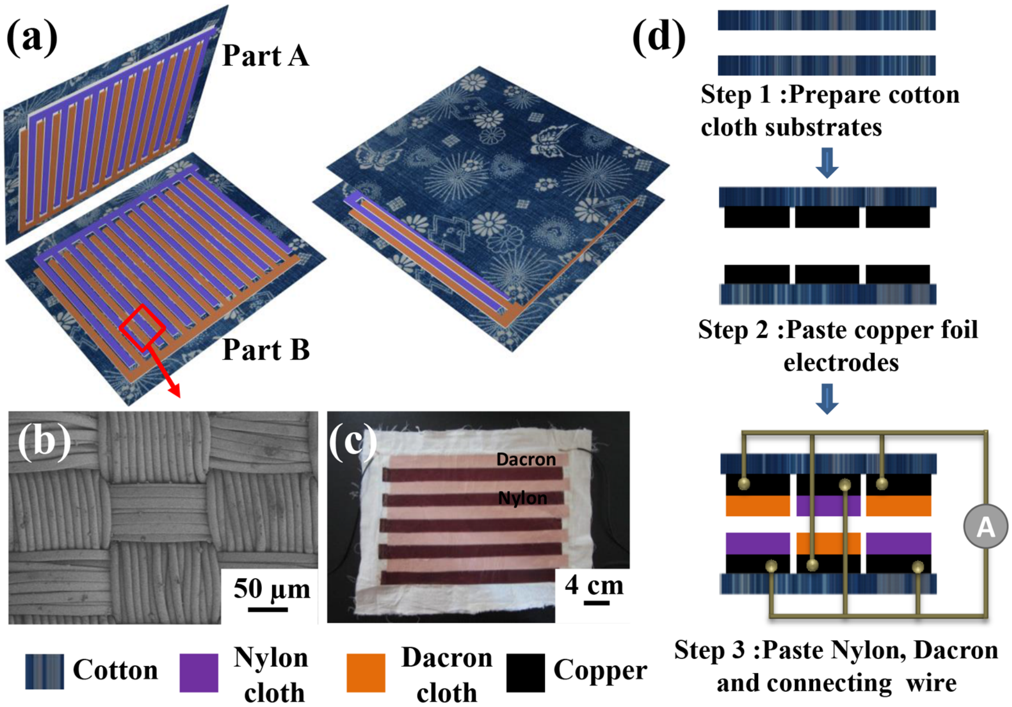


**Figure 1.** (a) Schematic diagram of the cloth-based wearable triboelectric generator. (b) SEM image of the microstructure of nylon cloth's surface. (c) Photograph of half part of the fabricated wearable triboelectric generator. (d) Fabrication process of the wearable triboelectric generator.

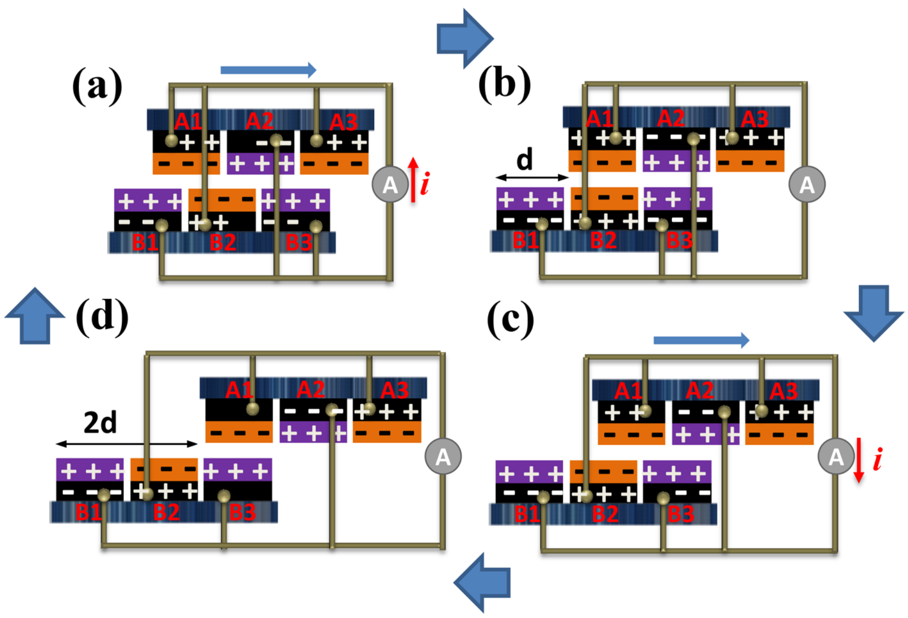


**Figure 2.** Working mechanism of the wearable triboelectric generator. (a) The slide and friction between Nylon and Dacron make nylon cloth carry positive triboelectric charges and Dacron cloth carries negative charges. The potential difference drives current from Nylon side to Dacron side. (b) The inductive charges screen the triboelectric charges to form a static equilibrium state. (c) When the slide continues to make the relative displacement S increase, the static equilibrium state is broken, and the current flows in a reversed direction. (d) When the relative displacement reaches one cycle, the static equilibrium state forms again by the positive and negative triboelectric charges screen each other.

## ■ RESULTS AND DISCUSSION

The wearable triboelectric generator has a layered structure with two parts, as schemed in Figure 1a. The purple and orange striped surfaces are the internal friction surfaces of the device which are composed of nylon cloth and Dacron cloth, respectively. Figure 1b shows the details of the surface microstructures on the cloth. These microstructures are naturally knitted with numerous threadlike fibers. The abundant microstructures on the surface of nylon and Dacron cloth play an important role to enhance the output. A photo of half part of the fabricated generator is shown in Figure 1c. And the details of the fabrication process can be summarized into three steps as sketched in Figure 1d. First, two pieces of cotton cloth are selected as the substrate for the generator. Then, ten strip electrodes are prepared to form a grating structure clinging to the cotton cloth by the adhesive. The size of the electrode



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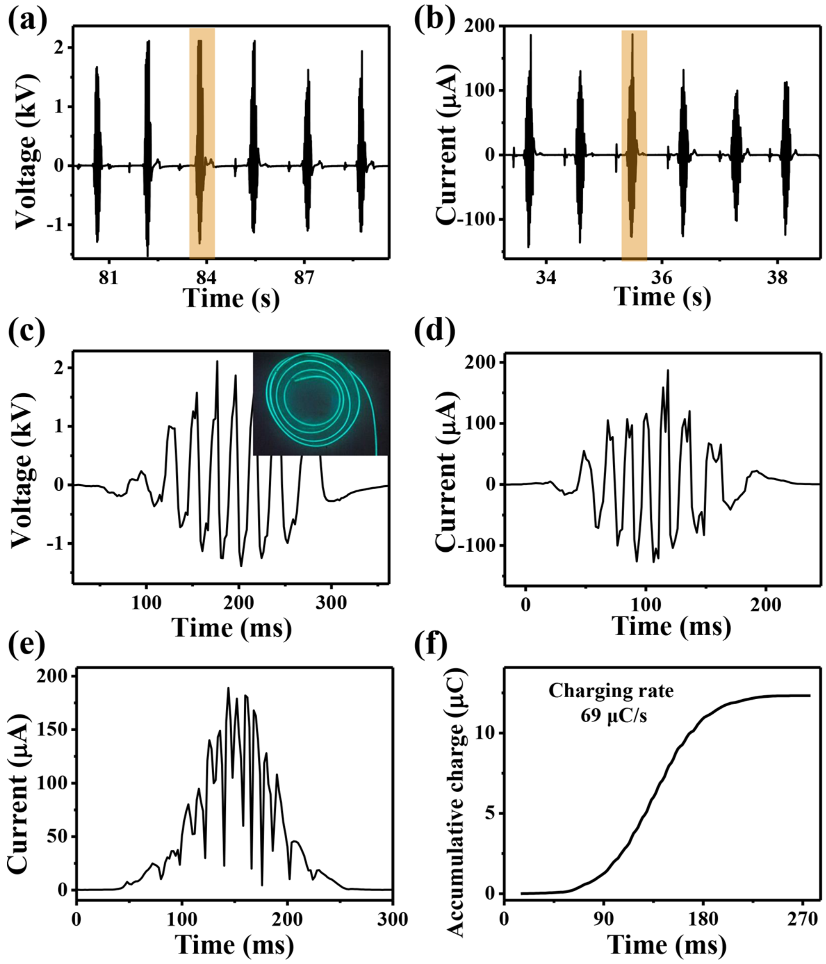


**Figure 3.** (a) Open-circuit voltage and (b) short-circuit current at an average sliding velocity of 1.7 m/s. (c) Enlarged view of the voltage output signal and (d) current output signal. Inset: an EL lamp lighted by the generator. (e) One current wave packet of rectified short-circuit current by a full-wave bridge. (f) Charging curves of the triboelectric generator. Via a full-wave bridge the electrons of one wave packet are pumped into a capacitor of 100 $\mu$F.

strip is 2 cm × 28 cm × 0.05 mm, and each of them is separated with the others by a 1 mm gap. After that, all of these electrodes are covered by five nylon strips and five Dacron strips alternately. The size of these cloth strips is 2.1 cm × 28 cm × 0.045 mm, and each of the cloth strips is bonded with the corresponding electrode by the double-side tape. Finally, connect the strip electrodes covered by Dacron cloth in parallel to form the positive electrode of the generator, and connect the strip electrodes covered by Nylon cloth in parallel to form the negative electrode of the generator.

The working mechanism of the wearable triboelectric generator is shown in Figure 2. When the relative sliding occurred between the two contact surfaces of the device, nylon cloth and Dacron cloth rubbed with each other. According to the triboelectric series[31] that ranks materials' tendency to gain or lose electrons, Nylon is more likely to lose electrons than Dacron. So, as shown in Figure 2a, the electrons will be injected from nylon to Dacron, which leads to the periodically arranged nylon and Dacron carrying the positive and negative charges respectively. When continued the relative sliding, the Dacron strip moves from the position A1 to the position B2. This causes the matched area between the nylon/Dacron strips on the two parts increases and the Dacron strips possess a lower electric potential than the nylon strips. This potential difference drives electrons to flow through external circuit and screens the triboelectric charges which are trapped on the nylon and Dacron surfaces. When the relative displacement $S$ reaches the width $d$ of one grating unit shown in Figure 2b, the positive and negative charges which are retained on nylon and Dacron cloth are completely separated in lateral direction. And the triboelectric charges on the nylon and Dacron strips are completely screened, leaving an equal amount of opposite inductive charges on the rear electrodes (Figure 2b). As the relative sliding continues, the Dacron strip in the position A1 is close to the position B3, and the matched area decreases which results in an electric potential difference with reversed polarity between the nylon and Dacron strips. Consequently, electrons flow in a reversed direction, as shown in Figure 2c. As the relative displacement $S$ reaches $2d$, the matched area between the nylon/Dacron strips on the two parts decreases to zero; meanwhile, the positive charges on nylon are completely compensated by the negative charges on Dacron (Figure 2d). Through above description, a pair of alternate current peaks will be generated in one period that the relative displacement achieves two grating units $2d$. So we obtain an equation of the peak number

$$N = S/d \quad (1)$$

$$f = v/2d \quad (2)$$


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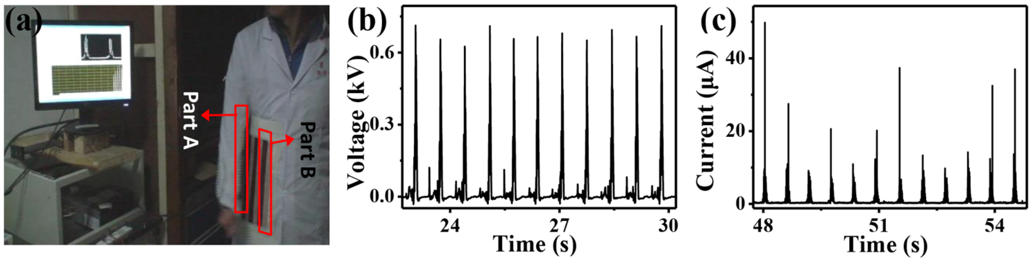


**Figure 4.** (a) Photograph of a working wearable generator sewn on the clothes. (b, c) Rectified output voltage and output current of the generator when swing arm.

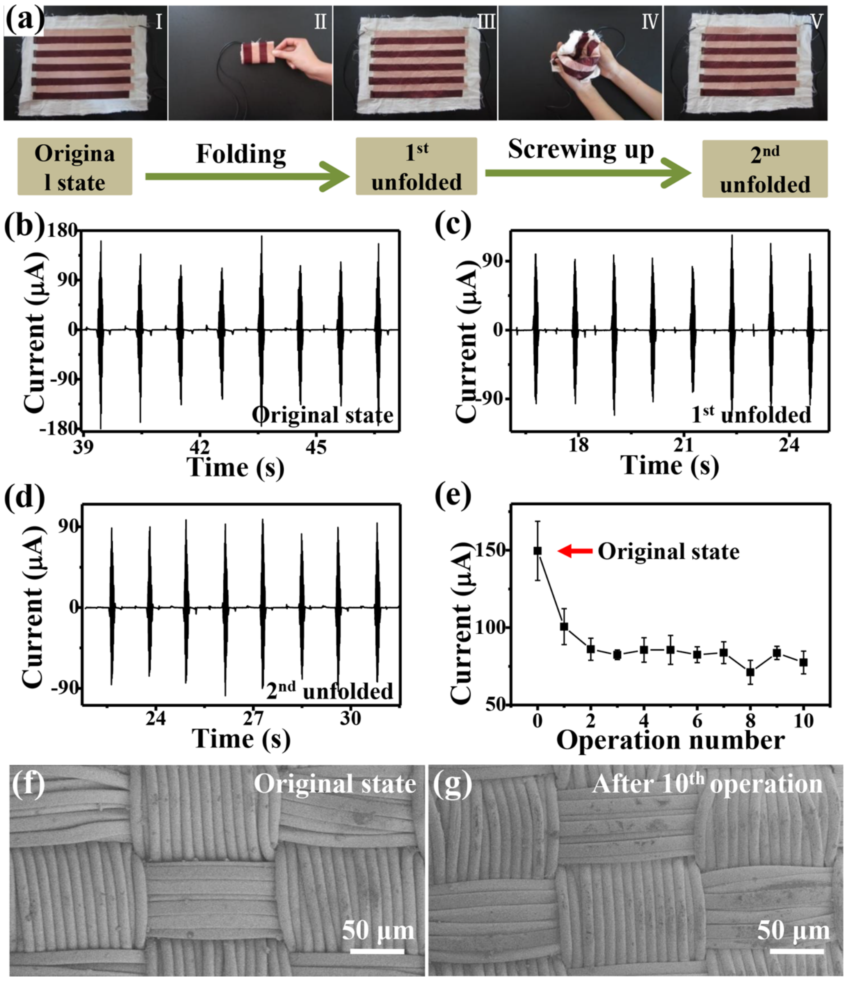


**Figure 5.** (a) Flexible performance test of the wearable triboelectric generator. (b) Output current of the generator in the original state. The output currents of the generator after unfolded operation at the (c) first time and (d) second time. (e) Average current peak values of the generator after each operation. (f, g) SEM images of the device surface before and after the flexible performance test.

Where $S$ is the relative displacement between the two parts, $d$ is the width of one grating unit, $N$ is the peak number of the output signal, $f$ is the frequency of output signal, and $v$ is the relative sliding speed of the device.

To trigger the generator, by pushing the top part of the device with two hands, the top part will slide on the bottom part, which is fixed on the table, just like Guang Zhu's work.[19] The open-circuit voltage ($V_{oc}$) and short-circuit current ($I_{sc}$) are measured under the condition with the average sliding velocity of 1.7 m/s, average pressure of 505 Pa and the relative displacement $S$ between the two parts is 32 cm. The relation between output and pressure is shown in Figure S1 in the Supporting Information. Panels a and b in Figure 3 show the $V_{oc}$ and $I_{sc}$, respectively; and each packet of the output signal is generated by a one-way sliding motion of the device. And the peak values of the $V_{oc}$ and $I_{sc}$ reach 2 kV and 0.2 mA. In the testing process, the output voltage is too large to use our common voltmeter. To reduce the voltage, a voltage division circuit is added. With the help of this circuit, only one two-hundredth of actual voltage needs to be measured. As shown in Figure 3c, d, the wave packet is composed of 16 current peaks and the frequency is 43 Hz, which meets eqs 1 and 2 well. It means that the frequency of the output current can be exactly controlled and adjusted by changing the width of grating unit $d$ and the sliding speed $v$ easily.


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**Figure 6.** Washing process of the generator: (a) washing with detergent and (b) washing with water. (c) The output current of the generator after washing.

A tubelike electroluminescence (EL) lamp with a length of 80 cm and 2.5 mm in diameter, which works under alternating current (AC) with high frequency and high voltage, is utilized as the operating load to demonstrate the capability of our device as a direct power source. As seen in the inset of Figure 3c, directly powered by the generator, the EL lamp emits bright green light. And the whole driving process is shown in the Supporting Information, Video 1. On the other hand, the AC output could be transferred to direct current (DC) pulse output by simply using a full-wave rectifying bridge (Figure 3e). The rectified current can be easily gathered by a capacitance. As demonstrated in Figure 3f, this curve represents a wave packet of the output current from a one-way sliding motion. During this process the charging rate, the ratio of the charge quantity and acquisition time, reaches 69 $\mu$C/s; and the corresponding charging rate per unit area of the generator is 1.23 mC/(m$^2$ s.)

To test the generator's energy harvesting ability from human activity, two parts of the device are attached on one experimenter's inner forearm and waist, respectively. By adjusting the positions of the two parts, they are kept to contact face to face when the arms droop naturally, as shown in Figure 4a. In this way, enough friction of these two parts can be guaranteed from the swing arms. The computer screen in Figure 4a real-time shows that the rectified current output signal generated by the experimenter's arm swinging. Supporting Information Video 2 records the working process of the device. The output voltage and current easily reach 0.7 kV and 50 $\mu$A, and each wave packet of the output signal accompanies a swing of the arm.

Comparing to other kinds of function devices, the wearable devices have strong demands for the flexibility and comfort of the power source. Herein, we characterize the performance of the wearable generator under some irregular deformations similar to the conditions of wearable clothes. First prepare one part of the generator on the table (Figure 5aI), and then fold it in half for five times into a small square of 5 cm × 8 cm (Figure 5aII). After unfolding the device (Figure 5aIII), the integral structure of the generator is still intact as the original state. Testing the output performance of the first unfolded generator, we find that the generator can still work well with a small decay (Figure 5c). After that, we screw up this device into a ball casually, as shown in Figure 5aIV, hold the kneaded device for several minutes and unfold it again. Figure 5aV shows that the device is still intact after it was unfolded after the second unfolding. As shown in Figure 5d, the generator generates almost the same output current as before. To demonstrate the robustness of this device, we continuously screw up and unfold the generator for ten times and test the output current of the generator after each unfolding. The output current signals are shown in Supporting Information, Figure S2. Figure 5e shows the average currents of the device after different cycles of folding and unfolding. After folding and unfolding the generator for the second time, the output current starts to level off. The result shows that current signals reduce obviously in the first two cycles. The reason for above phenomenon can be attributed to the wrinkles introduced by the operations of folding and kneading. These wrinkles decrease the contact area of the two parts. When new wrinkles cannot be produced, the contact area is unchanged, which leads to the stable output current. Besides, comparing the SEM images of the device surface before and after the experiments (Figure 5f, g), it appears that folding, kneading, and friction have very little impact on the surface microstructure of the generator. Besides, we add a durability test to verify that the generator is also suitable for long-term use. Figure S3 in the Supporting Information shows output current of the device after 90 min continuous work at a frequency of 60 cycles per minute. It can be easily seen that even after 5400 cycles of continuously working of the generator, the output signal is still as large as that at the beginning.

In addition, to check if the wearable triboelectric generator could be washed just like our clothes, it was washed with detergent and water (Figure 6a, b). After the washing process, there is no obvious damage to the device structure. Interestingly, the output current of the device after washing displays higher value (90 $\mu$A) than before washing (see the Supporting Information, Figure S2j). It may be attributed to that the wrinkles and dirts on the friction surfaces after washing are less than that before washing.

## ■ CONCLUSION

In summary, we invent a new type of cloth-based wearable triboelectric generator that can be attached on the surfaces of the clothes to harvest the mechanical energy of body motions. The generator not only has high output current and voltage of 0.2 mA and 2 kV, but also has a high charging rate of 69 $\mu$C/s. With the high voltage and high frequency characteristics, the generator can easily light an EL lamp. Furthermore, like the common clothes, this generator can be folded, kneaded and washed optionally with little impact on the performance of the device, which makes it possible to be integrated into clothes as a real wearable generator. With these virtues, the wearable triboelectric generator has a great potential to be developed into a new power source for the increasingly popular portable electronic devices and form a unique energy supply network.

## ■ ASSOCIATED CONTENT

### Ⓢ Supporting Information

Additional figures about the voltage and current output under different pressures, figures about the output current signals after


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folding and unfolding, figure about the durability test of the device, video showing the EL tubelike lamp lit by the wearable generator and video showing the driving process of the generator. This material is available free of charge via the Internet at http://pubs.acs.org/.

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### Notes

The authors declare no competing financial interest.

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## ■ REFERENCES

(1) Chen, J.; Zhu, G.; Yang, W.; Jing, Q.; Bai, P.; Yang, Y.; Hou, T. C.; Wang, Z. L. Harmonic-Resonator-Based Triboelectric Nanogenerator as a Sustainable Power Source and a Self-Powered Active Vibration Sensor. *Adv. Mater.* **2013**, *25*, 6094−6099.

(2) Hu, Y.; Yang, J.; Jing, Q.; Niu, S.; Wu, W.; Wang, Z. L. Triboelectric Nanogenerator Built on Suspended 3D Spiral Structure as Vibration and Positioning Sensor and Wave Energy Harvester. *ACS Nano* **2013**, *7*, 10424−10432.

(3) Zhang, H.; Yang, Y.; Su, Y.; Chen, J.; Adams, K.; Lee, S.; Hu, C.; Wang, Z. L. Triboelectric Nanogenerator for Harvesting Vibration Energy in Full Space and as Self-Powered Acceleration Sensor. *Adv. Funct. Mater.* **2013**, *24*, 1401−1407.

(4) Yang, J.; Chen, J.; Liu, Y.; Yang, W.; Su, Y.; Wang, Z. L. Triboelectrification-Based Organic Film Nanogenerator for Acoustic Energy Harvesting and Self-Powered Active Acoustic Sensing. *ACS Nano* **2014**, *8*, 2649−2657.

(5) Zhong, J.; Zhang, Y.; Zhong, Q.; Hu, Q.; Hu, B.; Wang, Z. L.; Zhou, J. Fiber-Based Generator for Wearable Electronics and Mobile Medication. *ACS Nano* **2014**, *8*, 6273−6280.

(6) Starner, T. Human-Powered Wearable Computing. *IBM syst. J.* **1996**, *35*, 618−629.

(7) Margaria, R. Positive and Negative Work Performances and Their Efficiencies in Human Locomotion. *Eur. J. Appl. Physiol.* **1968**, *25*, 339−351.

(8) Donelan, J.; Li, Q.; Naing, V.; Hoffer, J.; Weber, D.; Kuo, A. Biomechanical Energy Harvesting: Generating Electricity During Walking with Minimal User Effort. *Science* **2008**, *319*, 807−810.

(9) Hammock, M. L.; Chortos, A.; Tee, B. C. K.; Tok, J. B. H.; Bao, Z. 25th Anniversary Article: The Evolution of Electronic Skin (E-Skin): A Brief History, Design Considerations, and Recent Progress. *Adv. Mater.* **2013**, *25*, 5997−6038.

(10) Kim, D.-H.; Lu, N.; Ma, R.; Kim, Y.-S.; Kim, R.-H.; Wang, S.; Wu, J.; Won, S. M.; Tao, H.; Islam, A. Epidermal Electronics. *Science* **2011**, *333*, 838−843.

(11) Gong, S.; Schwalb, W.; Wang, Y.; Chen, Y.; Tang, Y.; Si, J.; Shirinzadeh, B.; Cheng, W. A Wearable and Highly Sensitive Pressure Sensor with Ultrathin Gold Nanowires. *Nat. Commun.* **2014**, *5*, 3132.

(12) Takei, K.; Takahashi, T.; Ho, J. C.; Ko, H.; Gillies, A. G.; Leu, P. W.; Fearing, R. S.; Javey, A. Nanowire Active-Matrix Circuitry for Low-Voltage Macroscale Artificial Skin. *Nat. Mater.* **2010**, *9*, 821−826.

(13) Schwartz, G.; Tee, B. C.-K.; Mei, J.; Appleton, A. L.; Kim, D. H.; Wang, H.; Bao, Z. Flexible Polymer Transistors with High Pressure Sensitivity for Application in Electronic Skin and Health Monitoring. *Nat. Commun.* **2013**, *4*, 1859.

(14) Fan, F.-R.; Tian, Z.-Q.; Lin Wang, Z. Flexible Triboelectric Generator. *Nano Energy* **2012**, *1*, 328−334.

(15) Lee, S.; Bae, S.-H.; Lin, L.; Ahn, S.; Park, C.; Kim, S.-W.; Cha, S. N.; Park, Y. J.; Wang, Z. L. Flexible Hybrid Cell for Simultaneously Harvesting Thermal and Mechanical Energies. *Nano Energy* **2013**, *2*, 817−825.

(16) Bai, P.; Zhu, G.; Liu, Y.; Chen, J.; Jing, Q.; Yang, W.; Ma, J.; Zhang, G.; Wang, Z. L. Cylindrical Rotating Triboelectric Nanogenerator. *ACS Nano* **2013**, *7*, 6361−6366.

(17) Bai, P.; Zhu, G.; Lin, Z.-H.; Jing, Q.; Chen, J.; Zhang, G.; Ma, J.; Wang, Z. L. Integrated Multilayered Triboelectric Nanogenerator for Harvesting Biomechanical Energy from Human Motions. *ACS Nano* **2013**, *7*, 3713−3719.

(18) Wang, S.; Lin, L.; Xie, Y.; Jing, Q.; Niu, S.; Wang, Z. L. Sliding-Triboelectric Nanogenerators Based on In-Plane Charge-Separation Mechanism. *Nano Lett.* **2013**, *13*, 2226−2233.

(19) Zhu, G.; Chen, J.; Liu, Y.; Bai, P.; Zhou, Y. S.; Jing, Q.; Pan, C.; Wang, Z. L. Linear-Grating Triboelectric Generator Based on Sliding Electrification. *Nano Lett.* **2013**, *13*, 2282−2289.

(20) Zhu, G.; Lin, Z.-H.; Jing, Q.; Bai, P.; Pan, C.; Yang, Y.; Zhou, Y.; Wang, Z. L. Toward Large-Scale Energy Harvesting by a Nanoparticle-Enhanced Triboelectric Nanogenerator. *Nano Lett.* **2013**, *13*, 847−853.

(21) Zhu, G.; Pan, C.; Guo, W.; Chen, C.-Y.; Zhou, Y.; Yu, R.; Wang, Z. L. Triboelectric-Generator-Driven Pulse Electrodeposition for Micropatterning. *Nano Lett.* **2012**, *12*, 4960−4965.

(22) Zhong, J.; Zhong, Q.; Fan, F.; Zhang, Y.; Wang, S.; Hu, B.; Wang, Z. L.; Zhou, J. Finger Typing Driven Triboelectric Nanogenerator and Its Use for Instantaneously Lighting Up LEDs. *Nano Energy* **2013**, *2*, 491−497.

(23) Lin, Z. H.; Xie, Y.; Yang, Y.; Wang, S.; Zhu, G.; Wang, Z. L. Enhanced Triboelectric Nanogenerators and Triboelectric Nanosensor Using Chemically Modified $TiO_2$ Nanomaterials. *ACS Nano* **2013**, *7*, 4554−4560.

(24) Zheng, Y. B.; Cheng, L.; Yuan, M. M.; Wang, Z.; Zhang, L.; Qin, Y.; Jing, T. Electrospun Nanowire-Based Triboelectric Nanogenerator and Its Application on the Full Self-Powered UV Detector. *Nanoscale* **2014**, *6*, 7842−7846.

(25) Wang, S.; Lin, L.; Wang, Z. L. Nanoscale Triboelectric-Effect-Enabled Energy Conversion for Sustainably Powering Portable Electronics. *Nano Lett.* **2012**, *12*, 6339−6346.

(26) Yang, Y.; Zhang, H.; Liu, R.; Wen, X.; Hou, T. C.; Wang, Z. L. Fully Enclosed Triboelectric Nanogenerators for Applications in Water and Harsh Environments. *Adv. Energy Mater.* **2013**, *3*, 1563−1568.

(27) Zhang, H.; Yang, Y.; Hou, T.-C.; Su, Y.; Hu, C.; Wang, Z. L. Triboelectric Nanogenerator Built Inside Clothes for Self-Powered Glucose Biosensors. *Nano Energy* **2013**, *2*, 1019−1024.

(28) Qin, Y.; Wang, X.; Wang, Z. L. Microfibre−Nanowire Hybrid Structure for Energy Scavenging. *Nature* **2008**, *451*, 809−813.

(29) Wu, W.; Bai, S.; Yuan, M.; Qin, Y.; Wang, Z. L.; Jing, T. Lead Zirconate Titanate Nanowire Textile Nanogenerator for Wearable Energy-Harvesting and Self-Powered Devices. *ACS Nano* **2012**, *6*, 6231−6235.

(30) Bai, S.; Zhang, L.; Xu, Q.; Zheng, Y.; Qin, Y.; Wang, Z. L. Two Dimensional Woven Nanogenerator. *Nano Energy* **2013**, *2*, 749−753.

(31) Gooding, D. M.; Kaufman, G. K. Tribocharging and the Triboelectric Series. In *Encyclopedia of Inorganic and Bioinorganic Chemistry*; Scott, R. A, Ed.; John Wiley & Sons: Hoboken, NJ, 2014; pp 1−9.



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