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# Two dimensional woven nanogenerator

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**Abstract**
Nanogenerator (NG) plays an important role in harvesting energy from the ambient environment. Here, we have developed a two dimensional woven nanogenerator (WNG), which imitates the textile's woven structure and is composed of two kinds of fibers crossing with each other, one kind of fibers grown with ZnO nanowires (NWs) and the other kind of fibers covered with the ZnO NWs coated with palladium (Pd) on their surface. Depending on the coupled piezoelectric and semiconducting properties of ZnO, it can generate electricity driven by the external tiny mechanical force such as tiny wind, sounds. The open-circuit voltage and short-circuit current of the WNG were 3 mV and 17 pA, respectively. Furthermore, the WNG was successfully used to power a microfiber/ZnO NWs hybrid UV sensor to form a wearable self-powered system, which can quantitatively detect the intensity of UV light.
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## Introduction

In recent years, harvesting energy from the various and ubiquitous mechanical movements existing in ambient environment to power the low power consumption micro/nanodevices, has attracted quite a lot of interests and been widely studied [1-5]. Owing to the outstanding electromechanical conversion performance [6], NG has become a promising approach of converting the widespread mechanical energy into electric energy. From the first demonstration of generating electricity through a single ZnO NW [4], great progresses have been made for NGs. The output electricity has been developed from direct-current (DC) [7] to alternating current (AC) [8], the output voltage has been increased from several millivolts (mV) to more than 1 V [9], tens of volts [10], and even more than 200 V [11], the driven mode of NG has been developed from direct contact mode to non-contact mode [12]. Up to now, the output of NG is enough to power some micro/nanodevices to form a self-powered system by harvesting energy from the environment. As for a self-powered system, its NG must be adaptable to its surrounding environment and easy to be integrated with the functional micro/nanodevices. A wearable and self-powered system is very

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desirable because of its applications on personal health monitoring and environmental monitoring, et al. And a natural way to power such a system is to explore a wearable NG to harvest body movement's energy and convert it into electricity. Considering the safety requirements of wearable self-powered system, both the NG and the functional devices should be innoxious. Owing to the excellent mechanical property and the coupling effect of piezoelectric property and semiconductor property, ZnO NWs have the potential to convert the body's tiny mechanical movement energy in wide frequency range into electricity [13]. And their biocompatibility further makes them a perfect candidate for wearable NGs [14]. Based on Kevlar microfiber/ZnO NWs hybrid structure, we once demonstrated a one-dimensional fiber-based NG to harvest low frequency mechanical movement energy, which demonstrates the possibility for a wearable NG [15]. But for a wearable "power shirt" which can scavenge energy from human activity, two dimensional fabric-like NG is necessary. Here, we developed a fabric NG woven by two kinds of fibers, one kind of fiber was covered by ZnO nanowires (NWs) grown on it, while the other one was the same as the former except for a Pd coating layer on the ZnO NWs. The fabricated WNG composed of 20 above fibers, can give a maximum output of 3 mV and 17 pA, respectively. And it can be driven by tiny wind. In addition, the WNG has been demonstrated to power a fiber-based sensor to form a wearable self-powered UV light detecting system.

## Results and discussions

### Fabrication and characterization of the WNG

The WNG's design is shown in Figure 1(a and b), where two kinds of fiber were woven together on the surface of a wood block and slider which served as substrate. The ends of these fibers were fixed by four pieces of strip electrodes, from which these fibers were connected to the external circuit via Cu wires. The green fibers depicted in Figure 1(a and b) were the ones with ZnO NWs grown on it, while the golden ones represented the ZnO NWs covered fibers further coated with a Pd layer. Due to Pd's high work function compared with the *n*-type ZnO, Schottky contacts will be formed at the intersections, which is fundamental for a ZnO NW NG [4]. The optical image of a fabricated WNG was shown in Figure 1(c), from which we can see its woven structure. The detailed structure of the intersection of these fibers was shown in Figure 1(d), which shows that the radially aligned structure of ZnO NWs was preserved very well.

In the experiment, the slider can shift for a short distance along the slot back and forth periodically driven by a linear motor. When the slider with coated fibers moving to one side of the slot, the as-grown ZnO nanowires on the fibers fixed on the standing block are deformed by the friction force. A reverse bias will be generated on the Schottky diode between the Pd electrode and the stretching side of ZnO nanowires, the charges create and accumulate, but there is no charge flowing through ZnO NWs. Subsequently, the Pd electrode reaches the compressed side and a forward bias forms on the Schottky diode, resulting in the accumulated electrons flowing across ZnO NWs and generating electricity [16]. After that, while the slider moving back, the same condition will happen and generate electricity again. As a result, in the output voltage and current curves, there will be two peaks in one motion cycle as shown in Figure 2. In Figure 2(a and b), the black curves indicate forward connection (FC), that is, the positive electrode of measurement system connecting with the uncoated fibers. Meanwhile, the red curves represent reversed connection (RC), namely the negative electrode connecting with the Pd-coated fibers. Both the output voltage and the current reverse their signals when the measurement system is reversely connected with the WNG, which eliminates the interference of noise in a certain degree [17]. The output voltage can reach about 3 mV and the output current is around 17 pA.

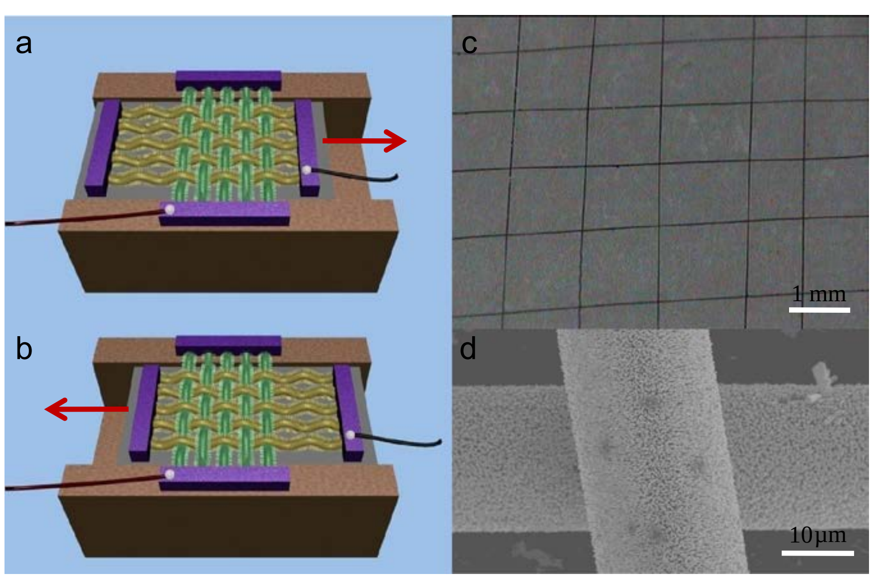


**Figure 1** Structure of the WNG. (a and b) Schematic and working mechanism of the WNG. The red arrows represent the slider shifting directions along the slot. (c) A photograph of intersection area of the WNG and (d) a scanning electron microscopy (SEM) image of one intersection point of the WNG.

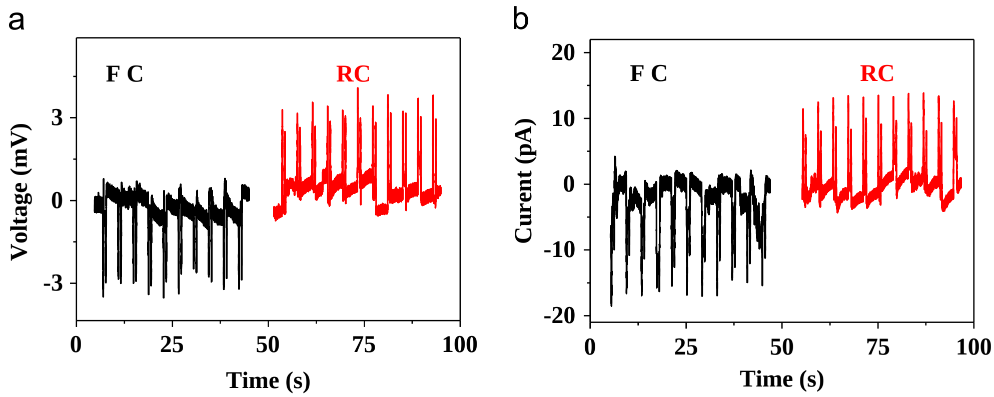


**Figure 2** The open-circuit voltage (a) and short-circuit current (b) of the WNG. Their amplitudes reached 3 mV and 17 pA. The black curves represented the output of the forward connection (FC) and the red curves stood for the reversed connection (RC).

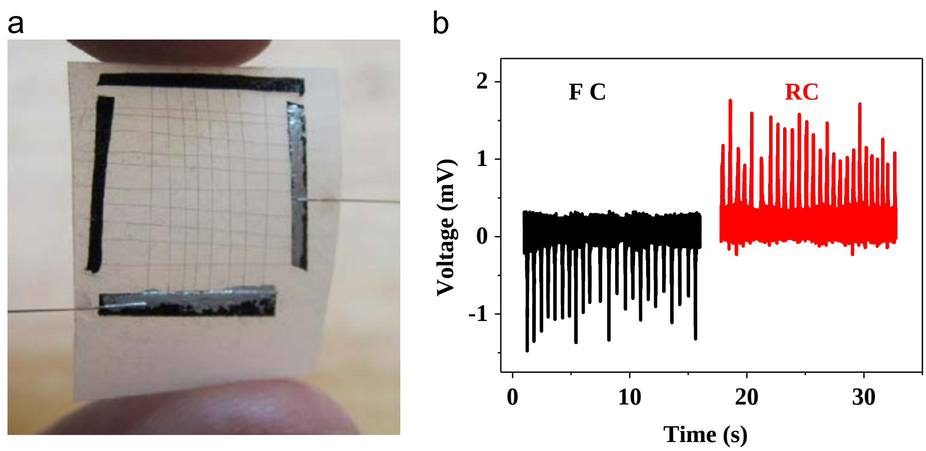


**Figure 3** (a) A photograph of the WNG fabricated on a paper sheet. (b) The open-circuit voltage of the airflow stimulated WNG, which can reach 1.5 mV.

## Airflow stimulated WNG

In order to further demonstrate the applicability of WNG and simplicity of harvesting energy from the environment, the WNG was fabricated on a quadrate paper as shown in Figure 3(a), a photograph of the WNG, which could be driven by a little disturbance such as light wind just as the energy harvesting technology through PVDF microbelt [18], vibration, acoustic wave and so on. The fabricating process of woven structure of the paper-based WNG is as same as the depicted above, but the wood block and slider are replaced by a piece of paper as a support. This design not only facilitates the fabrication process of WNG, but also simples the driven method. Driven by a little airflow produced by a pipette bulb, the WNG gave an output voltage of around 1.2 mV. Although the output of this design is small, it can convert tiny mechanical force existing in the environment into electric energy easily.

## Towards all fiber-based self-powered UV sensor

A sustainable self-powered UV sensor possessing woven structure, portable and easily driven properties has versatile applications. Based on synthesized fiber grown with ZnO NWs, a flexible fiber-based UV sensor was fabricated according to our former work [19]. If we power this fiber-based sensor with the above fabric WNG, a wearable self-powered system can be demonstrated successfully, as shown in Figure 4(a). The WNG and UV sensor were connected in series, at the same time, a voltmeter was connected in parallel with the sensor to measure its voltage dropping when UV light is shining on the sensor at different light densities. When the UV light is off, the voltage dropping on the UV sensor is about 0.8 mV, which is shown by the black curve of Figure 4(b). With the UV light intensity increasing from 5 μW/cm$^2$ to 12 μW/cm$^2$, the voltage dropping decreases dramatically from about 0.5 mV–0.2 mV as shown in Figure 4(b and c). And from the change of the measured voltage dropping on UV sensor, the corresponding intensity of UV light could be read. Therefore, this kind of wearable self-powered system could be used to detect the UV irradiance quantitatively.

## Conclusions

In summary, a new kind of fabric WNG was successfully fabricated by weaving ZnO NWs covered fibers and that coated with Pd into a two dimensional textile structure. It could harvest tiny mechanical energy on different substrates such as a couple of wood block and slider, flexible paper. Moreover, the WNG was successfully used to power a

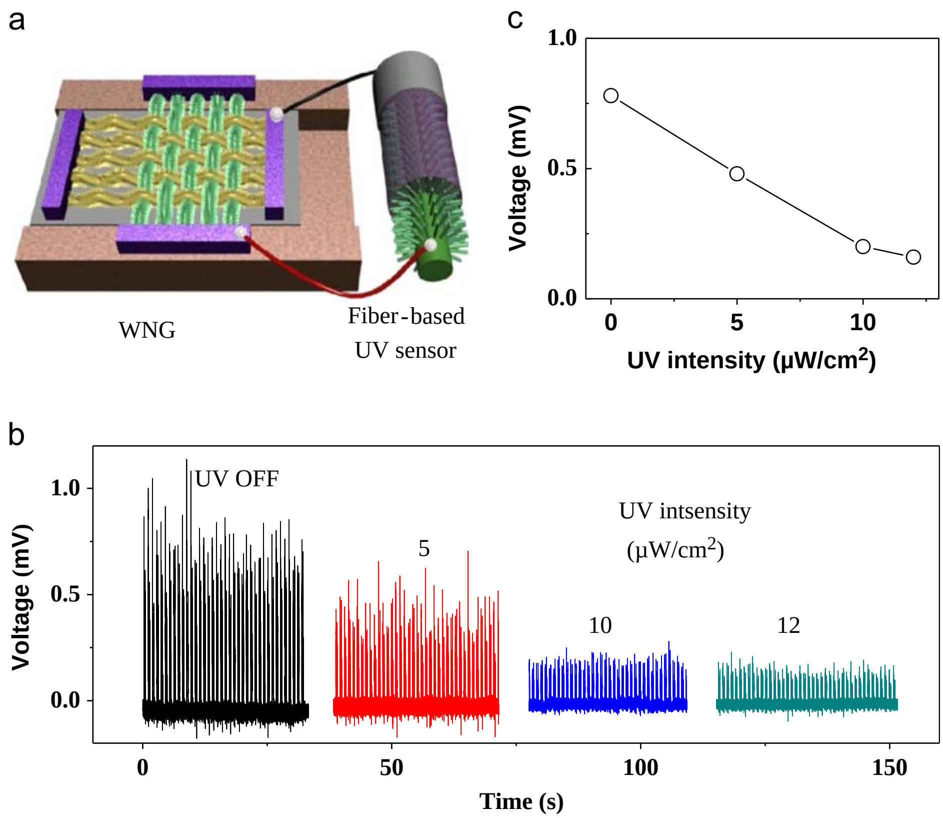


**Figure 4** (a) A schematic of the self-powered all-fiber-based UV detecting system. (b) Voltage drop across the fiber-based sensor driven by a WNG under different UV intensity. (c) Relationship between the averaged value of voltage drop's peaks and UV intensity.

fiber-based NW UV sensor to form a wearable self-powered system to quantitively detect UV light. The work will be beneficial to the wearable energy harvesting technology and wearable self-powered system.

## Experimental section

### Synthesis of ZnO NWs covered on fiber

Zinc nitrate hexahydrate ($Zn(ON_3)_2.6H_2O$), and hexamathylenetetramine ($C_6H_{12}N_4$), were used for the synthesis of ZnO NWs. All these chemical reagents were purchased without further purification. First, 0.7437 g of $Zn(ON_3)_2 \cdot 6H_2O$ and 0.3541 g of $C_6H_{12}N_4$ were dissolved in 1.0 L deionized water at room temperature. After 10 h aging in the solution at 80 °C, the Kevlar 129 fibers coated with a ZnO seed layer were grown with ZnO NWs. Finally, wash off the residual reagent and bake the sample at 100 °C for 1 h.

### Fabrication of the WNG

First, select some of the former fabricated coated fibers, and coat them with a Pd layer which served as the counter electrode via magnetron sputtering method. Second, weave these two kinds of fibers evenly. Third, two ends of the Pd-coated fibers and as-grown fibers were pasted on the slider and wood block, respectively. Finally, the two kinds of fibers were connected to the external circuit via Cu wires.

### Fabrication of the fiber-based UV sensor

The former fabricated ZnO NWs covered on Kevlar fiber were used to fabricate flexible fiber-based UV sensor. One end of the fiber was immersed in p-type conductive polymer PEDOT/PSS. Place the fiber on a substrate with its two ends bonded measurement system by silver paste.

### Test method

Sliding driven WNG. With the wood block fixed, the slider was connected to the *LinMot* linear motor (*E*1100) with a pre-set moving speed of 1 cm/s and maximum moving distance of 2 mm, respectively. During the movement of the slider along the slot, the WNG was driven periodically and its output was tested by the preamplifiers (*SR*570, *SR*560).

Airflow stimulated WNG. The paper on which a WNG was fabricated, was placed with one edge fixed and the opposite edge free. With the periodic tiny airflow produced by a pipette bulb exerting on the paper's free edge, the WNG was driven periodically and its output was also tested by the preamplifiers (*SR*570, *SR*560).

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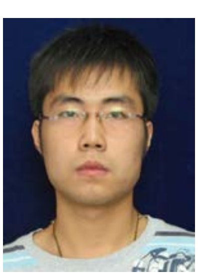

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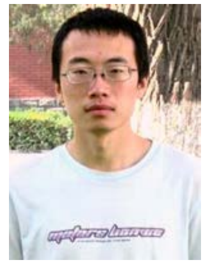

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