A Nanogenerator for Energy Harvesting from a Rotating Tire and its Application as a Self-Powered Pressure/Speed Sensor

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Harvesting unexploited energy in the living environment to power small electronic devices and systems is attracting increasing massive attention.[1–7] As the size of the devices has shrunk to the nano- or microscale, the power consumption also decreased to a modest level, i.e., the microwatts to milliwatts range. It is entirely possible to drive such a device by directly scavenging energy from its working environment. This self-powered technology makes periodic battery replacement or recharging no longer necessary and it is thus attractive for portable or inaccessible devices. Mechanical energy is a very conventional energy source in our living environment, with sources including the vibration of a bridge, friction in mechanical transmission systems, deformation in the tires of moving automobiles, etc., all of which are normally wasted. This form of energy is particularly important when other sources of energy, such as sun light or thermal gradients, are not available. A nanogenerator (NG) is designed to transfer such energy into electric energy by the piezoelectric effect.[8–14] The fundamental mechanism of a NG is that, when it is dynamically strained under an extremely small force, a piezoelectric potential is generated in the nanowire and a transient flow of electrons is induced in an external load, as driven by the piezopotential to balance the Fermi levels at the two contacts.

For bicycles, cars, trucks, and even airplanes, a self-powered monitoring system for measuring the inner tire pressure is not only important for the safe operation of the transportation tool, but also for saving energy. In this work, a NG was integrated onto the inner surface of a bicycle tire, demonstrating the possibility for energy harvesting from the motion of automobiles. A small liquid-crystal display (LCD) screen was lit directly using a NG that scavenges mechanical energy from deformation of the tire during its motion. The effective working area of the nanogenerator was about 1.5 cm × 0.5 cm and the maximum output power density approached 70 μW cm^{-3}. Integration of many nanogenerators is presented for scale-up. Furthermore, the NG showed the potential to work as a self-powered tire-pressure sensor and speed detector. This work provides a simple demonstration of the broad application prospects of NGs in the field of energy harvesting and self-powered systems.

In general, tires are turning and compressed during their rotations. The shape change rate of the tires at the position where they touch or detouch the road surface is very large and can be regarded as a good mechanical trigger to quickly introduce or withdraw a bending, as shown in **Figure 1**a. If a flexible NG is attached on the inner surface of the tire, an electric pulse is generated at the moment when it passes through such a position. Depending on the strain induced by such a trigger and the performance of the NG, the energy harvested in this process may be enough to directly power a small electronic device or system. The energy harvested for a number of cycles can be stored in a capacitor or battery for powering larger consumption electronics. In this study, we used a bicycle tire to simulate the working conditions of a tire because it is easier to handle in laboratory, but the approach can be applied to any tires.

Figure 1b shows the experimental setup. A tire (diameter ≈ 14 in.) was removed from a bicycle and caught between two rigid boards. One of the boards was fixed; the other one was connected to a linear motor and could be moved back and forth. The tire was squeezed and released periodically to simulate the conditions that occur at the position where touching or detouching of the road surface takes place. The NG used in this experiment was designed with a free-cantilever beam structure, as shown in Figure 1c. It consisted of five layers: a flexible polyester (PS) substrate, ZnO nanowire (NW) textured films on its top and bottom surfaces, and electrodes on the surfaces. The detailed fabrication and working mechanism of this type of NG can be found eleswhere.[15] Each time the NG was bent, an electric pulse was generated. Figure 1d shows that a NG was attached tightly on the inner surface of the tire using adhesive tape. Due to the good flexibility, the NG adhered tightly to the inner surface of the tire.

Electric measurements were carried out to characterize the performance of the NG under these conditions. The tire was squeezed and released by the movement of the board that was connected to a linear motor. Each time, there was an electric pulse generated corresponding to the trigger. The result is shown in **Figure 2**. The measured output voltage approached 1.5 V, and the measured output current was around 25 nA when the travel distance of the board was 12 mm with an acceleration of 30 m s^{-2}. Compared to the results reported previously,[15] the performance was somewhat degenerated under these conditions. This is because rubber is a plastic material, which absorbs some of the mechanical energy, and the strain rate in this material is smaller compared to a rigid material under the same trigger conditions. Despite this, the performance is still very good. A commercial LCD screen, taken from a Sharp calculator, was connected to the NG. The screen was lit

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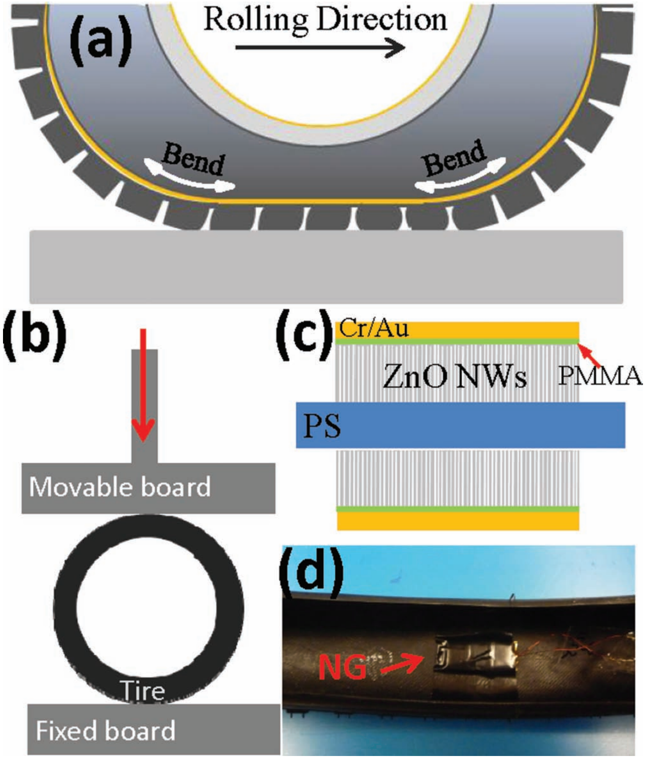

Figure 1. a) Shape change of the tire during the vehicle's movement. b) Experiment setup. A tire was caught between two boards to simulate the tire's deformation at the position where touching or detouching the road surface takes place. c) Sketch map of the NG's construction, which is a cantilever structure with five layers. d) A photograph showing that a NG was fixed on the inner surface of a tire using adhesive tape.

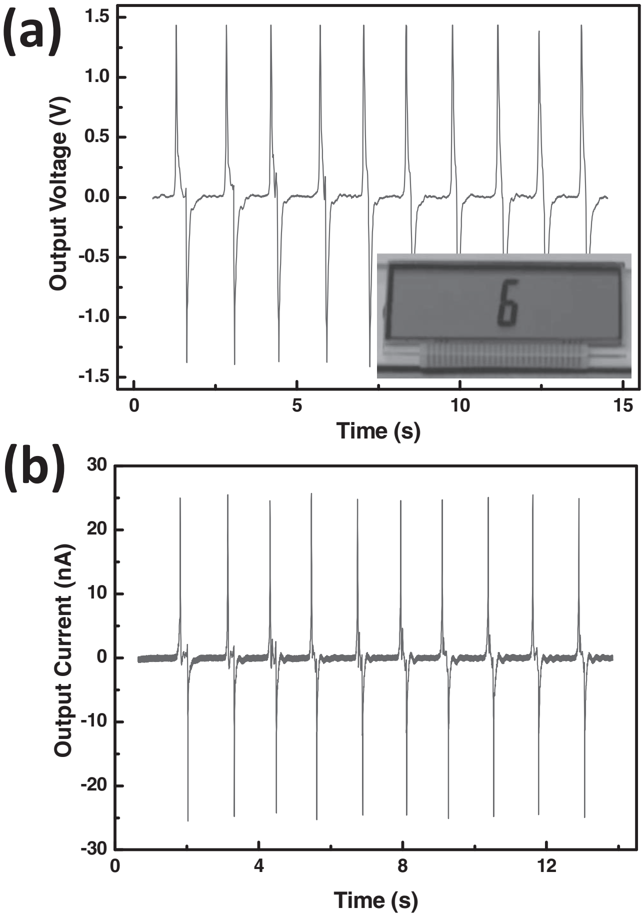

Figure 2. Performance of the NG attached to the inner surface of a tire, which was triggered by the deformation of the tire. The insert of (a) shows a LCD screen that was lit by the NG.

directly by the NG at each time it was triggered (see video in the Supporting Information).

The relationship between the measured output voltage V and the open circuit voltage V_{oc} of the NG is $V = V_{oc}R_m/(R_G + R_m)$, where R_G is the inner resistance of the NG and $R_m = 100\ \text{M}\Omega$ is the resistance of the voltmeter. This means that the true open circuit voltage can be significantly larger than the measured output voltage if R_G is comparable to R_m. The measured output current I is related to the short circuit current I_{sc} by $I = I_{sc}R_G/(R_G + R_m')$, where R_m' is the resistance of the amperemeter, which is 10 kΩ with a sensitivity of 10^{-8} A V^{-1}. According to the recorded data, the equivalent open circuit voltage is 3.4 V, the inner resistance of this NG is about 136 MΩ, and the maximum output power density is around 70 μW cm^{-3} at the volume occupied by ZnO. It should be noted that for real applications, the NGs could be integrated to the whole inner surface of the tire and could be stacked layer-by-layer. For a common automobile tire, the inner surface area is about 1.5 m × 0.2 m. The size of the effective working area of our NG was around 1.5 cm × 0.5 cm. Thus if a 1 cm thick working medium was attached, 50 W output power could be generated for one vehicle. Considering that the total vehicle population is over 1 000 000 000 worldwide, energy harvesting technology based on this design has amazing application potential.

To demonstrate the possibility of scale-up, we attached two NGs in parallel on the inner surface of the tire. They experienced the same strain conditions when the tire was triggered. In other words, the output signals of these two NGs were in the same phase and could be added. First, the performance of these two NGs was tested separately, and then the two NGs were connected in parallel. The results are shown in **Figure 3**. The measured output currents for the two NGs, NG1 and NG2, in individual tests were 6.4 nA and 13 nA. After parallel connection, the output current was 20 nA. The maximum output power density approached 120 μW cm^{-3}.

Another very important application of the NG in mobile vehicles is that it can work as a self-powered tire pressure sensor and speed detector. Prior research has indicated that the magnitude of the NG output signal is closely related to the applied strain and the strain rate.[12,13] Because the tire was compressed during the movement, the magnitude of deformation was correlated to the tire pressure. Lower pressure results in a flatter tire. Thus we can expect that a NG will provide a larger magnitude of the output signal when the tire pressure is reduced. We changed the travel distance of the trigger board to introduce a different deformation status of the tire (**Figure 4**a). As the travel distance increased from 8 mm to 16 mm, the deformation of the tire increased, or, in other words, the strain applied on the NG increased, which results in an increase in the

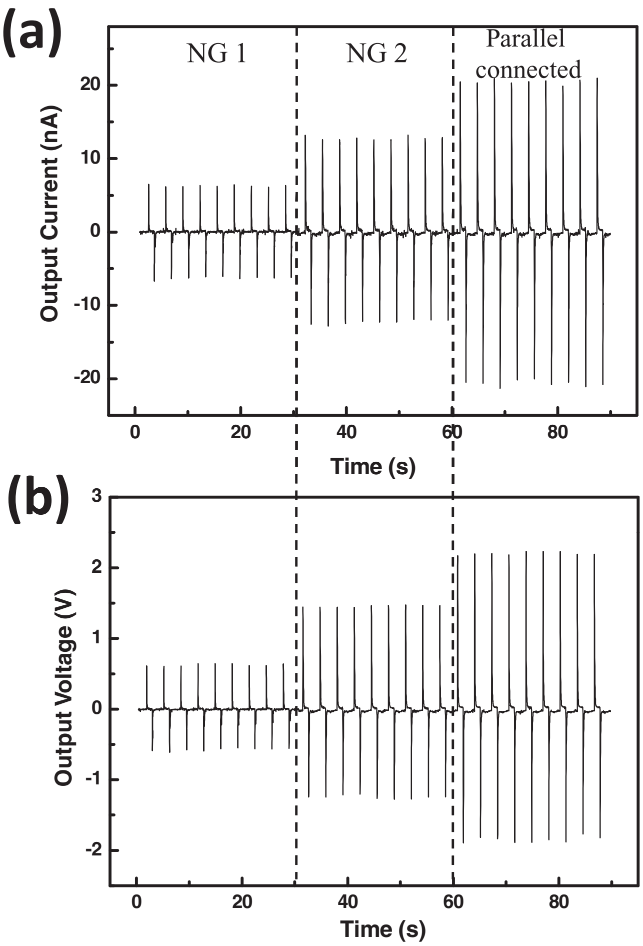

Figure 3. Two NGs were connected in parallel to demonstrate the possibility of integrating more NGs on the tire to improve the overall output performance.

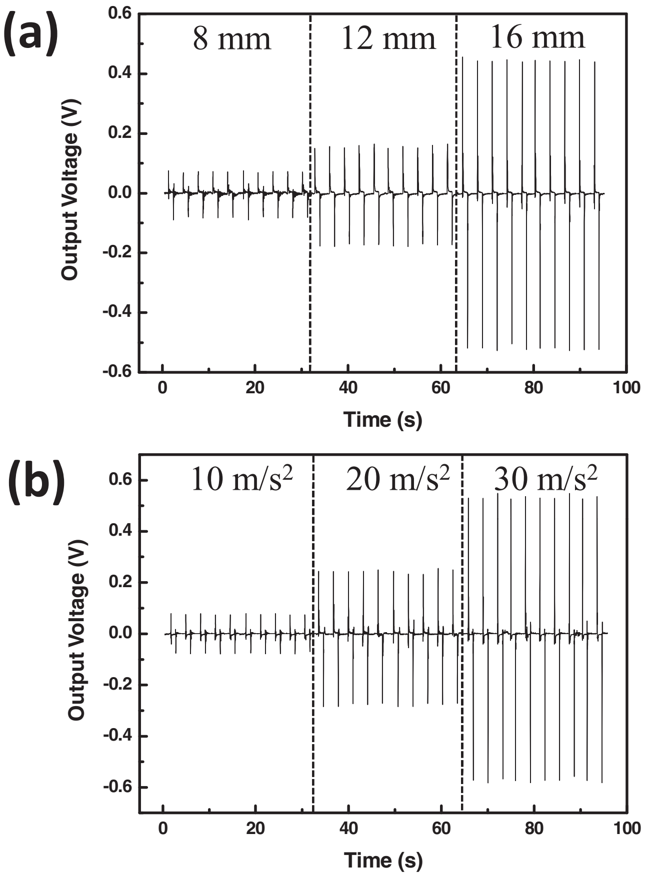

Figure 4. The measured output voltage of the NG increased step-by-step a) when the travel distance of the trigger board increased from 8 mm to 16 mm, which simulated the tire presure decreased step-by-step and b) when the acceleration of the trigger board increased from 10 m s^{-2} to 30 m s^{-2}, which represented the increasing speed of the vehicle.

output voltage from 0.1 V to 0.5 V. Also, when the speed of the vehicle increased, the rotation velocity of the tire increased. The NG attached on the inner surface of the tire will experience a larger straining rate as it passes through the position where the tire touches or detouches the road surface more quickly. An increased output voltage is expected for the increased vehicle speed. To demonstrate this idea, we increase the velocity of the trigger board while keeping the travel distance at the same and the result is shown in Figure 4b. Alternatively, there is another easy way to check the speed: one can use the NG to power a counter. A pulse would be sent to the counter for each turn of the tire.

In conclusion, nanogenerators were integrated onto a tire's inner surface. The deformation of the tire during the rotation was simulated by squeezing the tire periodically. The measured output voltage and current of the nanogenerator under these conditions were 1.5 V and 25 nA, respectively, and the maximum output power density was 70 μW cm^{-3}. A LCD screen was lit directly by the nanogenerator. The possibility of further integration was shown by two nanogenerators connected in parallel. The application of nanogenerators in energy harvesting from the motion of automobile tires was demonstrated. Additionally, the nanogenerator demonstrated its potential to work as a self-powered tire pressure sensor and speed detector in mobile vehicles.

Experimental Section

For the nanogenerator fabrication, flexible polyester (PS) film was chosen as the substrate. A 50 nm thick ZnO seed layer on the top of a 5 nm thick Cr adhesion layer was deposited at the central region on the top and bottom surfaces of the substrate. Densely packed ZnO nanowires were grown on the ZnO seed layers using a hydrothermal method.[16,17] An equal molar aqueous solution (0.1 M) of $Zn(NO_3)_2 \cdot 6H_2O$ and hexamethylenetetramine (HMTA) was used in the chemical growth process of ZnO densely packed nanowires textured films. The nanowire films at the top and bottom surfaces were grown sequentially by placing the substrate at the top of the nutrient solution with one face down. Because of the surface tension, the substrate floated on the solution surface. Growth of ZnO nanowires was carried out in a mechanical convection oven (model Yamato DKN400, Santa Clara, CA) at 95 °C for 5 h. The as-grown ZnO nanowire was 150 nm in diameter and 2 μm in length. A 2 μm thick poly(methyl methacrylate) (PMMA) layer was spin-coated on and subsequently a Cr/Au layer serving as the electrode of the NG was deposited on the top. Finally, after two leads were connected to the top and bottom electrodes, the whole device was fully packaged with poly(dimethylsiloxane) (PDMS) to enhance the mechanical robustness and flexibility. The output signal of the nanogenerator was recorded by using a low-noise voltage preamplifier (Stanford Research System Model SR560) and a low-noise current preamlifier (Stanford Research System Model SR570).

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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