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RAPID COMMUNICATION

Transparent flexible nanogenerator as self-powered sensor for transportation monitoring

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Abstract
In this paper, we fabricated transparent flexible nanogenerators (NGs) by employing flexible polydimethylsiloxane (PDMS) substrate for the growth of ZnO nanowires. The fully packaged NG showed good transparency with a transmittance of 50–60% in the visible range. The output voltage and current was 8 V and 0.6 μA, respectively, corresponding to an output power density of ~5.3 mW/cm^3. The NG also showed excellent robustness and could stably scavenge energy from the motion of a vehicle. Based on this characteristic, we demonstrated its application as a self-powered sensor for monitoring vehicle speed and detecting vehicle weight.

Introduction

Harvesting energy from our living environment has been a critical issue for sustainable development and has attracted long-lasting interest since the beginning of this century [1]. Mechanical energy is among the most abundant and reliable energy sources in our daily life, which is accompanying us regardless of the weather or temperature conditions as for solar [2] and thermoelectric energy [3]. Recently, piezoelectric nanogenerator (NG) has been developed that converts mechanical energy into electric energy employing the coupled piezoelectric and semiconducting properties of ZnO nanostructures [4–6]. The advancement of NG provides us with an alternate energy resource and pushes forward the investigation on wireless self-powered systems [7–9]. Various types of mechanical energy sources have been scavenged by NG including sonic wave [10], respiration [11], and air/liquid pressure [12]. In our previous work, the application of NG has been demonstrated as a self-powered tire-pressure sensor [13]. However, the setup required that NG should be installed inside the tire of the vehicles, which resulted in relatively high cost and sophisticated manipulation. Therefore, it will be more favorable if NG can be fixed onto the road and be applied as a self-powered sensor for transportation monitoring.

As for practical applications of NGs, both high output and excellent performance in other aspects are required to better

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accommodate the environment and human activity. The integration of transparency and flexibility characteristics is of dramatic importance in the development of NGs, especially for its potential applications in flexible electronics, artificial skins, and touch screens. Several works focusing on this issue have been reported [14–16] by using flexible polymeric substrate and transparent electrode materials like ITO [14], graphene [15], and carbon nanotube [16]. Though good flexible and transparent performance has been achieved, rare attention was paid to the real applications of the transparent flexible NG.

Polydimethylsiloxane (PDMS) is an optically clear, biocompatible, and fully rollable silicon elastomer, which is the core material for soft lithography to fabricate micro-fluidic devices [17]. It has been widely applied in the field of biological sensing [18], flexible solar cell [19], and tissue engineering [20]. We also have previous investigation that utilized PDMS as a template for the growth of ZnO NW array [21]. In this work, we successfully fabricated transparent and flexible NGs using ZnO nanowire (NW) array grown on PDMS substrate by the wet chemical approach. The fully packaged NG showed good transparency, flexibility, and robustness. Furthermore, the NG device had the capability to harvest energy under the rolling vehicle tire with stable output. Based on this character, we demonstrated its unique application as a self-powered dynamic sensor to detect vehicle speed and vehicle weight, which is of significance for practical applications in monitoring transportation flow.

Results and discussions

The structure of the transparent flexible nanogenerator (TFNG) is schematically shown in Figure 1a. First, the PDMS substrate was prepared by the gel-casting technique. A transparent and stretchable substrate with an ideal thickness was obtained. Closely packed ZnO NWs were uniformly grown on the PDMS substrate by the wet chemical approach, as the core component of the TFNG. The scanning electron microscopy (SEM) images of the NWs are shown in Figure 1b (top-view) and c (cross-sectional view). The diameter of the NWs was around 500 nm as indicated by the inset of high magnification image in Figure 1b, and the length of the NWs was around 6 μm. It was observed that the NWs had a hexagonal cross-section, and were grown densely to form a textured film, which was similar with the results in our previous works [7]. Then, polymethyl methacrylate (PMMA) was spin-coated on the NWs as an insulation layer. Finally, transparent ITO electrodes were deposited on the top and bottom surfaces of the composite structure. The effective size of the TFNG was 1.5 cm × 1 cm.

The working mechanism of the NG is based on the piezoelectric property of the ZnO textured film, according to our previous model [7]. When the flexible NG device is deformed by an external force, a piezoelectric potential (piezopotential) will be introduced in the ZnO textured film. As a result, a potential difference will be generated across the top and bottom electrodes due to induced charges, and it will drive the electrons flowing in the external load until equilibrium. When the external force is released and the NG recovers to its original shape, the piezopotential vanishes and the accumulated electrons will flow back in the opposite direction. Thus, an alternating current output signal is expected from the electrical measurement [22]. Here, we used numerical calculation to theoretically estimate the generated piezopotential with an applied stress,

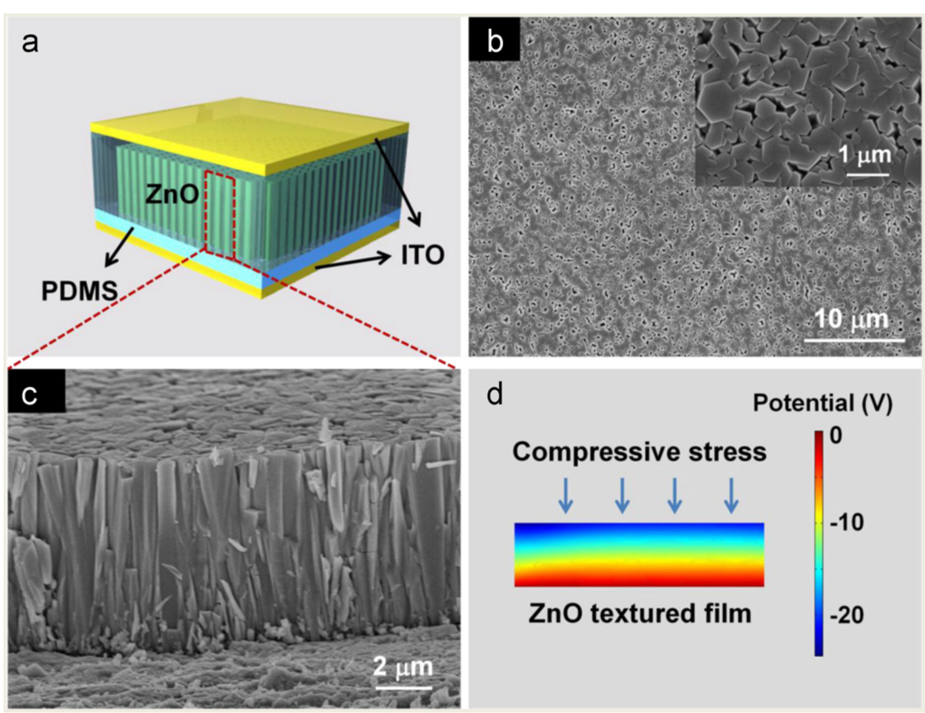

Figure 1 Structure and working principle of the transparent flexible nanogenerator (TFNG): (a) A schematic illustration of the typical composite structure of the TFNG. (b) The top-view SEM image of the as-grown ZnO NW arrays. The inset is a high magnification of the image. (c) The cross-sectional SEM image of the as-grown ZnO NW arrays. (d) Demonstration of the working principle of the TFNG from numerical calculation of the piezopotential in the ZnO textured film.