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Highly sensitive and flexible strain sensors based on vertical zinc oxide nanowire arrays

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ABSTRACT

In this paper, a highly sensitive strain sensor with vertically aligned zinc oxide (ZnO) nanowire arrays on polyethylene terephthalate (PET) film was reported. The device fabrication includes conventional photolithography, metallization, and ZnO nanowire growth through a hydrothermal method. *I–V* characteristics of the device were highly nonlinear due to the Schottky contact between the nanowire and the gold (Au) electrode. The conductivity of the device is significantly tuned by the change of ZnO/Au Schottky barrier that reflects the strain-induced piezoelectric potential. A gauge factor up to 1813 was obtained from this strain senor, which is higher than the previously reported device based on a lateral ZnO microwire. Theoretical analysis of the piezotronic effect shows that the working nanowire with the largest conductivity change dominates the performance of the device. The non-working nanowire has limited adverse effect on the performance, which explains the robust performance of this novel strain sensor. The stability and fast response of the sensor were also investigated. The sensitive and robust strain sensor is expected to find applications in civil, medical, and other fields.

1. Introduction

Flexible or stretchable strain sensors based on nanowire, nanotube or polymer composite have been widely studied in the last decade for potential applications in portable and wearable personal devices [1–24]. Many nanomaterials like carbon nanotube (CNT) [1–12], graphene [13–18] and ZnO nanostructure [19–24] have been investigated for the design of strain sensors. Compared to conventional rigid strain sensors using metal or silicon, flexible strain sensors based on nanomaterials exhibit high strain tolerance, ultra-fast response, high sensitivity, and low power consumption. Nanowires with piezoelectric and semiconducting properties are particularly suitable for this purpose due to the recently discovered piezotronic effect, in which the piezoelectric potential from a strained wire can dramatically tune the current flow through the nanowire by the change of Schottky barrier [23–27]. Flexible piezotronic strain sensor has been demonstrated based on individual ZnO microwire, with a gauge factor of 1250 [22]. The nanowire-based sensor is expected to provide even better performance due to the much higher surface-volume ratio and significant spatial confinement.

In this paper, a novel strain sensor based on vertical ZnO nanowires grown on PET substrate has been designed and fabricated, and the improved sensitivity, flexibility, robustness as well as fast response have been examined. ZnO is an environment friendly material with outstanding piezoelectric and semiconducting properties. ZnO nanowires can be achieved in high yield with physical or chemical approaches [28–30], which facilitates future scale up and massive production. It has been revealed that the *I–V* characteristics of the strain sensor are dominated by Schottky contact at ZnO/Au interfaces and are thus highly nonlinear. The Schottky barrier height is tuned by piezoelectric potential from stressed ZnO nanowires when the strain sensor is deformed. The strain sensor is extremely sensitive to the local strain and a gauge factor up to 1813 was observed. This gauge factor is higher than that of previous reported strain sensors with single ZnO microwire in lateral configuration [22]. In the Section 2 of this paper, the fabrication procedure of the device and the measurement system are introduced. In Section 3, the performance of the strain sensor is tested. Finally, the performance as well as the piezotronic working principle of the device is discussed.

2. Fabrication procedure and measurement setup

The fabrication procedure of the strain sensor and the measurement setup are shown in Fig. 1. A piece of PET substrate with a length of ~3 cm, a width of ~1 cm, and a thickness of ~200 μm was rinsed with acetone, isopropyl alcohol, and deionized water and then blow-dried with nitrogen. The dry and clean PET substrate was placed in a RF/DC sputtering system (AJA-Sputter, 200 W), in

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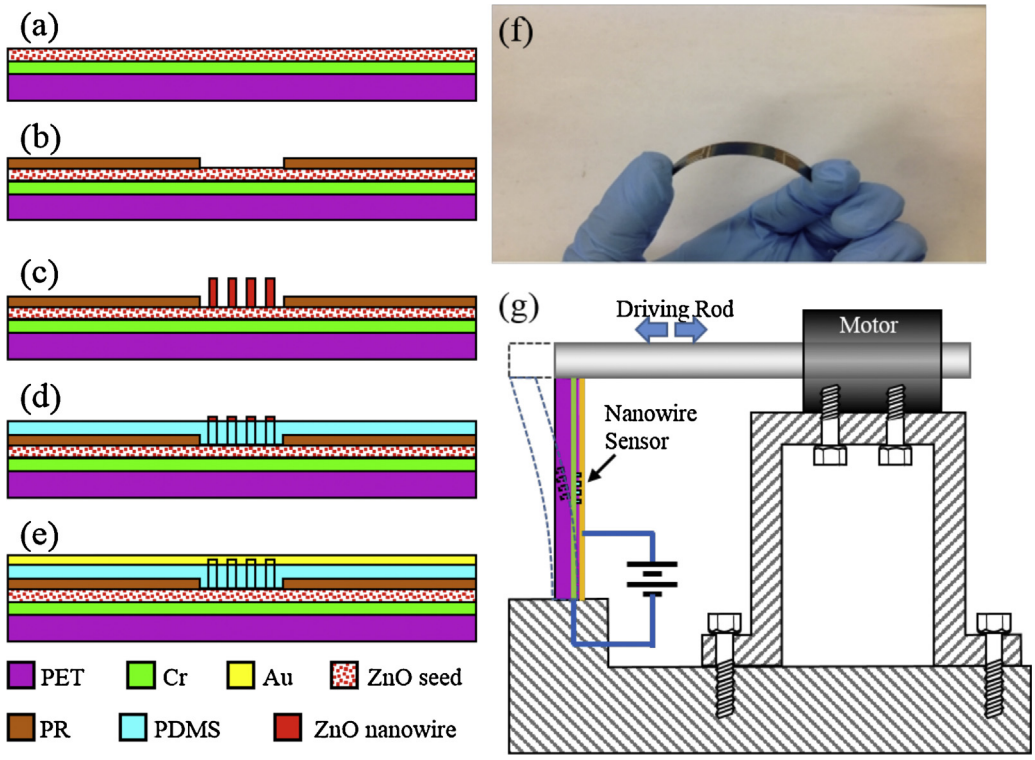

Fig. 1. Schematic fabrication process of the strain sensor and measuring system. (a) Deposit Cr bonding layer and ZnO seedlayer on PET substrate. (b) Open the window through photolithography. (c) Grow ZnO nanowire with hydrothermal solution. (d) Spin-coat PDMS protection layer for ZnO nanowire and dry etch to exposure nanowire tips. (e) Deposit Au as top electrode. (f) Optical image of the final device. (g) Sketch of measuring system that includes sample holder and linear motor with moving rod.

which a bonding layer of Cr (~40 nm) and a seed layer of ZnO (~200 nm) were deposited in sequence, as shown in Fig. 1(a). Shipley S1813 photoresist was spin-coated (~2 μm, 3000 rpm for 30 s) on the substrate and a pattern of 2 × 2 windows (50 μm × 50 μm each) was opened in Fig. 1(b) through photolithography for the growth of ZnO nanowire arrays in Fig. 1(c). In order to obtain uniform, long and high quality of ZnO nanowires, the growth solution of 16 mmol/L hexamethylenetetramine and 16 mmol/L zinc chloride was mixed with 4% volume concentration of ammonia (30% w/w NH_3). The substrate was floated upside down on the surface of the solution. After the growth at 95 °C for 14 h, ZnO nanowire arrays were obtained in the 2 × 2 windows. A thin layer of polydimethylsiloxane (PDMS, ~20 μm, 3000 rpm for 2 min) was spin-coated on the surface of the PET substrate and cured at 80 °C for 2 h, which served as a protection layer for the nanowire arrays. Top part of the PDMS layer was then etched away in a reactive-ion etching system (STS Dry Etcher, with O_2:CF_4 = 1:3 for 15 min), which exposed the tip of nanowires in Fig. 1(d) for electrode connection in Fig. 1(e). A thin layer of Au (~120 nm) was deposited by a RF/DC sputtering system to serve as the top electrode and form ZnO/Au Schottky barrier. Finally, the strain sensor was packaged by spin-coating a thin layer of poly(methyl methacrylate) (~2 μm, NANO^{TM}950, MicroChem) on the surface. The final device was compact and highly flexible, as shown in Fig. 1(f).

The setup in Fig. 1(g) was used to test the performance of the strain sensor. One end of the strain sensor was fixed tightly on a sample holder while the other end was attached to a moving rod driven by a programmable linear motor. During the measurement, the linear motor was programmed to push/pull the lateral rod with specified distance, acceleration, maximum speed and deceleration, so that the strain sensor was bent back and forth in a well-controlled manner. A sinusoidal bias voltage was applied across the nanowires with a functional generator (Keithley 3390) and the current was monitored with a current amplifier (Keithley 428). The measurement was carried out in atmosphere at room temperature. The strain sensor was located in a home-built Faraday cage so that the environmental influence and electromagnetic noises were excluded.

The performance of strain sensor largely depends on the quality of ZnO nanowire arrays. Fig. 2 shows typical ZnO nanowire arrays from hydrothermal growth. Fig. 2(a) confirmed that ZnO nanowire arrays grew uniformly within designed pattern with a length of ~10 μm and a diameter of ~100 nm. The PDMS layer was spin-coated on the substrate and then partially etched to expose the tip of the ZnO nanowire for the electrode deposition, as shown in Fig. 2(b). After etching, ZnO nanowires in Fig. 2(b) were intact and surrounded by PDMS. The distorted and very bright area in Fig. 2(b) is due to the common charging effect in the scanning electron microscopy.

3. Experimental result

The typical *I–V* characteristics of the strain sensor and its response to the strain are shown in Fig. 3. The nonlinear and rectifying behavior in Fig. 3(a) is due to the Schottky contact formed between the ZnO nanowire and the Au electrode. Fig. 3(a) also indicates that the *I–V* characteristic is dramatically changed when the devices is stressed. Because the dimension of the nanowire is much smaller than PET and PDMS is much thinner (15 μm) and more compliant (360–870 kPa) than the PET (200 μm and 2–2.7 GPa), PET dominates the elastic behavior of the device. The longitudinal normal strain at the surface of the sensor was estimated from equation

$$\varepsilon = \frac{3aD}{l^2}\left(1 - \frac{x}{l}\right) \quad (1)$$

Here, a is the half thickness of the PET substrate (~100 μm), D is the maximum bending deflection of the device, l is the length from