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Effect of seed layer thickness on optoelectronic properties of ZnO-NRs/p-Si photodiodes

M. Lajvardi [a,b], M.E. Ghazi [a,*], M. Izadifard [a], H. Eshghi [a], I. Hadi [b]

[a] Physics Department, Shahrood University of Technology, Shahrood, Iran
[b] Iranian National Center for Laser Science and Technology, Tehran, Iran

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ABSTRACT

In this work, the effect of seed layer thickness on the optical and electrical properties of a photodiode based on zinc oxide nanorods (ZnO-NRs)/p-Si was studied. ZnO thin films of different thicknesses were deposited on a p-type single crystalline silicon substrate by the spin-coating method, and then well-aligned ZnO-NRs were grown on a seed layer by the hydrothermal method. The seed layer thickness increment enhanced the NR lengths and improved their crystallinity. Longer NRs showed lower reflectance and band gap measurements were carried out using the reflectance spectrum. The current-voltage (I–V) measurements were performed under dark and UV illumination to study the photodetection properties of the ZnO-NRs/p-Si photodiode with different seed layer thicknesses. The diode ideality factor, barrier height, saturation current and series, and shunt resistance were determined by the dark current-voltage measurements. The dark current-voltage characteristics demonstrated an excellent rectifying behavior, and the seed layer thickness increment decreased the diode ideality factor. It was shown that the current-voltage characteristics of the fabricated devices with different seed thicknesses under UV light illumination had good sensitivities.

1. Introduction

Zinc oxide (ZnO) is an inherent n-type transparent II–VI semi-conductor with a wide and direct band gap of about 3.36 eV at room temperature and a large exciton binding energy of 60 meV [1]. High quality ZnO nanostructures can be synthesized using simple methods such as the thermal evaporation, sol-gel, zinc oxidation, and hydrothermal ones [1]. Various morphologies of the ZnO nanostructures including nanoparticles [2], nanorods (NRs), and nanowires [3–5] with their own novel physical, optical, and electrical properties have been synthesized and characterized in the recent years.

The growing ZnO facility in a nanostructure form makes ZnO a promising candidate for diversified applications in the microelectronic and optoelectronic devices [6,7]. UV photo-detection is one of the significant applications of ZnO nanostructures. The performance of a UV photodiode has been correlated with different ZnO morphologies [8–10]. ZnO-based UV photodiodes including Schottky metal-semi-conductor junctions and p-n junction devices have also been demonstrated [8,11].

From the electrical viewpoint, the growth of p-type ZnO is not achievable yet because of the deep acceptor levels and low dopant solubility [12]. Due to the limited efficiency of ZnO homo-junctions, the researchers have developed ZnO-based

* Corresponding author.
E-mail address: mghazi@shahroodut.ac.ir (M.E. Ghazi).

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hetero-junctions using a number of p-type semi-conductors such as Si [7,9,10], GaN [13], and SiC [14]. Compared to other substrates, the development of n-ZnO/p-Si hetero-junctions seems to be more convenient because of the low cost, non-toxicity, and environmental characteristics of Si. However, a large lattice mismatch between Si and ZnO that results in a poor quality hetero-junction should not be ignored [15].

Some works have been performed on the electrical properties of n-ZnO/p-Si hetero-junctions [16–18], and their application as UV and visible light detectors [19–21]. A ZnO thin film has been deposited on p-Si through the sol-gel spin-coating technique by Mansour et al. [18], and the voltage current analysis has confirmed the rectifying behavior of the fabricated junction with a diode ideality factor of about 4.17 and a barrier height of 0.79 eV. Luo et al. [20] have fabricated ZnO nanowires on a p-type silicon through the vapor-liquid-solid method. This system has exhibited a low UV responsivity of about 0.07 A/W under a 20 V reverse bias. Hazra et al. [21] have employed the atomic layer deposition technique for deposition of a 100-nm ZnO thin film on a silicon substrate. The fabricated hetero-junction device has demonstrated a suitable UV responsivity of about 0.075 A/W at a 2 V reverse bias voltage. The UV photodiodes based on n-ZnO-NRs/p-Si hetero-junctions through the hydrothermal method have been fabricated by Hardan et al. [9], and an excellent rectifying ratio of 370 at 10 V has been reported. The UV responsivity of the device was about 0.38 A/W at 360 nm. To the best of our knowledge, few studies have considered the effect of seed layer thickness on the electrical properties of a fabricated hetero-junction. Also comparative studies about the effect of NR lengths on the responsivity rise and decay time of the ZnO-based photodiode could not be observed in the literature.

In this work, a ZnO seed layer was deposited on a silicon wafer by the spin-coating technique, and then ZnO NRs were grown through the hydrothermal method. It was investigated that how different seed layer thicknesses would affect the structural and optical properties of the ZnO NRs. Moreover, the effects of different seed layer thicknesses on the electrical properties and UV responsivity of this fabricated n-ZnO NRs/p-Si hetero-junction were studied.

2. Experimental details

Two-step processes were used for the synthesis of ZnO NRs on a p-type (100) single-crystalline silicon substrate including the seed layer deposition followed by the growth of NRs using the hydrothermal method. Prior to the seed layer deposition, the silicon wafers were ultrasonically vibrated in acetone, ethanol, and deionized (DI) water, respectively, to remove the organic grease. Then the substrates were heated in boiling Piranha solution (H_2SO_4 97%:H_2O_2 30% = 3:1; v/v) for 20 min to remove the heavy metals, and subsequently rinsed in DI water and dried with N_2. The spin-coating method was employed for the ZnO seed layer deposition. For the seed layer synthesis, first 5 mM of zinc acetate dehydrate was dissolved in ethanol, and a milky solution was formed. Then the prepared solution was spin-coated on to the Si substrate at 1800 rpm for 30 s. The coating process was repeated for 10 and 20 times to prepare the ZnO seed layer. After each time, the substrate was dried in an oven at 90 °C for 120 s. The coated substrates were then annealed at 350 °C for 30 min in air atmosphere to improve the grain structure.

For the growth of NRs, firstly, equi-molar (100 mM) solutions of zinc nitrate hexahydrate and hexamethylenetramine in DI water were mixed. Then the coated substrates were horizontally immersed in this solution. The autoclave was put in the oven at 95 °C for 5 h. Finally, the samples were washed with DI water for several times, and dried at room temperature. To measure the electrical properties, the ohmic contacts were fabricated on both sides of the n-ZnO-NRs/p-Si junction using the sputtering technique. 30 nm/75 nm/200 nm titanium/platinum/gold (Ti/Pt/Au) was deposited on the ZnO-NRs as the top electrode through the shadow mask technique. Also to make the back-ohmic contact, 200 nm aluminum was deposited at the bottom of the silicon substrate. In the rest of the work, we investigated the optical and electrical properties of 10-layer seeds (S1) and 20-layer seeds (S2) n-ZnO-NRs/p-Si hetero-junctions.

The surface and cross-section morphologies of the prepared ZnO-NRs were characterized by field emission scanning electron microscopy (FESEM, MIRA3 TESCAN). The X-ray diffraction (XRD) pattern for ZnO-NRs was examined by a Philips Xpert MPD diffractometer (40 kV, 40 mA) with Cu K_α radiation (λ = 0.1542 nm). The photoluminescence (PL) spectra of the samples were measured by a Varian Cary Eclipse 1.1 spectrophotometer with a xenon lamp and an excitation wavelength of 340 nm. The reflectance spectra of the samples were measured using a UV-visible-NIR spectrophotometer (Cary 5000, Varian). The current-voltage and capacitance-voltage measurements were performed by Keithley 2361 using a standard probe station measurement technique and a computer-controlled auto-prober.

3. Results and discussion

3.1. Structural and optical properties of ZnO-NRs

The plan-view FESEM images of the 10 (S1) and 20 (S2) layer ZnO-coated silicon substrates are shown in Fig. 1(a and d). The uniform ZnO layers with distinct grain boundaries were formed on the silicon for the S1 and S2 samples. The grain sizes for the S1 and S2 samples were about 50–70 and 70–90 nm, respectively.

Figs. 1(b,c,e and f) show the FESEM images for the plan-view and cross-section of ZnO-NRs/p-Si with different seed layer numbers. The FESEM images showed that the 10 (S1) and 20 (S2) layer seed coatings had 100 and 180 nm thicknesses, respectively. The length and diameter of S1 were 1 μm and 70–90 nm, and for S2, increases in the length (1.8 μm) and diameter (80–110 nm) of the rods were observed. The results obtained showed that the crystallite size of the seed layers