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Interface architecture determined the performance of ZnO nanorods-based photodetectors

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ABSTRACT

High density ZnO nanorods grown on silicon oxide-coated Si (1 1 1) substrates were used to fabricate an MSM UV photodetector. The maximum sensitivity of the detector was about 1150, which was maintained over the wide range of applied bias. The photodetector responsivity increased slightly until reaching a maximum value at 374 nm and exhibited a sharp cutoff at 378 nm. The obtained photodetector responsivity was as high as 1.1 A/W. The detector shows fast photoresponse with a rise time of 0.008 s and a decay time of 0.021 s.

1. Introduction

The mutual advantages of wide direct band gap (3.37 eV), high exciton binding energy (60 meV), and strong room temperature emission characteristics of ZnO led to numerous in-depth studies to synthesize a variety of ZnO nanostructures [1–7]. Among these various morphologies, the one-dimensional (1D) ZnO nanorods have recently attracted significant attention due to their unique shape and structure resulting in remarkable optoelectronic, piezoelectric, and magnetic properties [8–14]. Specifically, the high optical gain of ZnO makes it the material of focus in sensing and optoelectronics applications. A number of researchers have focused mainly on the ZnO-based metal–semiconductor–metal (MSM), which includes ohmic contact-based photoconductive type. Xu et al. [15] reported RF sputtered ZnO on quartz to fabricate a photoconductive UV detector with planar interdigitated Al electrodes. The current–voltage (I–V) measurements showed a dark current of only 38 μA, which increased to 882 μA upon illumination (365 nm) at an applied bias of 5 V. Sputtering Au as a catalyst onto the quartz substrate, Li et al. [16], was able to fabricate a nanowatt UV photodetector. He et al. [8] reported a photocurrent of 0.15 mA using a more complex structure (glass/Ag/ZnO seed layer/ZnO nanowires). Based on the reported devices, it seems that the interface architecture is the limiting factor. This limitation can be related to the crystal mismatch between ZnO and most of the tested substrates. Therefore, the current study proposed a method to overcome such limitations by using a thin film ZnO buffer layer, to avoid crystal mismatch and enhance the integration of ZnO nanorods in UV photodetectors. More advantages of growing ZnO nanorods on SiO_2-coated Si (1 1 1) substrates include the low cost preparation approach for high-gain UV photodetectors and the ease of device integration, which is compatible with the existing silicon technology.

2. Experimental procedure

After the standard RCA cleaning of the n-type Si (1 1 1) substrate, a 200-nm SiO_2 layer was deposited on its surface by RF sputtering. High-purity zinc powder (1 g, 99.999%, Sigma–Aldrich) was then thermally evaporated on the Si/SiO_2 substrate using vacuum thermal evaporator. The resulting sample ($Si/SiO_2/Zn$) was successively transferred into a thermal tube furnace for oxidation at 700 °C and O_2 flow rate of 5 l/min for 90 min, and then cooled to room temperature. The resulting $Si/SiO_2/ZnO$ film was used as the substrate to grow ZnO nanorods. The substrate was placed in a small quartz tube (25 cm in length and 2 cm in diameter), which was inserted inside the furnace, as described in detail in our previous studies [17,18]. The furnace temperature was gradually increased from room temperature to 900 °C at a rate of 10 °C/min under the flow of N_2 gas (1 l/min), and then maintained at 900 °C under the flow of O_2 gas (0.2 l/min) for 90 min. Finally, the furnace temperature was cooled to room temperature under natural conditions.

The morphology and crystallinity of the ZnO nanorods were characterized using scanning electron microscopy (SEM) JEOL

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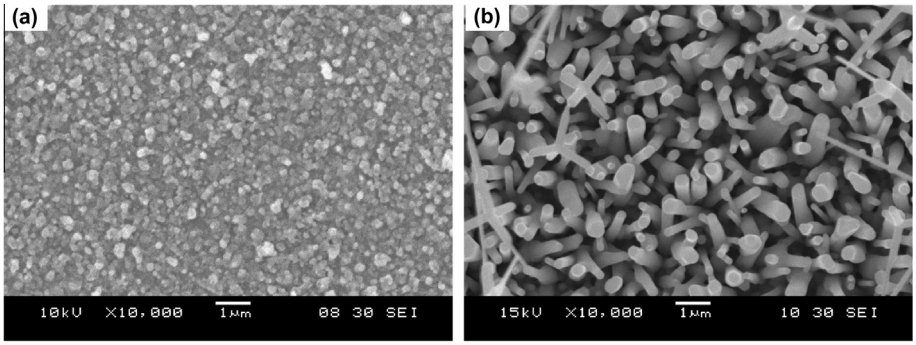

Figure 1. SEM images of (a) ZnO buffer layer and (b) ZnO nanorods grown on Si (1 1 1)/SiO_2/ZnO substrate.

model JSM-6460LV and X-ray diffraction (XRD) (PANalytical X'Pert PRO diffractometer, with Cu Kα radiation), respectively. The photoluminescence (PL) spectra were recorded with a He–Cd laser (325 nm) at room temperature. The MSM photodiode consists of two interdigitated electrodes with four fingers each. Each finger is 230 μm wide and 3.3 mm long, and the spacing between each finger is 400 μm. Silver (Ag) contacts were deposited by vacuum thermal evaporation using a metal mask based on the pattern of the contact structure. The device was then annealed at 425 °C for 5 min under N_2 atmosphere. The spectral UV photoresponse of the fabricated ZnO photodetector was measured using a monochromator with a 150 W xenon lamp as UV light source. A Keithley – 2400 source meter unit was employed to measure the photocurrent. The unit was controlled by a PC using LABVIEW via a GPIB interface. The measurements were performed at ambient conditions (temperature was 25 °C, and humidity was 62%).

3. Results and discussion

3.1. Characterization of the ZnO nanorods

Figure 1a,b shows the typical SEM images of the ZnO buffer layer and nanorods, respectively that were grown on Si (1 1 1)/SiO_2 substrates. High density ZnO nanorods with average diameters of 200 nm were successfully obtained. No delamination was observed, which highlights the importance of the ZnO buffer layer in preventing the direct growth of ZnO nanorods on non-crystalline SiO_2 substrates due to the importance of ZnO nanorods on SiO_2 substrates in optoelectronic applications.

The crystal quality and orientation of the grown ZnO buffer layer and nanorods on Si (1 1 1)/SiO_2 substrates were analyzed by XRD. Figure 2a,b shows the obtained XRD patterns of grown ZnO buffer layer and nanorods on Si (1 1 1)/SiO_2 substrates, respectively. The obtained diffraction peaks can be related to crystalline ZnO with hexagonal wurtzite structure, which agrees with the Joint Committee on Powder Diffraction Standards card for ZnO (JCPDS card no.-36–1451) [19,20]. The relatively high diffraction intensity obtained for both samples were in the (100), (002), and (101) planes. The ZnO nanorods diffraction pattern showed sharp and more intense peaks compared to those of the ZnO buffer layer. The narrow full width at half maximum of those peaks indicates the good crystallinity of the grown nanorods. This result also reveals the importance of the interface architecture in eliminating the effect of amorphous SiO_2 layer.

Figure 3a,b shows the room temperature PL spectra of the ZnO buffer layer and nanorods grown on the Si (1 1 1)/SiO_2 substrates, respectively. The PL emission spectrum revealed strong UV emissions at 372 nm and 374 for ZnO buffer layer and nanorods, respectively, which correspond to the near-band-edge (NBE) emission of ZnO. This obtained UV strong emission, coupled with a weak broad

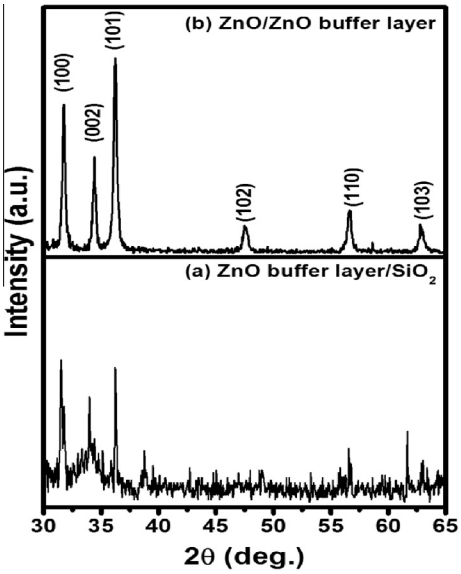

Figure 2. The XRD patterns of (a) ZnO buffer layer and (b) ZnO nanorods grown on Si (1 1 1)/SiO_2/ZnO substrate.

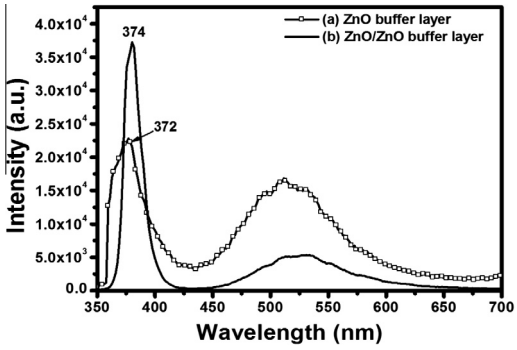

Figure 3. The PL spectra of (a) ZnO buffer layer and (b) ZnO nanorods grown on Si (1 1 1)/SiO_2/ZnO substrate.

green (DLE) emission bands at ~520 nm (sub-band transition) for ZnO buffer layer and nanorods may indicate the high crystal quality [18,19]. As the growth was performed using Zn powder under N_2 gas flow until the furnace reached 900 °C, the oxygen vacancies (the defects favorable to form under Zn-rich conditions) are expected to be the main reason for the emergence of the green emission (DLE). However, the energy intervals between these defect levels and valence band edge are ~0.9 eV [20,21], suggesting