Research Article

Zinc Oxide Nanoparticle Photodetector

Sheng-Po Chang^{1,2} and Kuan-Jen Chen³

¹ Center for Micro/Nano Science and Technology and Advanced Optoelectronic Technology Center, National Cheng Kung University, Tainan 70101, Taiwan

² Department of Electrical Engineering & Institute of Microelectronics, National Cheng Kung University, Tainan 70101, Taiwan

³ The Instrument Development Center, National Cheng Kung University, Tainan 701, Taiwan

Correspondence should be addressed to Sheng-Po Chang, changsp@mail.ncku.edu.tw

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A zinc oxide (ZnO) nanoparticle photodetector was fabricated using a simple method. Under a 5 V applied bias, its dark current and photocurrent were 1.98×10^{-8} and 9.42×10^{-7} A, respectively. In other words, a photocurrent-to-dark-current contrast ratio of 48 was obtained. Under incident light at a wavelength of 375 nm and a 5 V applied bias, the detector's measured responsivity was 3.75 A/W. The transient time constants measured during the turn-ON and turn-OFF states were $\tau_{\text{ON}} = 204$ s and $\tau_{\text{OFF}} = 486$ s, respectively.

1. Introduction

As the number of scaled-down components being developed gradually increases, it is apparent that high-quality wide-bandgap one-dimensional (1D) semiconductor nanostructures such as nanowires (NWs) [1–6], nanotubes [7, 8], and nanoribbons [9, 10] will most likely become promising functional components for next-generation nanometer-scale photonic and electronic devices. In recent years, semiconductor nanocrystals and NWs have been used to fabricate photoelectric devices owing to their large surface-to-volume ratio and tunable feature size [11–15]. Accordingly, the presence of deep-level surface trap states in NWs greatly prolongs the photocarrier lifetime, and the reduced dimensionality of the active area in NW devices shortens the carrier transit time. Although the surface and feature size of NWs can provide benefits similar to those associated with nanocrystals, better extraction of photogenerated carriers, and thus a substantial photoconductive gain, can be achieved only through a high-mobility NW core.

Among the available semiconductor materials, zinc oxide (ZnO) is one of the most appealing candidates because of its large exciton binding energy of 60 meV, wide bandgap energy of 3.37 eV at room temperature, excellent chemical and thermal stability, and biocompatibility [16, 17]. In the past

decade, the demonstration of a large variety of functional ZnO NW devices, such as field-effect transistors [14, 18–21], optically pumped lasers [22, 23], UV detectors [24–26], and chemical and biological sensors [25, 26], has attracted growing interest in this material. Law et al. [11] reported the use of aligned ZnO NWs in dye-synthesized solar cells to enhance the extraction of generated carriers, leading to higher external quantum efficiencies. In this work, ZnO nanoparticle UV photodetectors (PDs) were fabricated. The details of ZnO nanoparticle growth and detector fabrication are discussed. The electrical and optical characteristics of the fabricated PDs are also measured and analyzed.

2. Experiments

Well-dispersed nanoscale ZnO suspensions were obtained using ball milling equipment. The milling conditions were 3500 rpm and 24 h. The prepared ZnO nanoparticles were spin-coated on an Al_2O_3 substrate. Next, the resulting ZnO nanoparticle thin films were dried at 60°C in an oven. The baked films and substrates were annealed at 800°C for 1 h in air. The films were analyzed by scanning electron microscopy (SEM), X-ray diffraction (XRD), and photoluminescence (PL) equipment. A JEOL JSM-7000 F field-emission scanning electron microscope operated at 10 keV was then used

FIGURE 1: Schematic diagram of the fabricated ZnO nanoparticle photodetector.

to characterize their structural properties. To fabricate the nanoparticle PD, a thick Ni-Au (20/100 nm) film was deposited through an interdigitated shadow mask onto the nanoparticle thin film to serve as contact electrodes. We designed the pattern on the metal mask such that the fingers of the interdigitated electrodes were 2 mm wide and 2.2 mm long with a finger spacing of 0.2 mm. The monochromatic light was then illuminated onto the fabricated PD with an active area of 4.4 mm^2 . It should be noted that the nanoparticle thin film shown in Figure 1 could provide electrical paths for the two interdigitated electrodes. The current-voltage (I - V) characteristics of the fabricated PDs were then measured by an HP 4156 semiconductor parameter analyzer at room temperature. The spectral responsivity of the PDs was also measured at room temperature by a Jobin-Yvon SPEX System with a 300 W xenon arc lamp light source (PerkinElmer PE300BUV) and a standard synchronous detection scheme.

3. Results and Discussion

Figure 2(a) shows SEM images of ZnO nanoparticles annealed at 400°C . The shapes of the nanoparticles were clearly spherical and column-like, and the average grain size was about 100 nm. These ZnO nanoparticles were in close contact with each other, forming a continuous film with an observable thickness of about 500 nm. Figure 2(b) shows SEM images of ZnO nanoparticles annealed at 600°C . The grain size was about 150 nm, and the shapes of the nanoparticles were also spherical and column-like. Figure 2(c) shows SEM images of ZnO nanoparticles annealed at 800°C . The nanoparticles were clearly in closer contact and melted together. Because of the high-temperature annealing, the crystallization properties were much better than those obtained at lower temperatures. Figure 3(a) shows the XRD spectrum of the ZnO nanoparticle film on the Al_2O_3 substrate. All the diffraction peaks of ZnO nanoparticles and Al_2O_3 could be indexed to the wurtzite structure ZnO and Al_2O_3 according to the standard JCPDS cards (no. 897716 and no. 751526). Figure 3(b) shows the range of energy-dispersive X-ray (EDX) spectrum detection in the ZnO nanoparticle film. We confirmed that the ZnO nanoparticles contained 31.5% zinc, 34.14% oxygen, 21.96% aluminum, 7.35% platinum, and 5.04% carbon by weight. The platinum (Pt) signals originated from the deposited platinum thin film that was used to increase the electric conductivity during

(a)

(b)

(c)

FIGURE 2: SEM images of ZnO nanoparticle film on Al_2O_3 substrate after annealing at (a) 400°C , (b) 600°C , and (c) 800°C .

SEM imaging. Because the nanoparticle film was 500 nm thick, the aluminum and oxygen content were attributed to the Al_2O_3 substrate. After the oxygen in Al_2O_3 was subtracted, the ratio of zinc to oxygen was still about 1 : 1.

Figure 4 shows the current-voltage (I - V) characteristics between two neighboring electrode bridges for a ZnO nanoparticle film measured in the dark and under UV illumination. Under a 5 V applied bias, the dark current and photocurrent of our ZnO nanoparticle PD were 1.98×10^{-8} and 9.42×10^{-7} A, respectively. In other words, we obtained a photocurrent-to-dark-current contrast ratio of 48. When the

FIGURE 3: (a) XRD and (b) EDX spectra of ZnO nanoparticle film on Al₂O₃ substrate.

FIGURE 4: *I-V* characteristics of the fabricated ZnO nanoparticle photodetector after annealing at 800°C.

sample was irradiated with UV light at room temperature, the conductance rose, as shown in Figure 5. The first time the film was irradiated, a shift in the dark conductivity occurred that was maintained during subsequent irradiations. As shown in Figure 5, the dynamic response of the ZnO nanoparticle PD was stable and reproducible, with an on/off current contrast ratio of around 160. The photocurrent decayed rapidly and could be well described by a stretched exponential function. From the data plotted in Figure 5, it was found that the corresponding time constant for turn-ON transient was $\tau_{\text{ON}} = 204$ s, while that for turn-OFF transient was $\tau_{\text{OFF}} = 486$ s. It should be noted that the current decrease rate is determined by the speed of oxygen molecule absorption on the ZnO nanoparticle surface, which captures excess

FIGURE 5: Transient response of the measured current under intermittent UV illumination.

electrons. Thus, the turn-off speed should be much slower than the turn-on speed for our ZnO UV PD. It should be noted that the turn-OFF transient time constant observed in this study was much smaller than that reported by Martins et al. [27]. The faster response indicates that the ZnO nanoparticle photodetector is suitable for high-speed operation.

Figure 6 shows the room-temperature spectral responses of the fabricated ZnO nanoparticle PD to a 300-W Xe lamp dispersed by a monochromator used as the excitation source. During these measurements, the monochromatic light was calibrated by a UV-enhanced Si diode, and an optical power meter was modulated by a mechanical chopper and collimated onto the front side (i.e., the metal side) of the fabricated devices using an optical fiber. The photocurrent was then recorded by a lock-in amplifier. It should be noted

FIGURE 6: Room-temperature spectral responses of the ZnO nanoparticle photodetector measured at different applied biases.

that the PD's photoresponses were flat in the short wavelength region, whereas a sharp cutoff occurred at 375 nm. Under incident light at a wavelength of 375 nm and a 5 V applied bias, the PD's measured responsivity was 3.75 A/W, indicating that the high responsivity corresponds to the photoconductive gain. Previously, Chen et al. observed an ultrahigh photoconductive gain from a single GaN NW, which was three orders of magnitude larger than that of a GaN film PD [28]. The large photoconductive gain has also been shown to originate from carrier multiplication and the electron-hole spatial separation induced by strong surface band bending. Similar phenomena should also occur in our ZnO nanoparticle PD. The results suggest that the ZnO nanoparticle PD reported in this study is potentially useful for UV light sensing.

4. Conclusion

In summary, a zinc oxide (ZnO) nanoparticle PD was fabricated using a simple method. Under incident light at a wavelength of 375 nm and a 5 V applied bias, the PD's measured responsivity was 3.75 A/W. The transient time constants measured during the turn-ON and turn-OFF states were $\tau_{\text{ON}} = 204$ s and $\tau_{\text{OFF}} = 486$ s, respectively.

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