



Inserting an i-ZnO layer to increase the performance of p-Si/n-ZnO heterojunction photodetectors

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ABSTRACT

By inserting an intrinsic-zinc oxide (i-ZnO) layer into conventional p-Si/n-ZnO (p–n) heterojunction photodetectors (HPDs), the structure of p-Si/i-ZnO/n-ZnO (p–i–n) was prepared. It is evident that the i-ZnO layer could effectively reduce leakage current by about three orders, which leads to rectification ratio increasing from 70 to 6.6×10^4 for p–n and p–i–n HPDs, respectively, at +2 V bias-voltage. With bias-voltages, the responsivity of p–n HPDs shows less variation. In contrast, the p–i–n HPDs demonstrate a greatly increasing in ultraviolet (UV) response. Such a result causes the UV (350 nm)-to-visible (550 nm) rejection ratio is enhanced from 14.1 to 39.7 for p–n and p–i–n HPDs, respectively. The UV response of p–i–n HPDs is roughly proportional to bias-voltages, however the p–n HPDs has less responsivity dependence on bias-voltages. Related mechanisms are studied here.

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1. Introduction

Zinc-oxide (ZnO)-based ultraviolet (UV) photodetectors (PDs) such as p-Si/n-ZnO heterojunction PDs (HPDs) [1–5], Schottky PDs [6,7], and metal–semiconductor–metal PDs [8] have been continuously studied because the ZnO material has many advantages, including a wide band gap (3.3 eV), high transparency (> 80%) in the visible wavelength region, high exciton binding energy (60 meV), and nontoxicity; moreover, the techniques for depositing ZnO material are low cost. Although Schottky PD has an excellent response speed and simpler fabrication processes compared to those of p–n junction PD, the leakage current of Schottky PD strongly depends on the barrier height and metal/semiconductor interface [9,10]. This leads to a high leakage current in ZnO-based Schottky PDs owing to large amounts of oxygen

vacancies on the ZnO surface and poor interface between metal and ZnO [4,9]. A reproducible and reliable p-type ZnO is still not available because of several factors such as deep acceptor levels, low solubility of dopants, and self-compensation process [1]. Therefore, instead of a ZnO-based homojunction, p-Si/n-ZnO HPDs have been developed because the Si material is inexpensive and facilitates integrated circuit fabrication. Previously, many p-Si/n-ZnO HPDs were reported with ZnO deposited by various methods [1–5]. However, these PDs have large leakage currents and low UV-to-visible rejection ratios, which are critical issues in degrading the performance of PDs.

It was known that the intrinsic (i) layer between p and n layers could reduce dark current and increase photocurrent. A reduction in dark current and increasing in UV-to-visible rejection ratio were achieved in GaN-based PDs by inserting an i-layer to form p–i–n structure [10–12]. In this work, an i-ZnO layer was inserted between p-Si and n-ZnO layers to fabricate p-Si/i-ZnO/n-ZnO (p–i–n) HPDs. Also conventional p-Si/n-ZnO (p–n) HPDs were fabricated. The p–i–n HPDs, in comparison with conventional p–n HPDs, could effectively

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reduce dark current and thus enhance UV-to-visible rejection ratio by about three orders and three times, respectively.

2. Experimental details

P-type (100) silicon wafers with a resistivity of $1\text{--}5\ \Omega\text{-cm}$, corresponding to a hole concentration of $6 \times 10^{15}\ \text{cm}^{-3}$, were used as substrates to fabricate p-Si/i-ZnO/n-ZnO and conventional p-Si/n-ZnO HPDs. Two targets of pure ZnO and aluminum-doped ZnO (2% wt. in Al_2O_3) were employed to deposit i-ZnO and n-ZnO thin films with thicknesses of 60 and 20 nm, respectively, by using a radio-frequency (RF) magnetron sputtering system. The deposition conditions were RF power of 120 W, working pressure of 10 mtorr with Ar gas of 12 sccm. Deposition temperatures were 450 and 200 °C for n-ZnO and i-ZnO films, respectively. Through a Hall measurement by Van der Pauw method, it was shown that both n-ZnO and i-ZnO thin films were n-type with carrier concentrations of approximate $8 \times 10^{18}\text{--}3 \times 10^{19}\ \text{cm}^{-3}$ and $(2\text{--}6) \times 10^{15}\ \text{cm}^{-3}$, respectively. Their electron mobility and resistivity are $27\ \text{cm}^2/\text{V-s}$, $1.04 \times 10^{-2}\ \Omega\text{-cm}$ and $21.5\ \text{cm}^2/\text{V-s}$, $1.31 \times 10^2\ \Omega\text{-cm}$, respectively, for n-ZnO and i-ZnO films. Al electrodes were evaporated on front (n-ZnO) and back (p-Si) sides as Ohmic contacts with a device area of $0.2\ \text{cm}^2$. The current density–voltage (J – V) characteristics of the fabricated p-i-n and p-n HPDs were measured using an HP-4155B semiconductor parametric analyzer. A 300-W Xe-arc lamp was used to illuminate the fabricated HPDs from n-ZnO side and a grating monochromator was used to measure photocurrent responsivity. For measurements at a wavelength of 600 nm (or longer), a red filter was employed to eliminate the illumination from second-order diffraction line.

3. Results and discussion

Fig. 1 shows X-ray diffraction patterns of 60-nm-thick n-ZnO and i-ZnO thin films grown on Si substrate ranging from 30° to 60° . Both films have approximate the same intensity and peak location of 34.3° , corresponding to a (002) peak, revealing that they have a prominent c-axis-oriented structure. Scanning electron microscopy measurement shows the n-ZnO and i-ZnO films appear monolithic geometry with grain size ranging 30–100 nm. Dark J – V characteristics of the fabricated p-i-n and p-n HPDs are

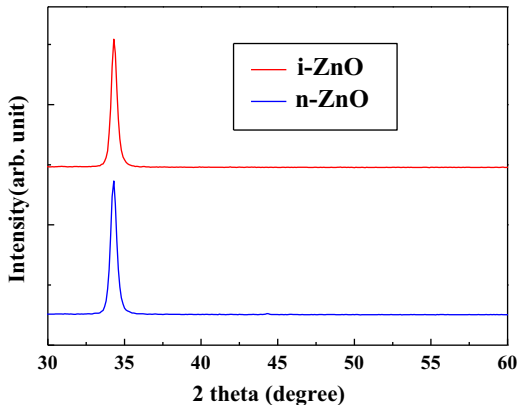


Fig. 1. X-ray diffraction patterns of n-ZnO and i-ZnO thin films grown on Si substrate.

shown in Fig. 2. It is evident that, compared to p-n HPDs, the p-i-n HPDs can effectively reduce the leakage current by approximate three orders. It is well known that under reverse-bias condition, thermally generated current dominates leakage current, and current generation occurs in depletion region. In p-i-n structure, the depletion region is across i-ZnO layer; however, in p-n structure, most of the depletion region occurs at p-Si side due to n-ZnO having much high concentration ($10^{18}\text{--}10^{19}\ \text{cm}^{-3}$) than that ($10^{15}\ \text{cm}^{-3}$) of p-Si. Therefore, the leakage current in p-i-n structure is much lower than that in p-n structure because i-ZnO layer has a wider band gap (3.3 eV) than that (1.12 eV) of p-Si substrate. At 5-V reverse-bias voltage, the leakage current density of p-n HPDs is $1.45 \times 10^{-5}\ \text{A/cm}^2$, which approximates to previous report ($7.6 \times 10^{-5}\ \text{A/cm}^2$ at $-5\ \text{V}$) [13]; however, the leakage current density is greatly reduced to $1.67 \times 10^{-8}\ \text{A/cm}^2$ in p-i-n HPDs. The much lower leakage current leads to rectification ratio increasing drastically from 70 to 6.6×10^4 for p-n and p-i-n HPDs, respectively, at +2 V. For measuring the photocurrent response, UV light with a 350-nm wavelength is illuminated from n-ZnO side in both p-n and p-i-n HPDs. The photocurrent and dark current responses for these two HPDs are shown in Fig. 3. It is found that no significant difference is observed between photo- and dark-current for p-n HPDs. In contrast,

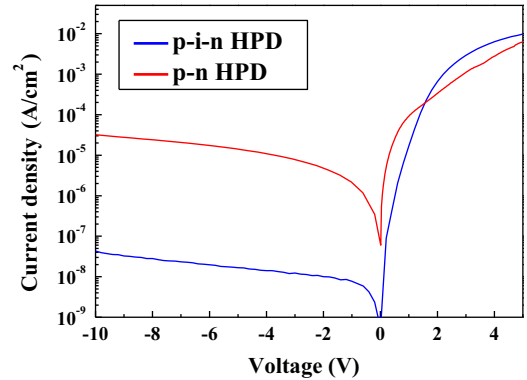


Fig. 2. J – V characteristics of the fabricated p-Si/i-ZnO/n-ZnO (p-i-n) and conventional p-Si/n-ZnO (p-n) HPDs.

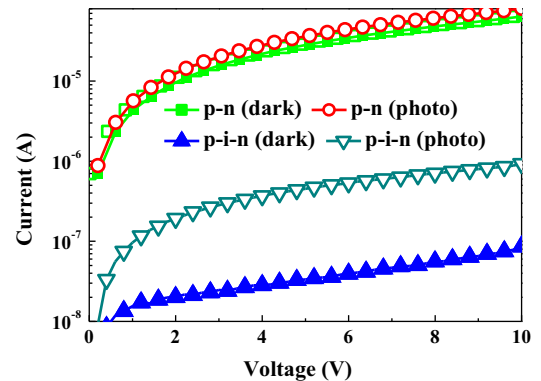


Fig. 3. Dark current and photocurrent (corresponding to 350 nm) for both p-i-n and p-n HPDs.

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