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Ultraviolet photodiode based on p-$Mg_{0.2}Zn_{0.8}O$/n-ZnO heterojunction with wide response range

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Abstract
P-$Mg_{0.2}Zn_{0.8}O$/n-ZnO heterojunction ultraviolet photodiode was fabricated on a sapphire substrate by plasma-assisted molecular beam epitaxy. The current–voltage measurement indicates that the heterojunction has a weak rectifying behaviour with a turn-on voltage of ∼5 V. The spectral response measurement shows that the photodiode has a peak responsivity at around 340 nm, and it has a wide detection range in the ultraviolet region from 400 to 320 nm. The response in the long and short wavelength region is due to the contribution of the n-ZnO and p-MgZnO layers, respectively. The ultraviolet–visible rejection ratio ($R$340 nm/$R$500 nm) of two orders of magnitude was obtained at a reverse bias of 8 V.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

In recent years, ZnO as an optoelectronic material has attracted much attention because of it possesses some excellent properties, such as wide direct band gap and high exciton binding energy. These properties make it well suited for realizing optoelectronic applications such as light-emitting diodes (LEDs), laser diodes (LDs) and ultraviolet (UV) detectors [1–4]. Meanwhile, the $Mg_xZn_{1-x}O$ alloy, which is realized by alloying MgO into ZnO, is an optically tunable wide band gap material that can be used in various UV luminescence and absorption applications in the wide range of 3.3–7.8 eV depending on the Mg content [5–7]. Therefore, $Mg_xZn_{1-x}O$ alloy is expected to realize UV detectors [8]. Most of the ZnMgO UV detectors are prepared as metal–semiconductor–metal (MSM) structures due to the difficulty of obtaining high quality and reliable p-type ZnMgO [9–11]. However, p–n and p–i–n photodiodes have advantages with respect to MSM structure, such as low dark current, fast responding speed and working without applied bias. Therefore, p–n and p–i–n photodiodes are the most suitable choice for future space application. Mandalapu *et al* has fabricated p–n homojunction photodiodes based on Sb-doped p-type ZnO with a good response to UV illumination [12]. Recently, our group has fabricated N-doped p-MgZnO thin films with a high hole concentration of 10^{17}–$10^{18}cm^{-3}$ and MgZnO p–n homojunction UV photodiode with a cutoff wavelength of 345 nm [13, 14]. Compared with MgZnO and ZnO homojunctions, MgZnO/ZnO heterojunctions have the advantage of a wider detection range in the UV region because they have different band gaps.

In this paper, a p-$Mg_xZn_{1-x}O$/n-ZnO heterojunction photodiode with a wide response range in the UV region was fabricated on a sapphire substrate by plasma-assisted molecular beam epitaxy (P-MBE). The electronic and optical properties of the photodiode were investigated. In addition,

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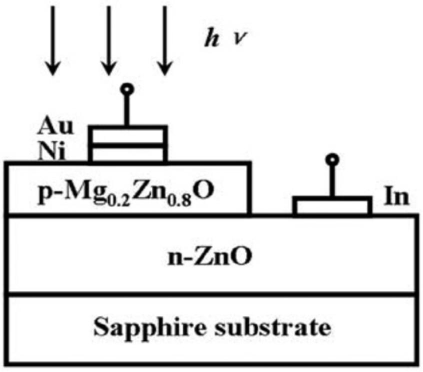

Figure 1. Schematic diagram of p-MgZnO/n-ZnO heterojunction photodiode.

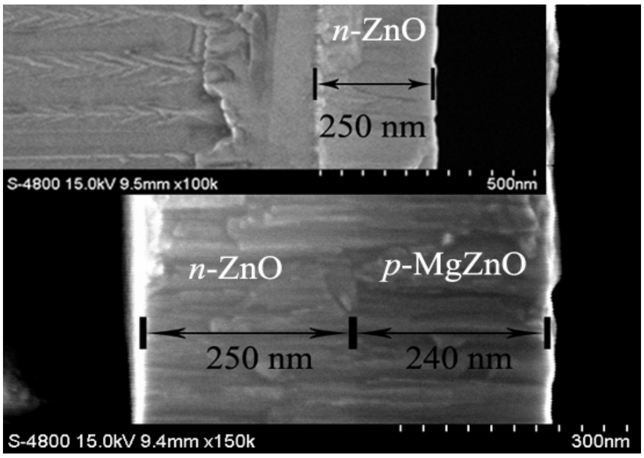

Figure 2. The SEM photograph of the thickness of the p-MgZnO/n-ZnO heterojunction photodiode. The inset shows the thickness of the n-type ZnO layer.

the photoresponse characteristics of the photodiode were also studied in detail.

2. Experiments

A ZnO layer was deposited on a c-sapphire substrate at 750 °C by P-MBE. The sample was split into two pieces. One was used to characterize the electrical properties and the other was used as the n-type layer to fabricate a p-$Mg_xZn_{1-x}O$/n-ZnO heterojunction by depositing p-$Mg_xZn_{1-x}O$ on it. The p-$Mg_xZn_{1-x}O$ was prepared by the incorporation of N into the MgZnO layer at 575 °C. NO gas was used as O source and N dopant and activated during the growth process by an Oxford Applied Research Model HD25 rf (13.56 MHz) atomic source. In the same experiment, the N-doped MgZnO film was also grown on the sapphire substrate for measurement of its electrical properties. In and Ni/Au metal were deposited using vacuum evaporation as n-and p-type contacts. The schematic illustration of the device structure is shown in figure 1. In addition, the thickness of the device is shown in figure 2. The thickness of the n-type ZnO layer and the p-type MgZnO layer is estimated to be about 250 nm and 240 nm, respectively. The photodiode is illuminated from the p-MgZnO layer.

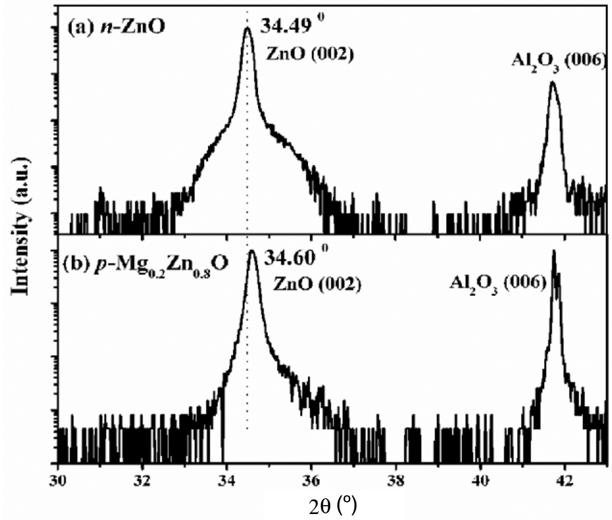

Figure 3. XRD patterns of (*a*) n-type ZnO and (*b*) p-type MgZnO thin films directly grown on sapphire substrate.

The electrical properties of the samples were characterized with a Lakeshore 7707 Hall system in a Van der Pauw configuration. To obtain a reliable result, the magnetic field strength of 3, 6, 9, 12 and 15 kG is adopted during the measurement process and data were collected with positive and negative currents and reversing magnetic fields. The results were averaged in order to reduce various electromagnetic effects. The electron and hole concentration of the n-ZnO and p-MgZnO are determined to be 3×10^{17} cm^{-3} and 1×10^{17} cm^{-3}, respectively. And the mobility is 13 cm^2 V^{-1} s^{-1} and 2 cm^2 V^{-1} s^{-1} for n-ZnO and p-MgZnO, respectively. The energy dispersive spectroscopy (EDS) measurement indicates that the composition of Mg(x) in the $Mg_xZn_{1-x}O$ layer is estimated as $x = 0.2$. The structures of the films were characterized by x-ray diffraction (XRD) with Cu Kα1 radiation ($\lambda = 0.15405$ nm). The room temperature optical absorption measurement was performed using a Shimadzu UV-3101PC scanning spectrophotometer. The dark current was measured by a semiconductor parameter analyzer with a sensitivity of 0.1 pA. A standard lock-in amplifier technique was employed for the spectral response measurements, where a 150 W Xe lamp was used.

3. Results and discussion

Figure 3 shows the XRD patterns of the n-type ZnO and p-type $Mg_{0.2}Zn_{0.8}O$ thin films grown on sapphire substrates. Only the (0 0 2) diffraction peaks for the ZnO and $Mg_{0.2}Zn_{0.8}O$ films are observed, indicating that the films have single wurtzite structures. The full width of half maximum (FWHM) of the (0 0 2) diffraction peaks of the ZnO and $Mg_{0.2}Zn_{0.8}O$ films are 0.17° and 0.18°, respectively, which reveals good crystalline quality. In addition, the diffraction peak position of the $Mg_{0.2}Zn_{0.8}O$ film shifts to a large angle with respect to that of the ZnO film, indicating the Mg is alloyed into the lattice of ZnO.

The current–voltage (I–V) characteristics of the photodiode measured in darkness at room temperature are shown

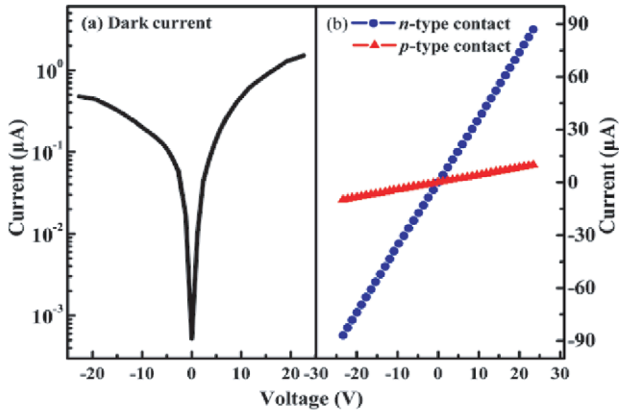

Figure 4. (*a*) *I*–*V* characteristics of p-MgZnO/ZnO heterojunction in dark and (*b*) p-type and n-type ohmic contacts.

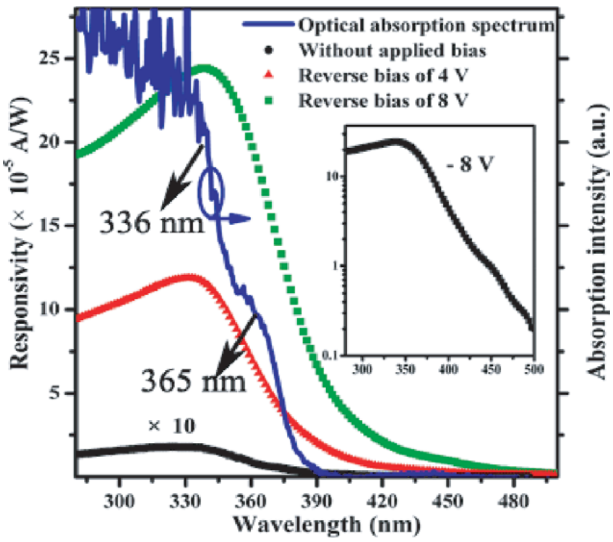

Figure 5. Spectral response of the p-MgZnO/n-ZnO photodiode at reverse biases of 0, 4 and 8 V and optical absorption spectrum of the p-MgZnO/n-ZnO heterojunction. The inset shows the responsivity in logarithm coordinates at the reserve bias of 8 V.

in figure 4(*a*). The measurements were performed in the bias voltage range of −23 to 23 V. It is found that the heterojunction has a weak rectification characteristic with a turn-on voltage of about 5 V. The dark current is about 100 nA at the reserve bias of 5 V. The large dark current comes from the poor quality of the p–n junction. Figure 4(*b*) shows the *I*–*V* plots from the Ni/Au–p-$Mg_{0.2}Zn_{0.8}O$ and In–n-ZnO contacts. The linear trend shows good Ohmic contacts for p-MgZnO and n-ZnO, implying that the rectifying behaviour originates from the p–n junction instead of the Schottky contacts.

The optical absorption spectrum of the p-$Mg_{0.2}Zn_{0.8}O$/n-ZnO heterojunction is shown in figure 5. Two sharp absorption edges in the UV region are clearly observed, located at 365 nm and 336 nm, respectively. The ZnO layer is responsible for the absorption edge at 365 nm. It is well known that the band gap of the MgZnO alloy increases with an increase in Mg content. Thus, the absorption edge at 336 nm originates from the MgZnO layer, which is in good agreement with the bandgap of MgZnO with Mg content of $x = 0.2$ calculated using

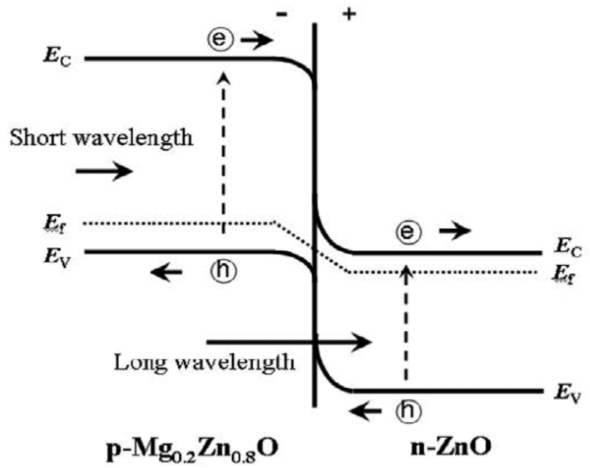

Figure 6. Schematic diagram of energy band of p-MgZnO/n-ZnO heterojunction at the reverse bias voltage.

the relationship between the band gap and Mg content [15]. The spectral responses of the photodiode at the reverse biases of 0, 4 and 8 V are also shown in figure 5. It was found that the cutoff wavelength appears at around 400 nm, which corresponds to the band gap of ZnO. The response peaks are located at around 332 nm, 335 nm and 340 nm at reverse biases of 0 V, 4 V and 8 V, respectively, corresponding to the band gap of $Mg_{0.2}Zn_{0.8}O$. The peak responsivity of the photodetector is determined to be 1.2×10^{-4} and $2.5 \times 10^{-4}\,A\,W^{-1}$ at the reverse bias of 4 and 8 V. The ultraviolet to visible rejection ratio ($R$340 nm/$R$500 nm) of two orders of magnitude was obtained at a reverse bias of 8 V (inset in figure 5).

In our previous report, the $Mg_{0.24}Zn_{0.76}O$ homojunction photodiode has a response range of 345–310 nm [14]. Unlike the the $Mg_{0.24}Zn_{0.76}O$ homojunction photodiode, the p-MgZnO/n-ZnO heterojunction photodiode exhibits a wider response range of 400–320 nm. In order to well understand the wide response range of the p-MgZnO/n-ZnO heterojunction photodiode, the schematic energy band of the p-MgZnO/n-ZnO heterojunction at the reverse bias voltage is shown in figure 6. Differing from the type-I band alignment of the n-ZnMgO/n-ZnO heterojunction [16–18], the p-MgZnO/n-ZnO heterojunction shows a type-II-like band alignment because acceptors doped into MgZnO result in a decrease in the Fermi level. When the light with low photon energy (smaller than the band gap of MgZnO) illuminates the p-MgZnO layer, it can transmit through the p-MgZnO layer and is absorbed by the ZnO layer. When the photon energy is close to or larger than the band gap of MgZnO, the light will be absorbed by the MgZnO layer. As a result, a wide response range in the UV region is obtained in the p-MgZnO/n-ZnO heterojunction photodetector.

4. Conclusions

In summary, a p-$Mg_{0.2}Zn_{0.8}O$/n-ZnO UV photodiode was fabricated on a sapphire substrate by P-MBE. The photodiode has a wider response range of 400–320 nm with respect to the MgZnO-based homojunction photodiode. The response in the long and short wavelength regions is due to the contribution of the n-ZnO and p-MgZnO layers, respectively. An ultraviolet–visible rejection ratio ($R340\,\text{nm}/R500\,\text{nm}$) of two orders of magnitude was obtained at a reverse bias of 8 V.

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