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$Zn_{0.76}Mg_{0.24}O$ homojunction photodiode for ultraviolet detection

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$Zn_{0.76}Mg_{0.24}O$ *p-n* photodiode was fabricated on (0001) Al_2O_3 substrate by plasma-assisted molecular beam epitaxy. Ni/Au and In metals deposited using vacuum evaporation were used as *p*-type and *n*-type contacts, respectively. Current-voltage measurements on the device showed weak rectifying behavior. The photodetectors exhibited a peak responsivity at around 325 nm. The ultraviolet-visible rejection ratio ($R$325 nm/$R$400 nm) of four orders of magnitude was obtained at 6 V bias. The photodetector showed fast photoresponse with a rise time of 10 ns and fall time of 150 ns. In addition, the thermally limited detectivity was calculated as 1.8×10^{10} cm $Hz^{1/2}$/W at 325 nm, which corresponds to a noise equivalent power of 8.4×10^{-12} W/$Hz^{1/2}$ at room temperature. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2805816]

$Mg_xZn_{1-x}O$, as a wide-band-gap optoelectronic material, has become a focus of extensive research.[1–5] It possesses unique figures of merit such as availability of lattice-matched single-crystal substrates (ZnO and MgO for hexagonal and cubic $Zn_{1-x}Mg_xO$ films, respectively),[1] tunable band-gap energy (3.3–7.8 eV),[6–8] relatively low growth temperatures (100–750 °C),[8] and intrinsic visible blindness and radiation hardness,[9] which are crucial for practical optoelectronic devices. However, due to the difficulty of obtaining high quality and reliable *p*-type ZnMgO, the reports on ZnMgO UV detectors mainly focused on metal-semiconductor-metal (MSM) structure[1–5] which contains either Schottky-barrier-based photovoltage type or Ohmic-contact-based photoconductive type. No information can be found on ZnMgO *p-n* photodiodes for ultraviolet detection. Compared with MSM photodetectors, *p-n* and *p-i-n* photodiodes have the advantages of fast responding speed, low dark current, and working without applied bias. Therefore, *p-n* and *p-i-n* photodiodes are the most suitable choice for future space application. Recently, our group has prepared *p*-type N-doped ZnMgO via plasma-assisted molecular beam epitaxy (PAMBE) followed by postannealing process.[10] The *p*-type MgZnO:N has a hole concentration of 6.1×10^{17} cm^{-3} and a carrier mobility of 6.42 cm^2/V s. In this paper, $Zn_{0.76}Mg_{0.24}O$ *p-n* photodiode was fabricated on sapphire substrate by PAMBE. The electronic and optical properties were investigated. Meanwhile, we have also studied the photoresponse of the $Zn_{0.76}Mg_{0.24}O$ *p-n* photodiode.

A schematic illustration of the device structure is depicted in Fig. 1. The structure was consisted of two epitaxial layers: *p*- and *n*-ZnMgO. *c*-plane sapphire was selected as substrate. *p*-ZnMgO film was grown by PAMBE at 425 °C, using NO gas (99.999%) as O source and N dopant. The film thickness is measured by ellipsometer to be about 300 nm. After the deposition of the *p*-type ZnMgO layer, the unintentionally doped ZnMgO layer was grown successively as *n* type with the thickness of 200 nm and O_2 (99.9999%) gas was used as O source. The *p*-type ZnMgO has a hole concentration of 1×10^{16} cm^{-3} and the *n*-type ZnMgO has an electron concentration of 1×10^{18} cm^{-3}. Ni/Au and In metals were deposited using vacuum evaporation as *p*-type and *n*-type contacts, respectively. In order to obtain good Ohmic contacts, the metalized devices were then thermally annealed in vacuum at 300 °C.

A Rigaku O/max-RA x-ray diffractometer with Cu $K\alpha$ radiation ($\lambda = 0.154\,178$ nm) was used to make θ-2θ scans to evaluate the crystalline property of the film. Both optical transmission and absorption spectra were recorded 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. Time-resolved response was obtained using a Nd:YAG (yttrium aluminum garnet) laser with a wavelength 266 nm and a

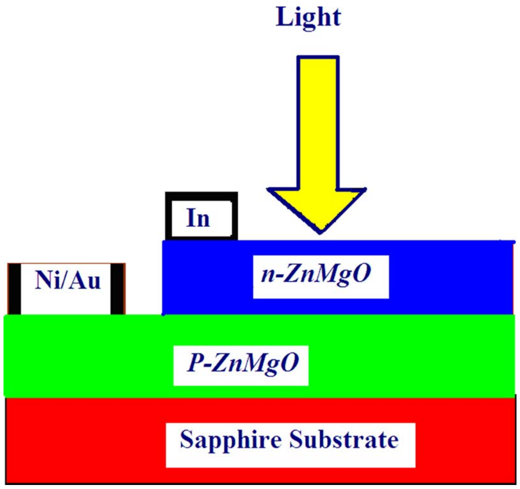

FIG. 1. (Color online) Schematic diagram of the $Zn_{0.76}Mg_{0.24}O$ *p-n* photodiode.

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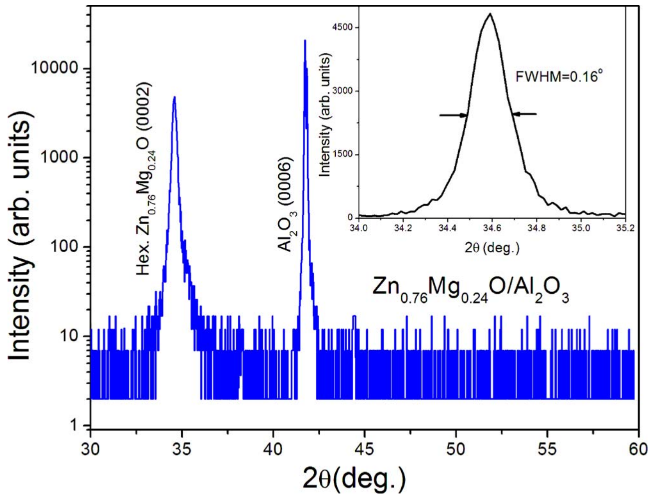

FIG. 2. (Color online) XRD spectra of the n-$Zn_{0.76}Mg_{0.24}O$/p-$Zn_{0.76}Mg_{0.24}O$ double layers prepared on sapphire by MBE.

pulse width of 10 ns. The transient signal was recorded by a boxcar with a 50 Ω impedance.

Figure 2 shows the x-ray diffraction (XRD) pattern of the n-$Zn_{0.76}Mg_{0.24}O$/p-$Zn_{0.76}Mg_{0.24}O$ double layers. Besides the (0006) diffraction peak of the sapphire substrate, only a (0002) diffraction peak can be observed, indicating that the film is hexagonal structured and highly c axis oriented. The full width at half maximum (FWHM) of the (0002) diffraction peak is 0.16°, as shown in the inset of Fig. 2, and the peak is Gaussian symmetrical. The XRD result indicates that the sample has good crystalline quality and the p-type and n-type layers have the same composition.

One of the characteristic features of ZnO-based materials is the sharp UV absorption and constant blueshift in absorption edge as a function of Mg composition.[1] Figure 3 shows the absorption and transmission spectra of $Mg_{0.76}Zn_{0.24}O$ p-n junction on Al_2O_3. It is clear from the transmission spectrum that the sample has more than 75% transmission in the visible region. The absorption spectrum shows a strong absorption at 345 nm corresponding to a band gap of 3.59 eV. The sharp absorption and transmission spectra reveal that only one band edge exists in the homojunction structure, which is in good agreement with the XRD results.

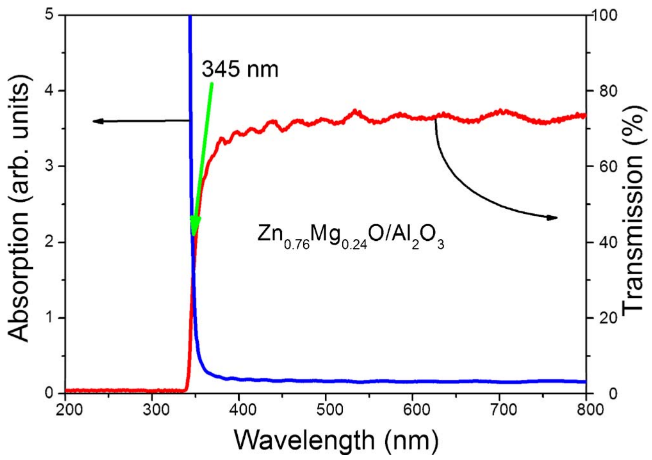

FIG. 3. (Color online) UV-visible transmission and absorption spectra of the $Zn_{0.76}Mg_{0.24}O$ p-n junction.

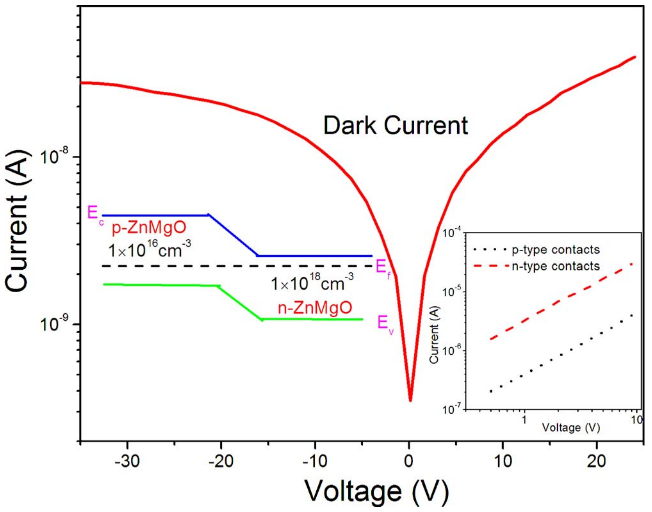

FIG. 4. (Color online) I-V plot of the homojunction diode in dark. The left inset gives the energy band diagram at equilibrium. The right inset gives the I-V plots of the p- and n-type Ohmic contacts.

I-V characteristics of the homojunction diode in dark are shown in Fig. 4. Weak rectifying behavior is observed in the I-V curve. The right bottom inset gives the I-V plots from the Ni/Au-p-$Zn_{0.76}Mg_{0.24}O$ and In-n-$Zn_{0.76}Mg_{0.24}O$ contacts. Both p and n electrodes are good Ohmic contacts. This result indicates that the rectifying behavior comes from the p-n junction instead of the metal-semiconductor contacts. The band diagram of the junction at equilibrium is shown in the left inset of Fig. 4. The turn-on voltage of the homojunction diode is about 2 V, and the dark current is about 5 nA at −5 V bias due to the poor quality of the p-n junction, which is in turn due to the poor quality of p-$Zn_{0.76}Mg_{0.24}O$ films at the room temperature. The weak rectifying behavior also confirmed the poor quality of the p-n junction.

The spectral response of the detector under 0 and 6 V bias is shown in Fig. 5. It was found that the cutoff wavelength occurs at around 345 nm (3.59 eV), which corresponds to the band gap of $Zn_{0.76}Mg_{0.24}O$. Meanwhile, it should be noted that the visible rejection ratio ($R$325 nm/$R$400 nm) is 10^4 under 6 V reverse bias and more than 10^2 under 0 V bias. The peak responsivity around 325 nm increased from 3.7×10^{-6} to 4×10^{-4} A/W with the

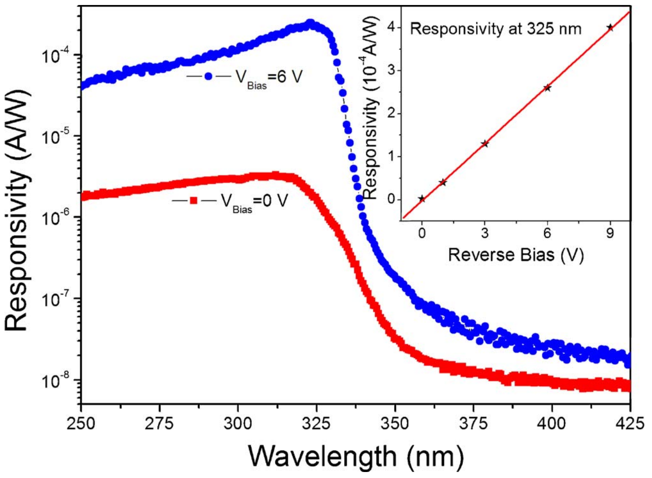

FIG. 5. (Color online) Spectral response of the $Zn_{0.76}Mg_{0.24}O$ p-n photodiode with the reverse bias of 0 and 6 V. The inset shows the responsivity at 325 nm as a function of reverse bias.

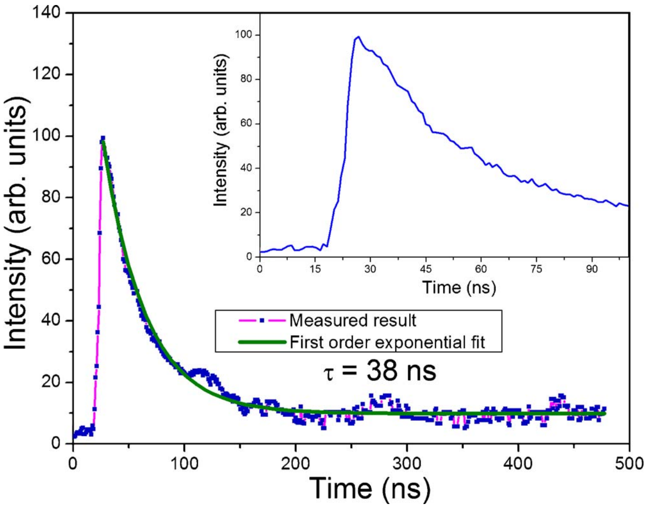

FIG. 6. (Color online) The pulse response measurement on the $\mathrm{Zn_{0.76}Mg_{0.24}O}$ *p-n* photodiode excited by Nd:YAG pulsed laser with a 50 Ω impedance.

reverse bias increase from 0 to 9 V, as shown in the inset of Fig. 5. A linear relationship was obtained between 0 and 9 V, indicating that no carrier mobility saturation even up to 9 V reverse bias.

The thermally limited detectivity (D^*) can be expressed using the following formula[11] $D^*=R_\lambda(R_0A/4kT)^{1/2}$, where R_λ is device responsivity at 0 V bias, R_0 is the differential resistance, and A is the area of the device. We obtain a detectivity of $1.8\times10^{10}\ \mathrm{cm\,Hz^{1/2}/W}$ at 325 nm, which corresponds to a noise equivalent power (NEP) of $8.4\times10^{-12}\ \mathrm{W/Hz^{1/2}}$ at room temperature. The small detectivity and large NEP may be due to the poor quality of the *p-n* junction and deep level defects in $\mathrm{Zn_{0.76}Mg_{0.24}O}$ film.

Figure 6 shows a typical transient response of the $\mathrm{Zn_{0.76}Mg_{0.24}O}$ *p-n* photodiode under the excitation of the 266 nm line of a Nd:YAG laser. The transient signal was recorded by a boxcar with a 50 Ω impedance. It can be found that the measured fall time is around 150 ns. Furthermore, a good fit was accomplished using a first-order exponential decay with time constant of 38 ns. From the inset of Fig. 6, it can be seen clearly that the rise time of the photodiode is 10 ns, which is limited by the excitation laser (the nominal pulse duration FWHM of the excitation laser is 10 ns).

In summary, we have fabricated $\mathrm{Zn_{0.76}Mg_{0.24}O}$ homoepitaxial *p-n* photodiode on (000l) $\mathrm{Al_2O_3}$ substrate. It shows an enhanced UV photoresponse in the peak wavelength around 325 nm with a cutoff wavelength of 345 nm. An ultraviolet-visible rejection ratio ($R$325 nm/$R$400 nm) of four orders of magnitude at 6 V bias is obtained from the structure. The peak responsivity around 325 nm increased from 3.7×10^{-6} to 4×10^{-4} A/W linearly with the reverse bias increasing from 0 to 9 V. It can be expected that solar-blind detector based on ZnMgO *p-n* homojunction could be realized with increasing Mg concentration and improving the quality of *p*-ZnMgO layer.

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