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Ultraviolet photodetector fabricated from metal-organic chemical vapor deposited MgZnO

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ABSTRACT

Wurtzite $Mg_xZn_{1-x}O$ thin films were grown on sapphire substrates by low-pressure metal-organic chemical vapor deposition. The as-grown films show clear exciton absorption at room temperature until the composition $x=0.25$. A representative metal–semiconductor–metal structured photodetectors were fabricated from $Mg_{0.06}Zn_{0.94}O$ film showed a peak responsivity of about 14.62 A/W at 340 nm, and the ultraviolet-visible rejection ratio ($R$340 nm/$R$400 nm) was more than two orders of magnitude at 3 V bias. The photodetector showed fast photoresponse with a rise time of 20 ns and a fall time of 400 ns.

1. Introduction

Recently, much attention has been paid to ZnO due to their wide direct bandgap of 3.37 eV and large exciton binding energy of 60 meV [1,2]. These excellent properties make ZnO potentially useful in ultraviolet (UV) optoelectronic devices, such as light-emitting diodes, laser diodes and photodetectors [3–6]. Since the ionic radius of Mg^{2+} (0.57 Å) is close to that of Zn^{2+} (0.60 Å), and the bandgap can be tuned from 3.37 to 7.8 eV by doping Mg ions into the lattice of ZnO [7], MgZnO alloys have been a research focus in recent years.

MgZnO-based UV photodetector has been prepared by a variety of deposition techniques such as pulsed laser deposition, radio frequency (rf) magnetron sputtering, and molecular beam epitaxy [8–10], etc. However, very few report on MgZnO photodetectors prepared by metal-organic chemical vapor deposition (MOCVD) can be found, although MOCVD has an advantage in achieving devices in commercial level for its high deposition rate and high crystalline quality [11,12].Yang et al. have reported $Mg_{0.34}Zn_{0.66}O$ photodetector with a fast rise time of 8 ns, but it has a long fall time with the value of 1.4 μs [13]. More recently, our group has reported solar blind UV photodetectors based on cubic $Mg_xZn_{1-x}O$ thin films with Mg content from 0.5 to 0.7. The cubic $Mg_xZn_{1-x}O$ thin films have been prepared by MOCVD [14]. However ultraviolet photodetector which is based on wurtzite MgZnO photodetector prepared by MOCVD with a fast response time has never been reported.

In this paper, high-quality wurtzite MgZnO thin films with different Mg content (0.06–0.25) were grown by MOCVD. A representative metal–semiconductor–metal (MSM) structured photodetectors were fabricated from $Mg_{0.06}Zn_{0.94}O$ film showed a peak responsivity of about 14.62 A/W at 340 nm, and the ultraviolet-visible rejection ratio ($R$340 nm/$R$400 nm) was more than two orders of magnitude at 3 V bias. The photodetector showed fast photoresponse with a rise time of 20 ns and a fall time of 400 ns. The effect of the electrode contact and its working environment on the dark current of the photodetector has also been investigated.

2. Experimental details

The $Mg_xZn_{1-x}O$ thin films were grown on (0001) sapphire substrate by MOCVD. Diethylzinc (DEZn), *bis*-cyclopentadienyl magnesium (Cp_2Mg) and ultrapure oxygen (99.999%) were employed as the precursors for the growth, and nitrogen (99.999%) was used as a carrier gas. The pressure in the growth chamber was kept at about 2×10^4 Pa, and the substrate temperature at 450 °C during the growth process. The flow rate of oxygen was controlled to be 20 sccm, while that of DEZn and Cp_2Mg were varied to obtain a series of MgZnO films with different Mg composition. The thickness of the thin films was 300 nm. Without any surface treatment, a 100 nm Au layer was evaporated on the MgZnO film using a vacuum evaporation method. Then MSM structured photodetector with interdigitated Au electrode was fabricated on the MgZnO thin films by lithography and wet etching route. The interdigital contact consists of 12 fingers at each electrode, and the fingers were 5 μm in width, and 500 μm in length, and the spacing between the fingers is 5 μm.

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A Ringaku D/max-RA X-ray diffraction (XRD) with Cu Kα radiation (λ = 0.154 nm) was used to evaluate the crystalline properties of the MgZnO thin films. A Hitachi S-4800 scanning electron microscope (SEM) was employed to study the surface morphology of the film when a voltage of 15 kV is applied. Energy dispersive X-ray spectroscopy (EDS) was used to determine the Mg/Zn ratio in the film. The operating voltage and spot size for EDS analysis on the Hitachi S-4800 are 15 kV and 3.5, respectively. Optical absorption spectra were recorded using a Shimadzu UV-3101 PC scanning spectrophotometer.

For the characterization of the photodetector, a pulsed Nd-YAG laser (266 nm, 10 ns) was used as the excitation source to measure the photoresponse time. The spectrum response was determined by a 150 W Xe lamp and a lock-in amplifier. The dark current was measured in a Hall measurement system (LakeShore 7707).

3. Results and discussion

As a representative, the SEM image of $Mg_{0.06}Zn_{0.94}O$ thin film. As can be seen from Fig. 1(a), the MgZnO layer is composed of many domains with their size ranging from tens to 100 nm. Note that some of the domains are shaped in hexagons, as shown in Fig. 1(b), revealing that the MgZnO layer may crystallized in hexagonal wurtzite. The conjecture is verified by the XRD pattern of the layer. Besides the diffraction from the sapphire substrate, only one peak at 34.94° corresponding to the diffraction from the (0002) plane of MgZnO alloy films can be observed. Note that the peak shifts to large-angle side compare to that of ZnO, which is resulted from the lattice shrinkage caused by the incorporation of Mg into the lattice of ZnO.

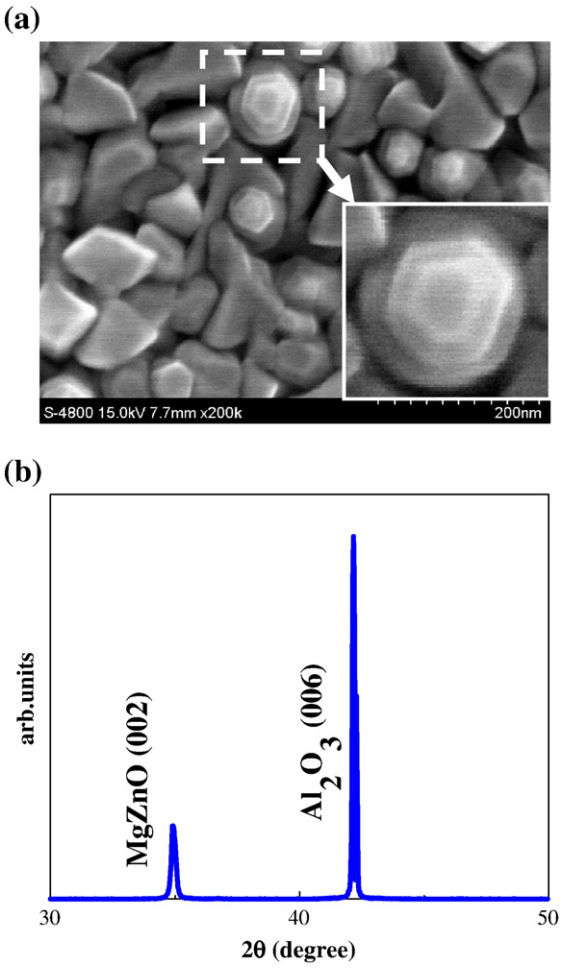

Fig. 1. (a) The SEM image of the $Zn_{0.06}$ $Mg_{0.94}$ thin film, the upper inset shows an enlarged magnified image of some domains in the film. (b) The XRD pattern of the $Mg_{0.06}Zn_{0.94}O$ film.

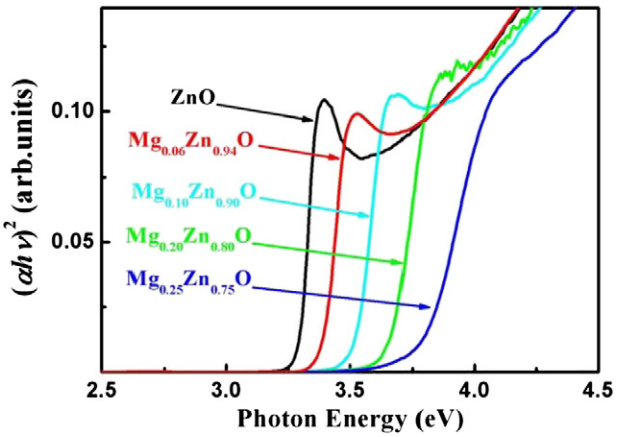

Fig. 2. UV–visible absorption spectrum of the $Zn_xMg_{1-x}O$ with Mg content of 0, 0.06, 0.08, 0.12, and 0.16.

The plots of $(\alpha h\nu)^2$ as a function of $h\nu$ for the $Mg_xZn_{1-x}O$ ($x = 0.00$, 0.06, 0.10, 0.20 and 0.25) thin films are shown in Fig. 2, where α is the absorption coefficient of the MgZnO and $h\nu$ is the photon energy. By using the relation between α and band gap: $a(h\nu) = A(h\nu - E_g)^{1/2}$ [15], the band gap was evaluated to be 3.29, 3.39, 3.51, 3.66 and 3.79 eV, respectively. We use the relation between band gap and Mg content [16] to calculate $x = 0.06$, 0.10, 0.20 and 0.25, respectively.

Fig. 3 shows the responsivity of the photodetector fabricated from $Mg_{0.06}Zn_{0.94}O$. At 3 V bias, the maximum responsivity of the photodetector is 14.62 A/W at around 340 nm. The UV-to-visible rejection ratio (R340/ R400 nm) is more than two orders of magnitude. Given that the dark current of the photodetector is about 9 μA at 3 V bias, the noise equivalent power (NEP) can be calculated by $NEP = (4k_BT/R_{dark} + 2qI_{dark})^{1/2}\Delta f^{1/2}/R$, where R_{dark} refers to the equivalent resistance obtained from the slope of the dark current I–V curve at the bias point, I_{dark} is the dark current at the bias point, T is the temperature of 300 K, Δf is the bandwidth of the measurement, and R is the measured responsivity. The noise equivalent power NEP calculated by placing the above parameters into the formula is 2.19×10^{-11} W/Hz$^{1/2}$ at room temperature. The normalized detectivity (D^*) can then be determined by $D^* = (A\Delta f)^{1/2}/NEP$, where A is the device area. Under 3 V bias, the detectivity D^* of 2.68×10^7 cm Hz$^{1/2}$ W^{-1} at 340 nm can be obtained. The responsivity of the photodetector at

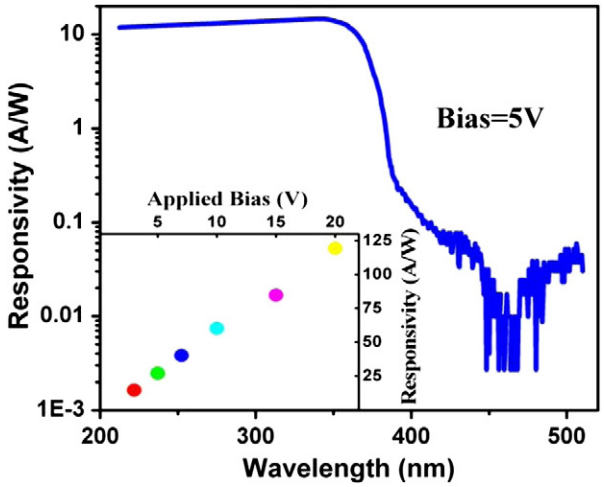

Fig. 3. The spectral response of the $Mg_{0.06}Zn_{0.94}O$ UV photodetector with a 5 μm finger spacing at 3 V bias. The inset shows the responsivity at 340 nm as a function of the applied bias.

340 nm increases almost linearly with the bias voltage between 0.6 and 20 V, as shown in the inset of Fig. 3.

Fig. 4(a) is a schematic structure of the MgZnO UV photodetector. The Au interdigital electrodes are deposited onto the MgZnO thin films and two In pallets are sintered at both ends of the gold electrodes forming ohmic contact. Fig. 4(b) shows the dark current curves of the photodetector measured at temperature of 300 K. Under 3 V bias, the dark current of the photodetector is 9 μA at 300 K. The above phenomenon may be related to the Au–MgZnO interface states. It is believed that MgZnO thin film tends to absorb water vapor or oxygen at the surface, and a large dark current is resulted from the adsorbed species.

Fig. 5 shows the pulse temporal response of the $Mg_{0.06}Zn_{0.94}O$ photodetector at 3 V bias and 50 Ω load. The rise time is about 20 ns, and the fall time was 400 ns. Note that the fall time was shorter than reported photoconductive MSM photodetectors [17]. It is known that the rise time of a photodiode is limited by the laser pulse. There are usually two mechanisms (RC time and transit time) contributing to the decay time. Usually, the response time of a photovoltaic photodetector is dominated by the RC time constant of the device due to the relative large junction capacitance. However, the RC time constant can often be neglected in MSM photodetectors because of the small capacitance in this kind of devices. Therefore, the decay component of our photoconductive should be determined by the transit time. The transit time of the carriers can be expressed as follows [9]:

$$t_r = d^2 / \mu_n V_b, \quad (1)$$

where d is the interelectrode spacing, μ is the electron mobility, and V_b is the bias voltage. From this formula, one can see that the transit time is inversely proportional to μ. We can see that our MgZnO thin film has a high crystal quality from Fig. 1, so μ will be high. The large mobility will shorten the transit time by decreasing the scattering and recombination in the transit of the carriers.

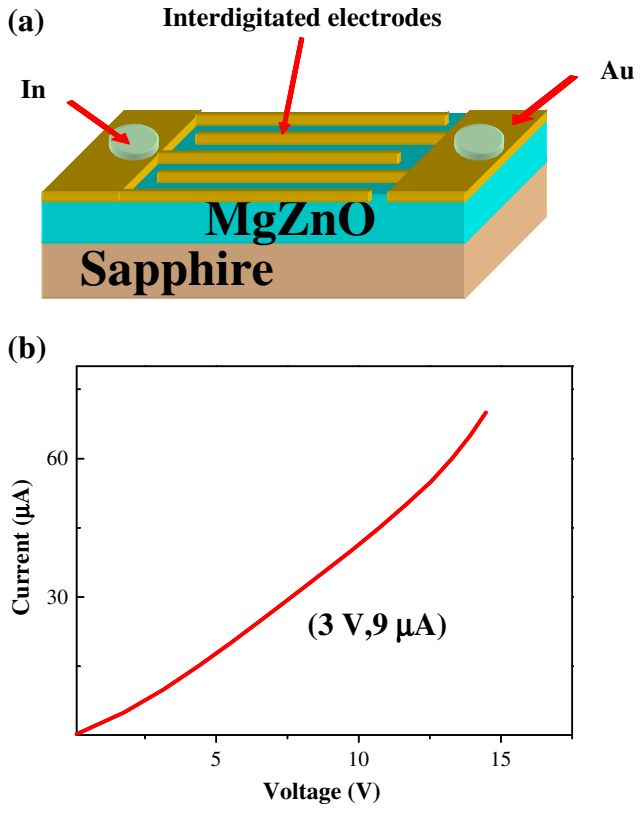

Fig. 4. The schematic structure (a) and *I–V* characteristics (b) of the $Zn_{0.06}$ $Mg_{0.94}$ photodetector.

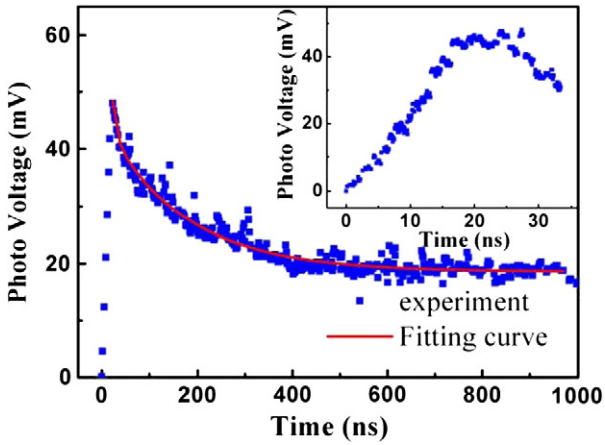

Fig. 5. The pulse temporal response of the $Mg_{0.06}Zn_{0.94}O$ photodetector excited by a Nd: YAG pulsed laser with a 50 Ω load at 3 V bias. The insert shows the enlarged impulse response.

4. Conclusion

In summary, we have finished the photoconductive UV photodetector with MSM structure based on MgZnO film prepared by MOCVD. The maximum responsivity of the photodetector was 14.62 A/W at 3 V bias and the noise equivalent power thermally limited detectivity was 2.19×10^{-11} W/Hz$^{1/2}$ at 340 nm. The rise time of the photodetector is 20 ns which is limited by the laser pulse. The fall time 400 ns is shorter than usually reported photoconductive MSM photodetectors which may be mainly caused by the transit time of the photo-generated carriers. The semiconductor thin film surface absorbed water vapor lead to an increase of the dark current, thereby reduced the detectivity of the photodetector.

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