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A high-speed photoconductive UV detector based on an Mg$_{0.4}$Zn$_{0.6}$O thin film

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Abstract

A high quality Mg$_x$Zn$_{1-x}$O thin film with up to ~40 at% Mg incorporation was grown on a quartz substrate by the rf magnetron sputtering technique. The photoconductive type of Mg$_{0.4}$Zn$_{0.6}$O metal–semiconductor–metal ultraviolet detector was prepared. The ratio of the ultraviolet to visible was more than four orders of magnitude; the 10%–90% rise and fall times were 16 ns and 250 ns, respectively. Furthermore, the dark current was below 40 nA under 3 V bias and the gain was observed which caused the high responsivity ($\sim$ 1.3 A W$^{-1}$) at 320 nm, and the corresponding detectivity $D^*$ was 1.37 $\times$ 10$^{11}$ cm Hz$^{1/2}$ W$^{-1}$. A high-speed response was attributed to the high quality of the Mg$_{0.4}$Zn$_{0.6}$O thin film, which was found to dramatically enhance the UV detection properties of the device. The effect of the gain on the fall time and responsivity was analysed in the present work.

1. Introduction

ZnO, a wide band gap ($E_g$ = 3.37 eV) semiconductor, is well known as one of the most promising materials for the application of an ultraviolet (UV) detector [1, 2]. Compared with other wide band gap semiconductor materials, such as diamond, GaN, SiC, ZnO, it has many advantages for device applications including lower growth temperature and higher radiation hardness, which are suitable for fabrication of long-lifetime devices. Owing to large exciton binding energy (60 mV), ZnO has attracted increasing attention that it can be integrated with photodetectors [3]. Additionally, it can be alloyed with MgO in order to tailor the band gap as demonstrated by Kawasaki et al [4] and Minemoto et al [5]. Due to the difficulty of the realization of p–n junction-based devices, metal–semiconductor–metal (MSM) structure UV photodetectors based on ZnO and Mg$_x$Zn$_{1-x}$O have been demonstrated in recent years [6–8].

Mg$_x$Zn$_{1-x}$O exists in the form of hexagonal and rock-salt structures corresponding to Mg composition in ZnO. By varying the Mg composition, the band gap can be tuned from 3.3 to 7.8 eV. Due to this advantage, Mg$_x$Zn$_{1-x}$O UV detectors have significant commercial and scientific potential application value for engine control, solar UV monitoring, astronomy, space-to-space communications and detection of missile plumes, located in the UV-B region. At present, most reports about the Mg composition in the Mg$_x$Zn$_{1-x}$O film show that it is usually less than 33% of UV detectors. That is because high Mg composition will produce phase splitting due to the different structures of ZnO and MgO. Furthermore, Mg$_x$Zn$_{1-x}$O UV detectors are of photoconductive type [8, 9], which primarily have a long response time and large dark current defects. In this paper, a high-speed photoconductive UV detector based on the Mg$_{0.4}$Zn$_{0.6}$O film with the MSM structure was obtained, and the factors which affected the response speed of the device have been analysed.

2. Experiments

An Mg$_{0.4}$Zn$_{0.6}$O thin film on a quartz substrate was fabricated by the rf magnetron sputtering technique, which had a base pressure of 5.0 $\times$ 10$^{-4}$ Pa. The Mg$_{0.16}$Zn$_{0.84}$O target to quartz substrate distance was maintained at 6 cm and the substrate temperature was 673 K. The working pressure in the chamber was kept at 1 Pa during the film growth. The rf power was kept at 100 W and the applied voltage was 500 V. Ultrapure (5 N) Ar and N$_2$ gases were introduced into the sputtering chamber through a set of mass flow controllers with flow rates of 22.5 sccm (standard cubic centimetre per minute). The rate of deposition was adjusted so as
to have a film thickness of nearly 500 nm (measured by scanning electron micrograph (SEM)) for a film growth for 60 min. Following, the Mg$_{x}$Zn$_{1-x}$O thin film was annealed at 673 K in vacuum about 5.0 x 10$^{-4}$ Pa for 30 min. Then, the high resistance ($\sim 10^{7}$ $\Omega$) Mg$_{x}$Zn$_{1-x}$O thin film was obtained. The MSM structure with interdigitated configuration on the Mg$_{0.4}$Zn$_{0.6}$O film was obtained by lithography and wet etching. It consists of 12 fingers at each electrode finger, which are 5 $\mu$m wide, 500 $\mu$m long and have a pitch of 2 $\mu$m.

The structure characterization of the alloy thin film was carried out by x-ray diffraction (XRD) using a D/max-RA x-ray spectrometer (Rigaku) with Cu K$\alpha$ radiation of 0.154 nm. A Hitachi S4800 SEM was employed to study the surface morphology of the film. Energy dispersive spectroscopy (EDS) was used to determine the Mg/Zn ratio in the film. The acceleration voltage and the magnification of EDS were 10 kV and 5000, respectively. Optical transmission spectra were recorded using a Shimadzu UV-3101 PC scanning spectrophotometer.

For the characterization of the Mg$_{0.4}$Zn$_{0.6}$O UV detectors, a pulsed Nd-YAG laser (266 nm, 10 ns) and a 150 W Xe lamp were used as the excitation source. The spectrum response was measured by a lock-in amplifier. The dark current was measured by the Hall measurement system.

3. Results and discussion

The crystal structure of the annealed film was shown by XRD measurement. As shown in figure 1, the peak at 2$\theta$ = 35.283$^\circ$ corresponds to (0 0 2) orientation of the wurtzite structure with the c-axis lattice parameter of 0.508 nm, which is close to the ZnO c-axis lattice constant. No signatures of the cubic phase (peak at 2$\theta$ = 36.70$^\circ$ for (1 1 1) orientation) were observed. The Mg composition in the film was measured by EDS and obtained to be Mg$_{0.4}$Zn$_{0.6}$O. No other impurities were detected within the detection limit of EDS ($\sim 0.5$ wt%).

With the higher thermodynamic solubility of Mg in ZnO (up to 40%), the alloy film remained in a single phase and was in close agreement with the observations of Kumar et al, who reported a solubility limit of 42% for Mg$_{x}$Zn$_{1-x}$O films prepared by the same technique at room temperature [10]. The difference between the Mg percentage in the target and in the film was attributed to the high vapour pressure of Zn, resulting in high Mg composition in the film with a larger band gap. The inset in figure 1 shows the SEM images of the Mg$_{0.4}$Zn$_{0.6}$O film. It has moderately smooth surface morphology. It is believed that the formation of the uniform interface between Au and ZnO conjunction.

Figure 2 presents the optical transmission in the wavelength range from 200 to 600 nm. From figure 2, it is observed that the transmittance varies significantly with the wavelength of 320 nm. The average transmittance in the visible part of the spectra was more than 85% after 340 nm. The band gap energy was derived from the line shown in the inset of figure 2. The optical band gap of Mg$_{0.4}$Zn$_{0.6}$O was about 4.2 eV [11]. A similar result has been reported by Minemoto et al who obtained a stable Mg$_{x}$Zn$_{1-x}$O alloy up to the solubility limit of 46% [12]. From the inset, we can see that the tail and bow of the absorption edge are shown, which would be attributed to the structural defects; for example, Mg may be incorporated at the interstitial sites and grain boundaries.

The Mg$_{0.4}$Zn$_{0.6}$O MSM structure with interdigitated configuration was used to evaluate the UV detector performance. The measured dark $I$–$V$ characteristics are shown in figure 3. The linear $I$–$V$ relations under both forward and reverse biases exhibit ohmic metal–semiconductor contacts. Under 3 V bias, the dark current was no more than 40 nA. The low dark current is helpful to enhance
the detector’s signal-to-noise (S/N) ratio since the shot noise, which exceeds the Johnson and 1/f noise if the operating frequency is not too low, is proportional to the dark current [8]. Hence, the low dark current, in our case, contributes to the high quality Mg0.4Zn0.6O film.

Figure 4 shows the spectral response of the Mg0.4Zn0.6O MSM UV detector. The responsivity is quite flat over the Mg0.40Zn0.60O thin film which we have prepared is of high quality, especially after annealing. However, the fall time was longer than the rise time. So it is necessary to consider various physical effects. The slower fall time can be very well fitted with a bi-exponential function with the time constants of 6.5 and 39.2 ns. They were attributed to the electron and the hole components, respectively.

The time response was measured at 3 V bias with a load resistance of 50 Ω. The transit time and RC constant are related to the time response. \( t_r = L^2/\mu_e V \), where \( L \) is the interdigitated spacing, \( \mu_e \) is the electron mobility and \( V \) is the voltage drop between the two electrodes. \( L, \mu_e \) and \( V \) are 2 μm, 6 cm²V⁻¹s⁻¹ (measured by the Hall measurement) and 3 V, respectively. So the transit time (≈3 ns) is ruled out, and it may contribute to the 20 ns rise time, but has a negligible effect on the fall time. The RC time constant is estimated about 10 ns (≈ 0.5 pF, measured by actual capacitance–voltage measurement), where \( C \) is the sum of the detector internal capacitance and the load capacitance, \( R \) is the load resistance and the series resistance [15]. The RC constant may be one part of the fall time. This indicates that mechanisms other than \( RC \) and transit limitations are responsible for the fall time part of the high-speed response of the Mg0.4Zn0.6O UV detector. We postulate that the long and bi-exponential fall times are mainly related to hole trapping at the semiconductor–metal interface in the Mg0.4Zn0.6O film [16], where photogenerated carriers can be trapped at these sites. The long decay tail is possibly formed by the arrival of such released carriers which are trapped in these sites for a rather long time. In addition, the oxygen adsorption at the interface of the Mg0.4Zn0.6O film may be another reason [17].

So there is a gain in the detector, and it performs a direct proportion with electron carrier lifetime and responsivity [18]. This can be explained by the effect of gain on the fall time and responsivity.

4. Conclusion

In summary, the high-speed photoconductive UV detector based on the high quality Mg0.4Zn0.6O film had been fabricated and characterized. The fabricated devices exhibited low leakage with dark current less than 40 nA below 3 V bias. The maximal peak responsivity of 1.3 A W⁻¹ at 320 nm was measured at 3 V bias, corresponding to an external
quantum efficiency of 505% and the detectivity $D^{*}$ of $1.37 \times 10^{11}$ cm Hz$^{1/2}$ W$^{-1}$. An ultraviolet-rejection ratio (320 nm/400 nm) of more than four orders of magnitude was obtained from the fabricated detector. The 10%–90% rise and fall times were 16 ns and 250 ns, respectively. We deem that the slow response in the Mg$_{0.4}$Zn$_{0.6}$O UV detector is usually attributed to the hole trapping at the semiconductor–metal interface and the oxygen adsorption at the surface. We deeply believe that if the quality of the Mg$_{x}$Zn$_{1-x}$O film is enhanced, the response time will be faster.

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