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Effects of continuous annealing on the performance of ZnO based metal-semiconductor-metal ultraviolet photodetectors

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ABSTRACT

In this study, metal-semiconductor-metal (MSM) Schottky ultraviolet (UV) photodetectors were based on *c*-axis preferred oriented zinc oxide (ZnO) films, which were prepared on quartz substrates by radio frequency (RF) magnetron sputtering technique. The responsivity of the photodetector was enlarged greatly after annealing the MSM device. Meanwhile, the enhancement in the dark current that resulted from the experiment was accompanied by the increasing annealing temperature. The origin is preliminarily discussed combining the observations of dark currents and responsivities. The physical mechanism of the continuous annealing is proposed on the basis of metal-semiconductor contact theory and diffusion effect. By this model, Au atoms from the electrode play an important role in the Schottky barrier during annealing process. These results demonstrate that a simple route to improve the responsivities of photodetectors can be realized easily by annealing the devices.

1. Introduction

UV photodetectors have received lots of attention in recent years, owing to their extensive applications, such as chemical and biological analysis, flame detection, solar astronomy, missile plume detection and combustion monitoring [1–6]. With the semiconductor materials being fully researched, scientists have started to manufacture UV photodetectors by using them [7–9]. As an attractive wide band gap (E_g = 3.37 eV at room temperature) oxide semiconductor, ZnO can be used for fabrication of short wavelength optoelectronic devices including UV photodetectors [10–12]. UV photoresponses of ZnO in the single crystal, thin film, and nanostructural forms have been studied in quantity by different groups, which have shown their complicated characteristics [13–17]. Efforts are still continuing to obtain ZnO based UV photodetectors with higher responsivity.

The near-term reports of ZnO based UV photodetectors mainly focus on MSM structure which contains either Schottky barrier based photovoltage type or Ohmic contact based photoconductive type [18–20]. They attempted to improve the responsivities of the photodetectors by means of optimizing ZnO films, but lacked of the optimization of the devices themselves. Annealing is an effective posterior treatment to enhance the properties of films. Up to now, a variety of techniques have been employed to deposit ZnO thin films demonstrating that annealing film can enhance the crystal quality effectively [21–23]. Unfortunately, very few references about annealing the device have been reported to date. Indian researchers have reported the effect of annealing device on the performances of ZnO based metal-insulator-semiconductor (MIS) ultraviolet photodetectors, which mainly discussed electrical property and lacked of systematic photoresponse performance [24]. For the moment, the understanding of the physical mechanism about annealing device is still poor. In the present study we will show some possible mechanisms toward achieving well understanding for annealing device.

In this letter, we report curtly on the growth of ZnO thin films on quartz substrates by RF magnetron sputtering technique, and focus on the continuous annealing craftsmanship of ZnO based MSM UV photodetectors which emphasizes annealing the same device at a temperature range, neither a certain temperature, nor annealing the different devices at different temperature, then pay close attention to the effect of continuous annealing on the performances of photodetectors. The annealing of photodetectors make the responsivity enhanced significantly, which demonstrates that this method is a powerful complement for the improving performance of photodetectors.

2. Experimental

The ZnO thin films were prepared on quartz substrates by RF magnetron sputtering technique. Before sputtering, the quartz

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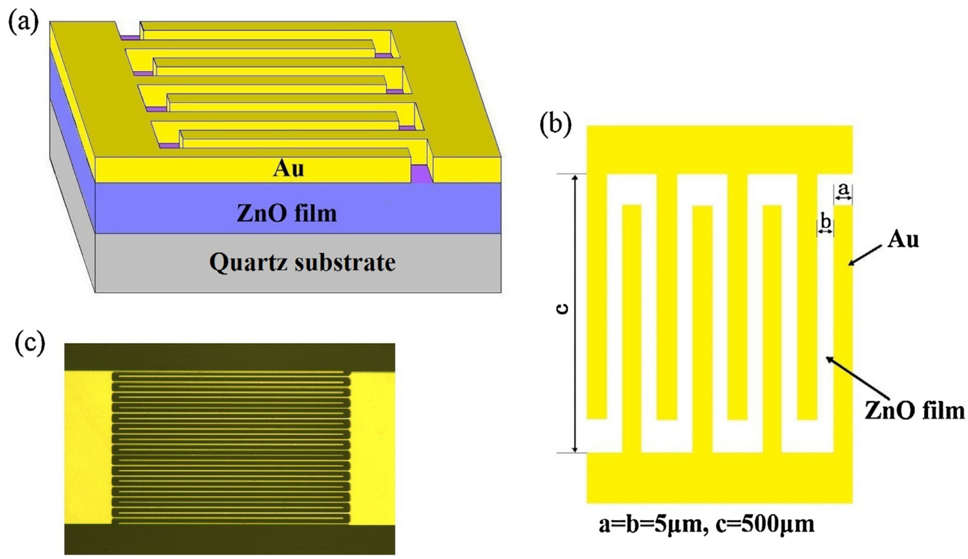

Fig. 1. (a) The stereo schematic of ZnO UV photodetector with MSM structure, (b) and (c) are the plan sketch and the metallographic microscope images of the photodetector, respectively.

substrates were cleaned respectively by acetone (≥99.5%) and absolute ethyl alcohol (≥99.7%) for 10 min in an ultrasonic bath, followed by distilled water washing and high purity nitrogen drying for standby. A ZnO ceramic (≥99.995%) was used as the sputtering target which diameter is 60 mm and thickness is 4.5 mm. The distance between target and quartz substrates was 50 mm. The double air suction system can make the vacuum degree of the system background be below 5×10^{-4} Pa. In order to complement oxygen deficiency of the ZnO thin films, mixed gases were the work gas which contains ultrapure (5N) oxygen and argon (15 sccm: 50 sccm, sccm stands for standard cubic centimeters per minute). In the sputtering chamber, the pressure was hold at 5.0 Pa and the quartz substrates temperature was kept at 683 K during ZnO films growth. The RF power was kept at 150 W and the sputtering time was 2.5 h. To ensure the uniformity of the deposited thin films, the objective table was twirling at the speed of 5 r/min.

For the sake of obtaining MSM UV photodetectors, a thin layer of Au was sputtered on the prepared ZnO films to realize electrode contact. We used UV exposure and wet etching to achieve the MSM structured electrode, whose fingers were 500 μm long and 5 μm wide with an interval spacing of 5 μm, and the sum of finger pairs was 15. The schematic of ZnO-based MSM structure photodetectors is shown in Fig. 1.

The same device was continuously annealed in the sputtering chamber from 373 to 673 K in steps 50 K for 15 min at each step when the pressure was kept at 40 Pa. The device was protected in the mixed gases which contained oxygen and argon (20 sccm:60 sccm) in the annealing process. The current–voltage (*I–V*) (Agilent 16442A Test Fixture) under dark and the responsivity (Zolix DR800-CUST) characteristics were measured after each annealing cycle at room temperature. The bias voltage in the responsivity testing was 30 V and the applied voltage in the *I–V* testing was tuned from −15 to +15 V. Furthermore, the crystal property of ZnO films in different periods was characterized by the Rigaku Ultima VI X-ray diffractometer (XRD) with Cu Kα radiation (λ = 1.543 Å) at 40 kV and 20 mA. A PerkinElmer Lambda 950 UV/VIS Spectrometer was used for absorbance spectra in the wavelength range from 300 to 600 nm.

3. Results and discussion

The XRD patterns of an unannealed ZnO thin film and another film which was from the MSM UV photodetector after continuous annealing at 673 K are shown in Fig. 2. It is found that both films have a preferential *c*-axis orientation and the emergence of the Au diffraction peak on the annealed film, which is due to contact electrode on the film from the Au–ZnO–Au MSM interdigital configuration. UV exposure and wet etching had an effect on decreasing the intensity of film, which gave rise to a small quantity of defects on the surface of ZnO film. But continuous annealing did not improve the intensity of ZnO film obviously. Fig. 3 shows the absorption and transmission spectra of the films. They were tested on the same conditions without the substrate contribution. Comparing with the results in the spectra, the absorption and transmission of both films are nearly the same. It is necessary to note that the crystal and optical qualities were not improved obviously by continuous annealing.

The Au–ZnO–Au MSM interdigital configuration was used to evaluate the performance of UV photodetectors. The measured dark *I–V* characteristics of the photodetectors annealed at different temperatures are shown in Fig. 4(a) and (b), showing in different coordinates. The nonlinear *I–V* characteristics indicate that Schottky metal-semiconductor contacts were achieved. The dark current of the unannealed photodetector is only 4.78 nA under

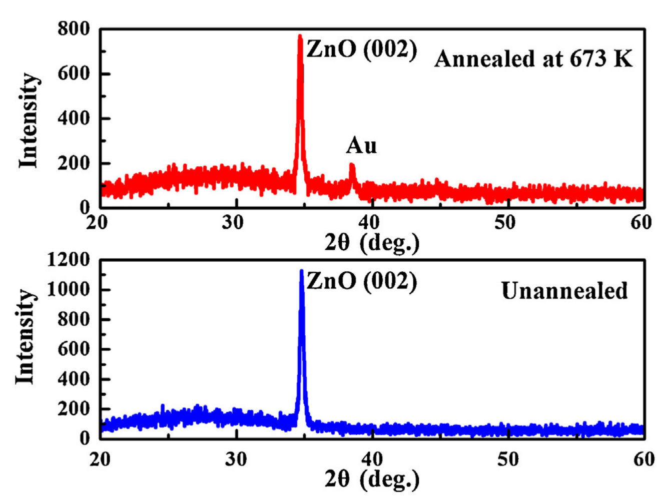

Fig. 2. XRD patterns of the unannealed ZnO thin film and the film from the MSM UV photodetector after continuous annealing at 673 K.