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Improvement in Rectifying Properties of Magnetron Sputtered-Zinc Oxide-based Schottky Diodes

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1. Introduction

To accomplish high-performance ZnO-based optoelectronic devices, the formation of high quality metal electrode contacts is essential. A superior rectifying junction with metals and low-resistance ohmic contacts onto the ZnO surface was the best mechanism that promoted their use in diode [1-2]. There were many reports addressing the mechanisms for the difficulties in the formation of ZnO-based Schottky diodes [3-5]. A variety of ZnO surface treatment methods were demonstrated to removal the interfacial states of the metal Schottky contact to ZnO [6-7]. To date, magnetron sputtering is a commonly used system for deposition crystalline ZnO films in application on the optoelectronic devices, but limited reports on sputtered-ZnO Schottky contacts [8-9].

In this study, with the aim to fabricate a high performance ZnO-based Schottky diode, the efforts of the optimization on the crystalline structure of the sputtered-ZnO films as well as the associated Schottky and ohmic contact surface were systematic discussed. The c-axis growth orientation was firstly improved using a post-annealing treatment at an elevated temperature under oxygen ambient. The Schottky contact surface was processed with an addition oxygen plasma treatment. The ohmic contact junction was approached to insert a homogeneity n-type ITO-ZnO cosputtered film.

2. Experimental procedure

A 2 μm-thick undoped-ZnO film was deposited onto silicon substrate using rf magnetron sputtering system and then annealed at 700^{o}C for 30 min under oxygen ambient. The films were undoped but show n-type conduction (~ 3.83×10^{11} cm^{-3}). Ni/Au and Al were respectively, employed to form Schottky and ohmic contact on the ZnO-based structures. These contact metals patterned directly by lift-off of evaporated films onto the ZnO film was denoted as the conventional Schottky diode (sample A), whereas that of the Schottky contact surface processed with an additive oxygen plasma passivation at 270 W for 10 min prior to metal deposition was classified as sample B. In addition to the conventional Schottky diode structure, another set of multilayer Schottky diode structure (sample C) with a homogeneity ITO-ZnO cosputtered layer (~ 250 nm) deposited onto the undoped-ZnO film also prepared. The ITO-ZnO cosputtered film at an atomic ratio of 90% [Zn / (Zn + In) at.%] was annealed at 300^{o}C for 30 min under oxygen ambient and possessed an electron carrier concentration of 7.01×10^{18} cm^{-3} [10]. Detail structures of the conventional and multilayer Schottky diodes structures are illustrated in Fig. 1(a) and (b), respectively. Electrical properties of the deposited films were measured by the van der Pauw method. The crystalline structures and surface morphologies were examined by XRD and AFM measurements. Current-voltage properties of these Schottky diode structures were characterized using a semiconductor parameter analyzer (HP4156C).

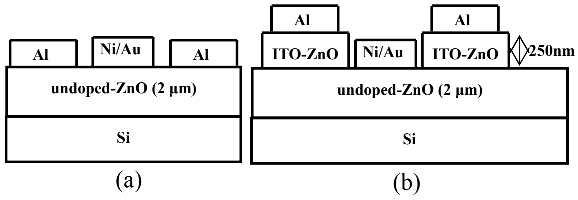


Fig. 1 Schematic of the (a) conventional and (b) multilayer ZnO-based Schottky diode structures.

3. Experimental results

Figure 2 shows the XRD spectra of the thick undoped-ZnO films before and after thermal annealing treatment. It was clear that both the c-axis (002) preferred orientation and crystal growth were markedly improved after thermal annealing. The grain size evaluated from the FWHM of ZnO (002) peak was increased from 19.58 to 37.4 nm according to Scherrer's formula, indicating the achievement of a superior crystalline structure. The AFM observations of the undoped-ZnO surface and that of processing with an additive oxygen plasma passivation are presented in Fig. 3 (a) and (b), respectively. There was a little increase in the surface roughness, confirming no obvious ion bombardment damages on the surface. A comparison for the *I-V* characteristic of Ni/Au Schottky contacts to the undoped-ZnO surface with and without oxygen plasma passivation is shown in Fig. 4. Both the reverse and forward currents of the conventional Schottky diodes were markedly reduced after oxygen plasma

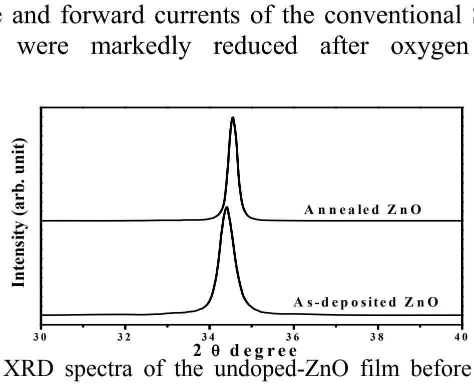
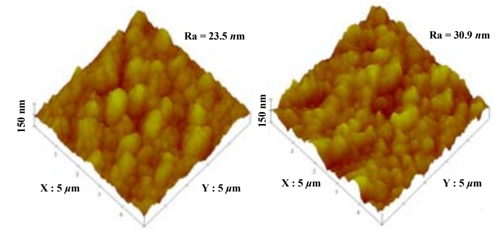


Fig. 2 XRD spectra of the undoped-ZnO film before and after thermal annealing treatment.



(a) (b)

Fig. 3 Surface roughness of the undoped-ZnO film (a) before and (b) after oxygen plasma passivation.

passivation. In addition, the ratios of the forward to leakage current measured at -2 and 2 V were also increased from 4.78 (sample A) to 14.25 (sample B), indicating a better rectifying behavior achievement. The associated Schottky diode parameters were derived from the following equation according to the well-known thermionic emission theory:

$$I = AA^{*}T^{2}\exp\left(\frac{-q\Phi_{B}}{kT}\right)\exp\left(\frac{q(V-IR)}{nkT}\right) \quad (1)$$

The conventional Schottky diode had a high ideality factor (n) of 2.47, meaning that the existence of multiple current pathways other than thermionic emission. In contrast, the ideality factor and barrier height (Φ_B) were evaluated to be 1.92 and 0.82 eV, respectively. The reduction in the ideality factor as well as the increase in the barrier height was consisted with the report that addressed to be the donor-like defect passivation of the oxygen radical in the plasma diffused into the ZnO films surface [11]. Although the rectifying behavior had been significant improved through the oxygen plasma passivation, the forward current was still too small due to the poor ohmic contact behavior at Al and un-doped ZnO junction. The specific contact resistance was greatly decreased to 1.44×10^{-3} Ω cm^2 with a homogeneity ITO-ZnO cosputtered film deposited onto the undoped-ZnO film. The associated forward current of this multilayer Schottky diode (sample C) measured at 2 V shown in Fig. 5 exceeds ten times higher than that of the single layer one (sample B). The ratio of the forward to leakage current measured at -2 and 2 V was about 146.05. In addition, the ideality factor and barrier height (Φ_B) were evaluated to be 1.49 and 0.82 eV, showing that both the

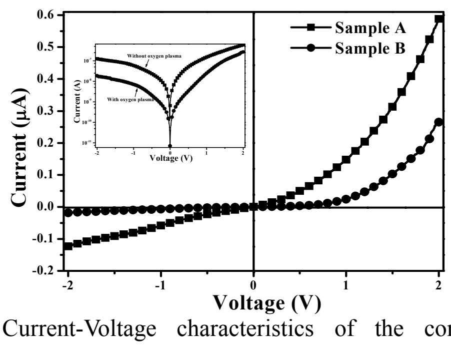


Fig. 4 Current-Voltage characteristics of the conventional ZnO-based Schottky diodes with (sample B) and without (sample A) oxygen plasma treatment

forward current and the Schottky diode parameters were effectively improved by using the ZnO/ITO-ZnO multilayer Schottky diode structure.

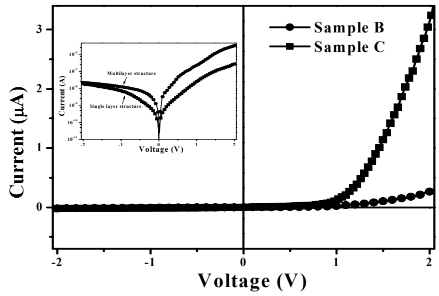


Fig. 5 Current-Voltage characteristics of the conventional (sample B) and multilayer (sample C) ZnO-based Schottky diodes.

4. Conclusions

The rectifying properties of the magnetron sputtered-ZnO based Schottky diode were systematic studied. The crystalline structure such as c-axis orientation and grain size of the as-deposited undoped-ZnO film was found to be markedly improved through an adequate post-annealing treatment. The reversed leakage current as well as the ideality factor of the conventional Schottky diode was effectively reduced with an additive oxygen plasma passivation on the Schottky contact surface. Elimination of the surface contaminations and the compensation of the oxygen-related vacancies were the mechanism to reduce the electron tunneling effect and led to the better Schottky diodes performance. In addition, the forward turn-on current also was obviously increased with a homogeneity ITO-ZnO cosputtered layer deposited onto the undoped-ZnO film due to the apparent improvement in the Al/ITO-ZnO ohmic contact behavior.

Acknowledgments

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