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Analysis of the electrical characteristics of the Ag/ZnO Schottky barrier diodes on F-doped SnO_2 glass substrates by pulsed laser deposition

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ABSTRACT

High quality semiconductor layer of n-type ZnO thin film was fabricated on F-doped SnO_2 glass substrates by pulsed laser deposition. The Schottky junction diodes with configuration of Ag/ZnO/FTO have been fabricated to study the devices electrical properties by current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) measurements. The results show that the devices have good rectifying behaviors with an ideality factor of 1.64 and a Schottky barrier height of 0.85 eV based on the *I*–*V* characteristics. Also, Cheung's functions and Norde's method were used to evaluate the *I*–*V* characteristics and to obtain the series resistance of the Schottky contact. From the *C*–*V* characteristics, the capacitance was determined to increase with decrease of frequencies. *C*–*V* measurements have resulted in higher barrier heights than those obtained from *I*–*V* measurements. The discrepancy between Schottky barrier heights obtained from *I*–*V* and *C*–*V* measurements was also interpreted.

1. Introduction

Zinc oxide (ZnO) is an interesting II–VI n-type compound semiconductor material that has attracted much attention in recent years. With large exciton binding energy of 60 meV and wide band gap energy of 3.37 eV at room temperature, ZnO has been regarded as a promising photonic material for applications such as UV detectors, solar cell, light emitting diodes (LEDs) and laser diodes (LDs) [1]. Developing a high performance ZnO based optoelectronic device requires forming perfect Schottky or Ohmic contacts between ZnO film and metal system. A superior rectifying junction with metals and low resistance Ohmic contacts onto a ZnO surface is crucial for many practical device applications. Ohmic contacts to ZnO can be prepared relatively easily but often need additional heat treatment. The realization of high quality Schottky contacts on ZnO seems to be more difficult, because of a high donor concentration at the surface region of n-type ZnO, which is caused by native defects such as oxygen vacancies and zinc interstitials [2].

Previous reports have shown that low reactive metals such as Au, Ag, Pt and Pd form rectifying contacts to n-type ZnO with Schottky barrier heights in the range of 0.6–0.8 eV [3,4]. In addition, the thermal stability of the Ag/n-ZnO Schottky contacts has been proven to be higher than that of Au Schottky contacts. However, the trend in barrier heights did not correlate with the metal work functions, suggesting many possible influences such as intrinsic surface states, surface morphology, and residual surface contamination are playing important roles in the electrical properties of the contacts. In recent years, a number of oxidation pretreatments have been shown to improve Schottky contact performance, and the role of oxygen vacancies in pinning the ZnO surface Fermi level has been established [5,6]. In addition, a process methodology for the reproducible fabrication of high quality Schottky contacts using non-stoichiometric silver oxide films has been developed [7]. However, those Schottky diodes are constructed on an n-type bulk single crystal of ZnO wafer or epitaxy ZnO films on Al_2O_3 substrates, and there are still many issues which are not completely understood theoretically. In the present work, we aim to fabricate high performance ZnO based Schottky diodes on transparent conductive oxide (TCO) film coated glass substrates by pulsed laser deposition. The electrical properties of the Ag/ZnO/TCO structure analyses by current–voltage (*I*–*V*) and capacitance–voltage (*C*–*V*) technique are presented.

2. Experiments

The ZnO films were deposited on F-doped SnO_2 (FTO) glass substrates by pulsed laser deposition. Before deposition, the FTO glass was cleaned in acetone and methanol for 10 min each with ultrasonic agitation to remove contamination. Finally, it was rinsed in deionized water for 30 s and was dried in N_2 atmosphere. The samples were grown in high vacuum chamber with a typical background pressure of 10^{-6} Pa. The oxygen gas (O_2, 99.99%) was introduced into the growth chamber through a mass flow controller with the velocity of 10 sccm, and the pressure was controlled to be 10^{-3} Pa. A KrF excimer laser ($\lambda = 248$ nm) was used to ablate a

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ceramic ZnO target (99.99%). The substrate was placed 70 mm away from the target and the temperature of the substrate was 500 °C. Both the target and the substrate were kept rotating to ensure the uniformity of the films. The pulse duration, repetition rate and fluence of the laser beam were 20 ns, 5 Hz and 2 J/cm^2, respectively. The film thickness measured by surface profilometer was about 500 nm. After deposition, 50 nm thick silver oxide film was deposited by the reactive rf sputtering of a Ag target (99.99%) using an Ar/O_2 atmosphere. Subsequently, a metallic capping layer was sputtered in pure argon using the same metal. The rf power was 50 W and the processing pressure was 2 Pa. Molybdenum steel shadow masks defined contact areas of 4×10^{-4} cm^2.

The crystal structure of ZnO films were investigated by X-ray diffractometry (XRD; DX2500) with CuKα radiation (λ = 0.1542 nm) in θ–2θ scan mode. The operation voltage and current were 35 kV and 30 mA, respectively. The surface image was examined by scanning electron microscopy (SEM, JSM5600LV). The electrical characteristics of the samples were measured by a semiconductor parameter analyser (KEITHLEY 4200).

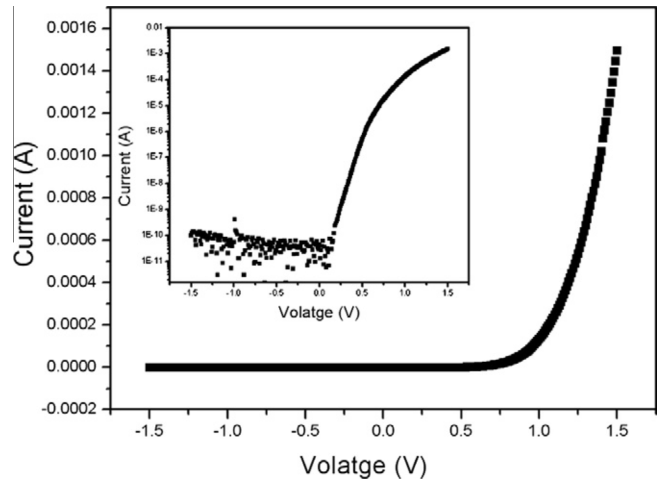

Fig. 2. The current–voltage characteristics of the Ag/ZnO Schottky diode.

3. Results and discussion

The XRD patterns of the ZnO film and the FTO substrate are shown in Fig. 1. The ZnO layer is grown with predominant ZnO(002) orientation accompanied by several SnO_2 from FTO substrates diffraction peaks, indicating that the ZnO film is of wurtzite crystal structures with a preferred *c*-axis orientation normal to the substrates. The full width at half maximum of the ZnO(002) diffraction peak is measured to be as narrow as 0.252°, which indicates that the laser deposited ZnO film has good crystallinity. The average crystallite size is estimated as about 330 nm from the ZnO(002) peak widths by Scherrer's equation [8]. The surface morphology image of the ZnO film was observed by means of SEM, which is shown in the inset of Fig. 1. It is seen that the ZnO film grown on FTO substrates is quite smooth, uniform, and compact, and that the ZnO crystallite size is observed to be about 300 nm.

To obtain information about the mechanism of carrier transport across the junction, the current–voltage (*I*–*V*) characteristics of the Ag/ZnO Schottky structure were measured at room temperature. The experimental forward and reverse bias *I*–*V* characteristics are shown in Fig. 2. The structure has exhibited excellent rectification characteristics with relatively low and saturated leakage current of 10^{-10} A and the rectification ratio is about 3×10^6 at 1 V. When the non-ideal Schottky barrier diode with a series resistance and an interfacial layer are considered, it is assumed that the net current of device is due to thermionic emission (TE) theory and it can be expressed as [9]:

$$I = I_0 \exp\left(\frac{qV}{nkT}\right)\left[1 - \exp\left(-\frac{qV}{kT}\right)\right] \quad (1)$$

where V is the applied voltage and I_0 is the saturation current derived from the straight line intercept of Ln(I) at $V = 0$ and is given by:

$$I_0 = AA^* T^2 \exp\left(-\frac{q\phi_b}{kT}\right) \quad (2)$$

where q is the electron charge, A^* is the effective Richardson's constant which equals 32 A/$cm^2 K^2$ for n-type ZnO, A is the effective diode area, T is the temperature in Kelvin, k is the Boltzmann's constant, n is the ideality factor, and ϕ_b is the effective barrier height at zero bias defined by Eq. (2). For bias voltage greater than $3kT/q$, the ideality factor from Eq. (1) can be determined from the slope of the linear region of the forward bias Ln(I)–V curve through the relation:

$$n = \frac{q}{kT}\frac{dV}{d\ln(I)} \quad (3)$$

The ideality factor is introduced to take into account the deviation of the experimental *I*–*V* data from the ideal TE model. For an ideal Schottky diode, n is unity. In this work, the value of the n obtained from *I*–*V* characteristics using Eq. (3) has been found to be 1.64. The value of the ideality factor is larger than unity. High values of n can be attributed to the presence of the interfacial layer at Ag and ZnO interface, barrier height inhomogeneity, or image-force lowering which is voltage dependent. Values of the saturation current I_0 were obtained by extrapolation of the linear region of the semi-logarithmic forward *I*–*V* curves to zero applied voltage and were used to calculate the apparent barrier height by the following function:

$$q\phi_b = kTLn\left(\frac{AA^*T^2}{I_0}\right) \quad (4)$$

The value of the ϕ_b obtained from the *I*–*V* characteristics using Eq. (4) is found to be 0.85 eV, which is comparable with the reported values of Ag/ZnO Schottky diode fabricated on bulk ZnO wafer.

The series resistance (R_s) is an important parameter in the characteristics of the Schottky barrier diodes because it controls the conduction process in wide band gap semiconductor materials. A

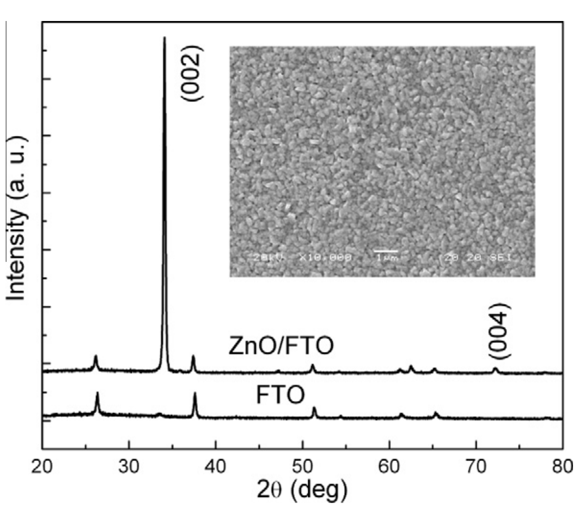

Fig. 1. XRD patterns and SEM image of the ZnO film on FTO substrates.