

Silver Schottky contacts to *a*-plane bulk ZnO

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The temperature dependent electrical properties of Ag Schottky contacts to *a*-plane bulk ZnO single crystal were investigated in the temperature range of 100–300 K. The variation in the barrier heights was described by a double Gaussian distribution with two different regions in the temperature range of 200–300 and 100–180 K. The modified Richardson plot in the temperature range of 200–300 K produced the Richardson constant of $29 \text{ A cm}^{-2} \text{ K}^{-2}$ which is similar to the theoretical value of $32 \text{ A cm}^{-2} \text{ K}^{-2}$ for *n*-type ZnO, indicating that the inhomogeneous barrier height with the thermionic emission model can explain the current transport well in this region. Below 200 K, the bulk carriers start to freeze out and the induced oxygen vacancies in the interface region, probably due to the formation of silver oxide at the Ag–ZnO interface, will influence significantly the current transport by creating very thin interfacial layer that is susceptible to electron tunneling.

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I. INTRODUCTION

ZnO has gained considerable interest for optoelectronic applications such as light emitting diodes, UV detectors, white light sources and solar cells due to its wide band gap (3.4 eV at 300 K), high exciton binding energy (60 meV) and excellent radiation hardness.^{1,2} ZnO crystallizes in the wurtzite structure like GaN, but, in contrast to GaN, ZnO is available as large bulk single crystals, which is a big advantage of ZnO over GaN.³ For example, GaN layers grown on sapphire substrates have a relatively high density of extended defects due to the thermal and lattice mismatch between GaN and sapphire.⁴ The epitaxy of ZnO films on native substrates can result in ZnO layers with reduced concentration of extended defects and, consequently, better performance in electronic and photonic devices.¹ Another big advantage over GaN is that ZnO is amenable to wet chemical etching, which is compatible with Si technology.⁵

In order to attain high performance ZnO devices, it is necessary to develop reliable and reproducible Ohmic and Schottky contacts. Previous researches have shown that low reactive metals such as Au, Ag, and Pd form rectifying contacts to *n*-type ZnO (*n*-ZnO) with Schottky barrier heights in the range of 0.6–0.8 eV.^{6,7} The thermal stability of the Ag/*n*-ZnO Schottky contacts has been proven to be higher than that of Au Schottky contacts.⁸ However, the barrier heights did not correlate with the metal work functions, suggesting many possible influences such as surface states, surface morphology, and surface contamination are playing important roles in the electrical properties of the contacts. Another factor that can be considered is the polarity of the ZnO surface. The existence of nonzero net dipole moments perpendicular to the Zn polar (0001) and O polar (000 $\bar{1}$) surfaces leads to differences in the interface structure of the Schottky contacts.⁹ Highly rectifying silver oxide Schottky contacts

fabricated on bulk ZnO wafers showed that the Schottky diodes fabricated on the Zn polar surface has higher barrier heights than those on the O polar surface.¹⁰ However, Coppa *et al.*¹¹ reported no significant polarity effect in the Au contacts to the Zn and O polar surfaces of single crystal ZnO wafers, which was attributed to the removal of hydrocarbon and hydroxide contamination.

Recently, as a means of eliminating the polarization-related effects in nitride-based optoelectronic devices, epitaxial growths of nonpolar GaN films on different substrates have been investigated.^{12,13} Owing to the relatively close lattice match, single crystal ZnO can be used to grow epitaxial GaN films with a low density of defects. To grow high quality nonpolar GaN or ZnO films on the nonpolar single crystal ZnO wafers, complete understating of electrical properties of single crystal ZnO wafers are required. Sheng *et al.*¹⁴ fabricated the Ag Schottky contacts to *a*-plane (11 $\bar{2}$ 0) epitaxial ZnO films grown by metal-organic chemical-vapor deposition (MOCVD) on *r*-plane (1 $\bar{1}$ 02) sapphire substrate and found that the flat band barrier height is 0.89 eV with an ideality factor of 1.33. Liang *et al.*¹⁵ reported similar results after characterizing Ag Schottky contacts to *a*-plane epitaxial ZnO films grown by MOCVD on *r*-plane sapphire. However, there exists little knowledge concerning the Schottky contacts to nonpolar single crystal ZnO wafers. In this work, we report on the electrical characterization of Ag Schottky contacts to nonpolar *a*-plane bulk ZnO wafer in terms of barrier inhomogeneity.

II. EXPERIMENTAL PROCEDURE

An unintentionally doped, hydrothermally grown, *a*-plane bulk ZnO single crystal from Alumatic, Inc. was used in this investigation. The wafer was $5 \times 5 \times 0.5 \text{ mm}^3$ and double sided polished by the manufacturer. The room temperature carrier concentration assessed by Hall effect measurements was $\sim 1 \times 10^{15} \text{ cm}^{-3}$. Before metallization

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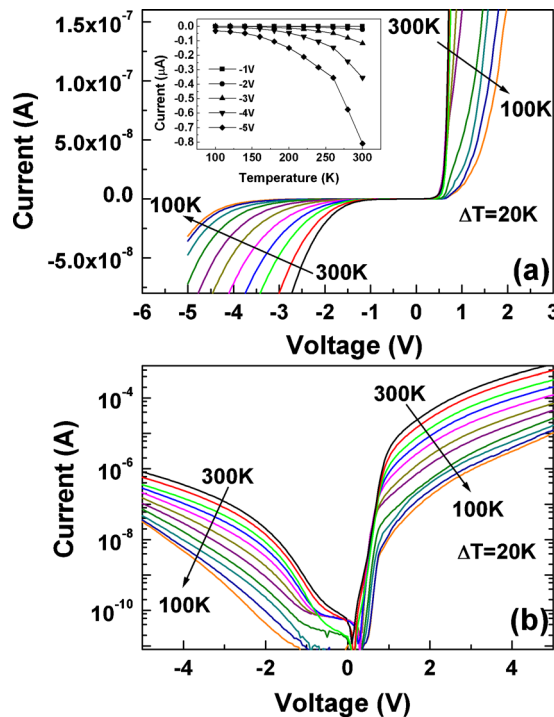


FIG. 1. (Color online) (a) Linear current-voltage (I - V) characteristics and (b) semilogarithmic I - V characteristics for the Ag/*a*-plane bulk ZnO Schottky diodes in the temperature range of 100–300 K. The inset in (a) depicts the reverse bias current values at different temperatures.

the sample was ultrasonically cleaned using organic solvents. A Ti/Au (30 nm/80 nm) bilayer was deposited over the full backside surface using an electron-beam evaporator to serve as the Ohmic contact, followed by thermal annealing at 300 °C for 1 min in an N_2 ambient. Then, 50 nm thick Ag Schottky contacts were formed by electron-beam evaporation through a shadow mask. Current-voltage (I - V) measurements were performed with a HP 4156B semiconductor parameter analyzer.

III. RESULTS AND DISCUSSION

Figure 1(a) shows the linear I - V characteristics measured in the temperature of 100–300 K. The current values for both the forward and reverse biases increase with increasing temperature. As shown in the inset of Fig. 1(a), the reverse current is very low and almost bias independent at 100 K, but that is quite high and very rapidly increases with increasing bias voltage at 300 K. The rectifying properties below 180 K becomes poorer compared to those at high temperatures, which may be due to the carrier freeze-out effect.¹⁶

Figure 1(b) shows the semilogarithmic I - V characteristics at different temperatures. The forward bias characteristics of a Schottky diode are given by the following equations using the thermionic emission (TE) model:¹⁷

$$I = I_0 \{ \exp[q(V - IR_S)/nk_B T] - 1 \}, \quad (1)$$

$$I_0 = AA^{**} T^2 \exp(-q\phi_B/k_B T), \quad (2)$$

where I_0 is the reverse bias saturation current, A is the device area, A^{**} is the effective Richardson constant, taken to be $32 \text{ A cm}^{-2} \text{ K}^{-2}$ for n-ZnO,¹⁰ ϕ_B is the effective Schottky

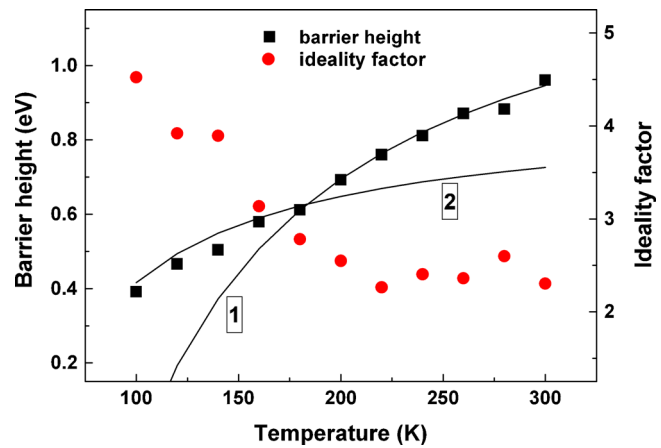


FIG. 2. (Color online) Effective barrier height and ideality factor as a function of temperature. Solid lines represent the calculated barrier height using Eq. (3) with a double Gaussian distribution of barrier heights in the temperature range of 200–300 K (region 1) and 100–180 K (region 2).

barrier height, n is the ideality factor, V is the applied voltage and R_S is the series resistance. For values of V greater than $3 k_B T/q$, the ideality factor can be obtained from the slope of the linear region of the $\ln(I) - V$ curves under the forward bias. The temperature dependence of the ideality factor and the barrier height determined from I - V measurements are shown in Fig. 2. The ideality factor decreases from 4.52 to 2.30 and the barrier height increases from 0.39 to 0.96 eV with increasing temperature from 100 to 300 K. This temperature dependence is commonly observed in real Schottky diodes and has been attributed to the lateral variation in the barrier heights.¹⁸ Electrons at a low temperature can surmount the lower barrier, and therefore, the current transport will be dominated by the current flowing through the lower barrier height. As the temperature increases, more electrons have sufficient energy to surmount the higher barrier. As a result, the dominant barrier height will increase with the temperature. It was reported that Ag Schottky contacts on the (0001) Zn surface of bulk n-ZnO crystals have the barrier heights of 0.68–0.70 eV at room temperature.¹⁹ Silver Schottky contacts fabricated on nonpolar thin film ZnO revealed the barrier height of 0.84 eV.¹⁵ Moreover, the different degrees of oxidation of the Ag contacts, causing an increase in the effective work function, produced the barrier heights varying from 0.77 to 1.02 eV in the Ag Schottky contacts to bulk n-ZnO crystals.⁹ The obtained barrier height at room temperature in our work suggests that there would be some degree of oxidation of the Ag contacts. In addition, it should be noted that the ideality factor at room temperature is much larger than unity. For the best diode, we obtained the ideality factor of 1.51, still larger than unity. Such a behavior has been attributed to the presence of interface states and insulator layer between metal and semiconductor.²⁰ Hence, we can deduce that an insulator layer was formed between Ag and ZnO and the interface states might contribute to the current transport.

When we examine the behavior of ideality factor shown in Fig. 2 in detail, it is observed that the ideality factor decreases with increasing temperature up to 180 K while its variation is very small above 200 K. Assuming a Gaussian