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Diffusion Currents in the Amorphous Structure of Zinc Tin Oxide and Crystallinity-Dependent Electrical Characteristics

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In this study, zinc tin oxide (ZTO) films were prepared on indium tin oxide (ITO) glasses and annealed at different temperatures under vacuum to investigate the correlation between the Ohmic/Schottky contacts, electrical properties, and bonding structures with respect to the annealing temperatures. The ZTO film annealed at 150℃ exhibited an amorphous structure because of the electron–hole recombination effect, and the current of the ZTO film annealed at 150℃ was less than that of the other films because of the potential barrier effect at the Schottky contact. The drift current as charge carriers was similar to the leakage current in a transparent thin-film device, but the diffusion current related to the Schottky barrier leads to the decrease in the leakage current. The direction of the diffusion current was opposite to that of the drift current resulting in a two-fold enhancement of the cut-off effect of leakage drift current due to the diffusion current, and improved performance of the device with the Schottky barrier. Hence, the thin film with an amorphous structure easily becomes a Schottky contact.

Keywords : Zinc tin oxide, Photo luminance, Diffusion current, X-ray diffraction, Tunneling, Schottky contact

1. INTRODUCTION

Instead of indium tin oxide (ITO), Zn-based oxide semiconductors have been investigated as promising transparent electrode materials because of their flexibility and cost-effectiveness. To overcome the humidity issues under air, ZnO has been doped with Al, Ga, Ag, Ge, and Sn [1-4]. Typically, the mobility and stability of oxide semiconductors have been improved by annealing because of the formation of oxygen vacancies as charge carriers and improvement of chemical and mechanical properties. The trapping phenomenon based on the Ohmic contact is responsible for the high mobility in transistors, which is proportional to the doping carrier content. However, the reduction of the device's size has limited the content of the doping carrier in the channel layer [5-9]. Therefore, transistors suffer from issues of low mobility and un-stability. Recently, several researchers have reported on transistors with a tunneling effect to increase the mobility and improve the threshold voltage shift. Ambipolar transfer characteristics in the depletion layer are observed for transistors exhibiting the tunneling phenomenon [10-12]. The diffusion current by potential barriers follows the negative resistive conduction as the opposite direction about the positive bias potential for the drift current. And the band-to-band conduction for the diffusion current in the depletion region exhibits the same effect as the tunneling phenomenon in case of the negative resistive conduction. Hence, mobility abruptly increases.

In this study, the correlation between the crystal structure and electrical properties of oxygen semiconductors was investigated. Zinc tin oxide (ZTO) films were annealed at different temperatures to examine the physical–electrical characteristics of ZTO. The correlation between the electrical properties and contact mechanism was investigated in terms of the crystal and amorphous structures; differences between the drift and diffusion currents were observed.

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2. EXPERIMENTS

ZTO thin films as oxide semiconductors were deposited on ITO glasses via RF magnetron sputtering at a pressure of 0.01 Torr. ZTO targets (99.99% purity) were supplied by LTS Research Laboratories, Inc., U.S.A. To obtain various bonding structures from amorphous to crystal structures, ZTO thin films were deposited under oxygen or argon (Ar) for 10 min in a vacuum chamber at a working pressure of 4.5×10^{-5} Torr. The flow of oxygen or Ar (99.9999%) was controlled using a mass flow controller from 18 sccm, with an RF sputtering power of 70 W. The as-deposited ZTO films were annealed at different temperatures to investigate the mechanisms of the Ohmic and Schottky contacts. X-ray diffraction (XRD) was employed to examine the physical properties of all samples, and photoluminescence (PL) studies were carried out to investigate the optical characteristics. The electrical properties were examined using an metal/oxide semiconductor/ITO glass structure and a mask pattern with a diameter of 200 µm. The correlation between the bonding structure and contact properties was investigated.

3. RESULTS AND DISCUSSION

Figure 1 shows the physical–electrical characteristics of the ZTO films deposited under Ar and annealed at different temperatures.

After annealing, the bonding structure and the electrical properties changed. A majority of the ZTO thin films changed to a crystal structure, but ZTO annealed at 150℃ exhibited an amorphous structure (Fig. 1(a)). With increasing temperature, the XRD peak intensity increased: The highest XRD peak intensity was observed for ZTO annealed at 250℃. From PL analysis, the optical properties were similar after the annealing of ZTO (Fig. 1(b)). Figure 1(c) shows the current–voltage characteristics. In particular, the ZTO current increased after annealing the material at 250℃. Figure 1(d) shows the current–voltage characteristics in the range of -1×10^{-8} A < I < 1×10^{-8} A to understand the contact properties between ZTO and ITO thin films. The lowest current was observed for ZTO annealed at 150℃. Hence, the interface effect of ZTO with an amorphous structure induces the decrease in current.

Figure 2 shows the electrical–physical properties with dependence on the annealing temperature of ZTO deposited under oxygen. Figure 2(a) shows the XRD pattern of ZTO films annealed at different temperatures and deposited under oxygen. ZTO films annealed at 150℃ and 250℃ exhibited amorphous structures. The amorphous structure of the ZTO films annealed at 150℃ was the same as that shown in Fig. 1(a). In the PL spectra shown in Fig. 2(b), the ZTO film annealed at 100℃ was different from the other ZTO films, which exhibited similar PL patterns. Figure 2(c) and 2(d) shows the electrical properties of ZTO at different annealing temperatures. The lowest current was observed for the ZTO film annealed at 150℃. The current decrease for ZTO with an amorphous structure is in agreement with that observed in Fig. 1.

The current decrease is related to the different current properties between the amorphous and crystal structures. Depending on the contact properties at the interface, two currents, i.e., drift current on the Ohmic contact and the diffusion current on the Schottky contact, respectively, are observed in the conduction mechanism of the semiconductor,. At different annealing temperatures, the ZTO bonding structure changed, and the bonding structure changed the interfacial contact properties. The Ohmic conduction mechanism in the crystal structure leads to the drift current, while the Schottky conduction mechanism in the amorphous structure leads to the diffusion current. The Schottky contact is based on the diffusion current at the potential difference of potential barrier. The diffusion current corresponds to the current in the amorphous structure, similar to the depletion layer. The diffusion current is less than the drift current; several differences exist between the drift and diffusion currents. The crystallinity of ZTO was changed by annealing, and an amorphous structure was obtained for ZTO annealed at 150℃. By these results, the bonding structure of ZTO thin films is closely related to the electrical properties, but the correlation between the optical properties and electrical properties is weak.

Figure 3 shows the current–voltage characteristics of the ZTO thin films annealed at 150℃. The ZTO were deposited with O_2=18 sccm and Ar=18 sccm, respectively. ZTO annealed at 150℃ exhibited the lowest current because of the Schottky barrier at the depletion region formed between ITO and ZTO. The depletion layer was extended as a result of the electron–hole recombination effect at the interface. The interfacial properties of the ZTO thin films originated from

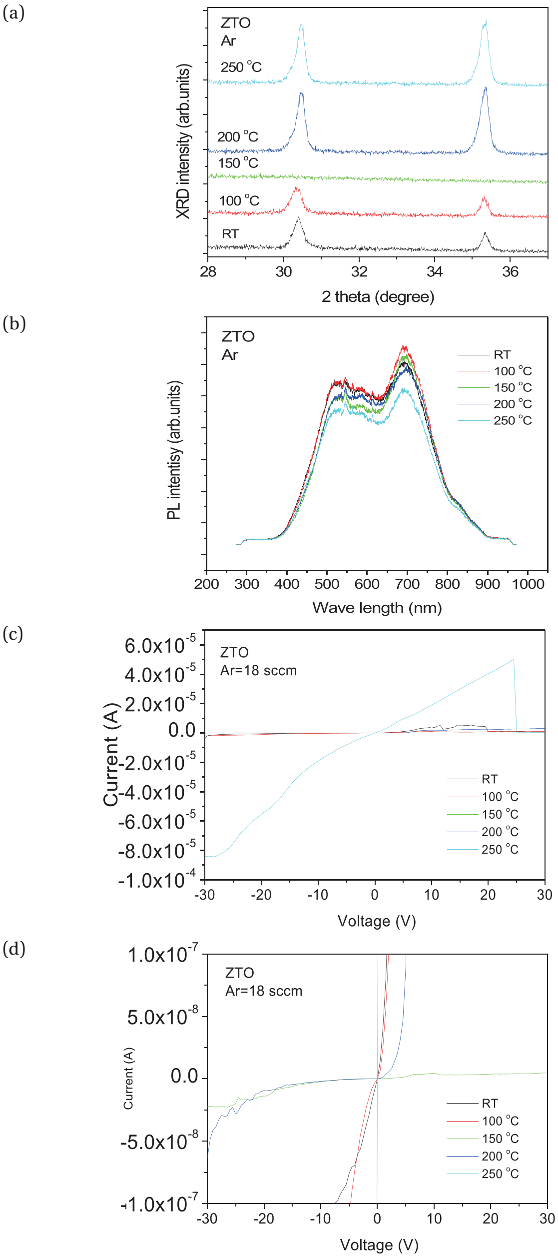

Fig. 1. Characteristics of the ZTO thin films deposited under Ar. (a) XRD patterns, (b) PL spectra, (c) drift current in the high range of -6×10^{-5} A < I < 6×10^{-5} A, and (d) diffusion current in a lower range of -1×10^{-8} A < I < 1×10^{-8} A.

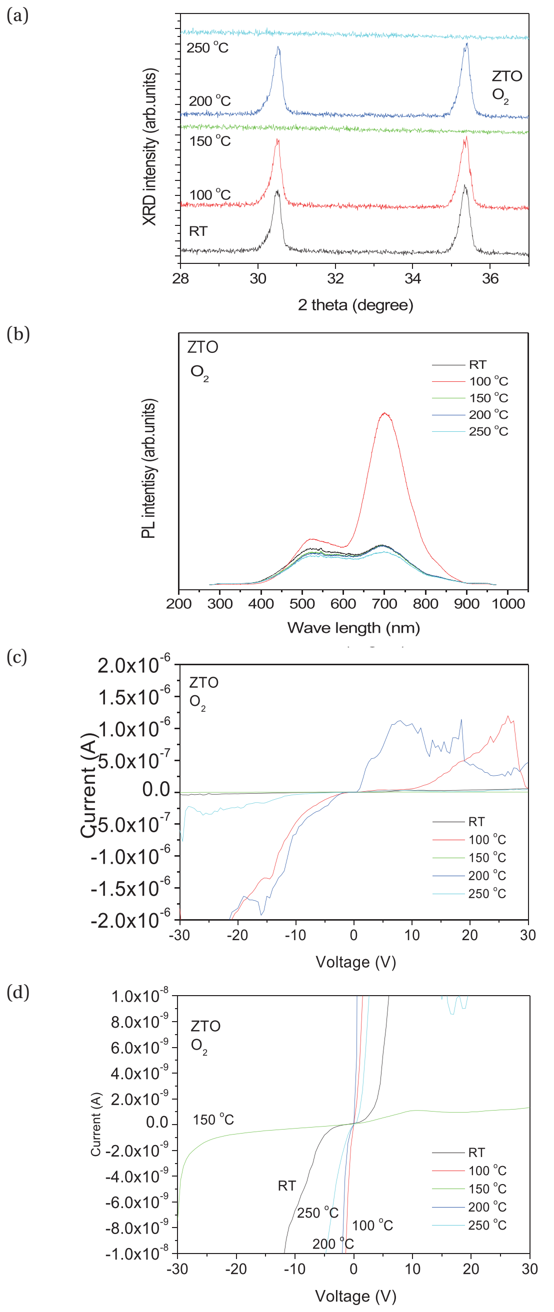

Fig. 2. Characteristics of ZTO thin films prepared by O_2. (a) XRD pattern, (b) PL spectra, (c) drift current in the high range of -2×10^{-6} A < I < 2×10^{-6} A, and (d) diffusion current in the lower range of -1×10^{-8} A < I < 1×10^{-8} A.

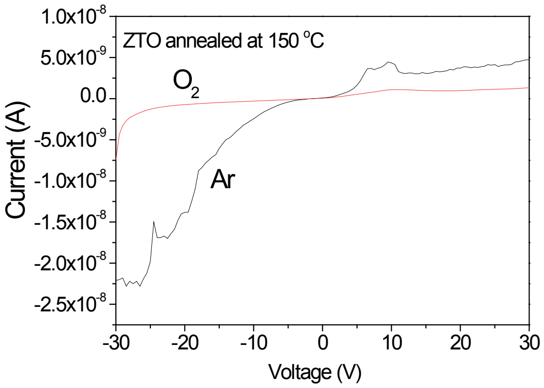

Fig. 3. Current–voltage characteristics of ZTO thin films annealed at 150℃.

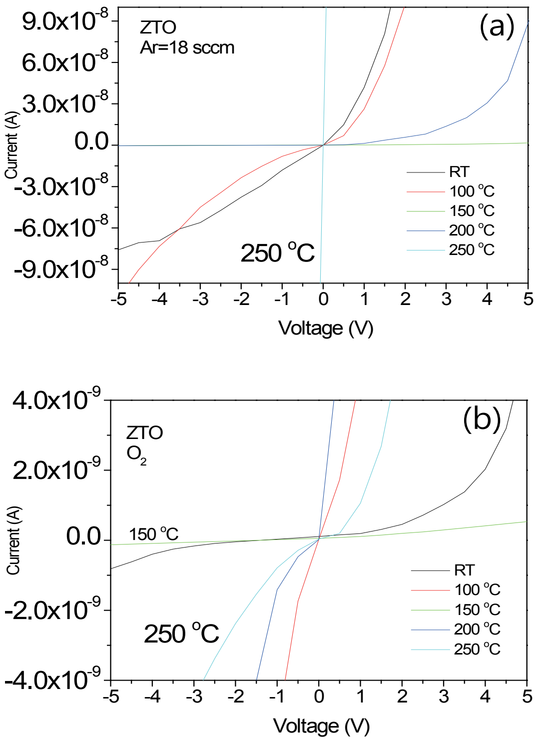

Fig. 4. Comparison the electrical characteristics with the contact properties. (a) ZTO by Ar and (b) ZTO by O_2.

the depletion layer of the Schottky contact. Hence, the Schottky contact exhibits the cut-off effect of leakage currents. The leakage currents originate from the majority carrier owing to the heating effect by the movement and collision effects between the majority carriers. The extension of the depletion layer due to the electron–hole recombination effect interrupted the flow of charge carriers and cut-off the leakage current, thereby improving the transistor performance.

Figure 4 shows the comparison of the electrical characteristics between ZTO deposited by Ar and O_2 to investigate the contact properties. From the I–V curves of ZTO annealed at 250℃, the contact properties exhibited different figures. ZTO deposited under Ar exhibited an Ohmic contact compared to ZTO deposited by oxygen, which exhibited a Schottky contact. These results are in agreement with the XRD patterns shown in Fig. 1. ZTO deposited under Ar by annealing at 250℃ changed into a crystal structure, but that deposited under O_2 by annealing at 250℃ exhibited an amorphous structure. The effect of the electron–hole combination leads to the change from the depletion layer to a Schottky barrier (SB). The physical properties of the depletion layer are similar to those of an amorphous structure. Hence, ZTO deposited under O_2 by annealing at 250℃ changes into an amorphous structure with a Schottky barrier. Similar results were observed for the optical–electrical characteristics of ZTO. ZTO deposited with Ar by annealing at 100 °C exhibited the Ohmic contact without a SB (Fig. 4(a)) and ZTO deposited with O_2 by annealing at 100℃ exhibited the Ohmic contact without a SB (Fig. 4(b)). This result indicates that it is hard to define the Ohmic and Schottky contact by the depletion effect. The strong Ohmic contact shown in Fig. 4(b) was observed for ZTO deposited with oxygen gas flows by annealing at 100℃: The PL spectral intensity of this sample increased with dependence on the crystal structure (Fig. 2(b)). By the comparison of the energy gap, the crystal structure gap was less than the amorphous structure gap as the depletion region. The PL spectra of ZTO deposited under O_2 by annealing at 100℃ comprised the low left and high right peaks. The high right peak in the PL spectra denotes the low energy gap. Hence, ZTO deposited under O_2 by annealing at 100℃ with a low energy gap exhibits a higher probability of being a crystal structure compared to ZTO deposited under Ar by annealing at 100℃ with a low energy gap does. Finally, from Figs. 2(a) and 2(d), the highest crystallinity was observed for ZTO deposited under O_2 by annealing at 100℃ as the Ohmic contact, and the highest amorphous structure was obtained for ZTO deposited under O_2 by annealing at 150℃ as the Schottky barrier.

4. CONCLUSIONS

The bonding structures of the ZTO film were changed by annealing. The Schottky contact was observed for ZTO with an amorphous structure annealed at 150℃, related to the electron-hole combination effect and Schottky barrier (SB) at the interface between different materials. The conduction mechanism in the depletion layer was based on the diffusion current in the presence of a gradient between different charges; therefore, the diffusion current depending on the potential difference at the Schottky barrier is in a direction opposite to the drift current. The energy gap of ZTO with an amorphous structure was greater than that with a crystal structure. Hence, the Schottky barrier is the cutoff effect of the leakage current and improves the performance of semiconductor devices.

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