High performance thin film transistor with ZnO channel layer deposited by DC magnetron sputtering

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Abstract

We studied ZnO thin films deposited with DC magnetron sputtering for channel layer of TFTs. After analyzing of the basic physical and chemical properties of ZnO thin films, we fabricated a TFT-unit test cell. The field effect mobility of 1.8 cm^2/Vs and threshold voltage of -0.7 V were obtained.

1. Introduction

Nowadays, interest in large area display electronics is emerging rapidly. In particular, high mobility in channel layer of thin film transistors (TFTs) is a key point for high performance of large area display devices. The elements of TFTs including a channel semiconductor should be fabricated at low temperatures for efficient process time and application for flexible displays. Recently ZnO-based TFTs have been reported, attracting much attention because of their potential to replace a-Si which has been widely used as a channel layer in conventional TFTs. ZnO films with its large band gap of 3.37 eV can also be employed to fabricate transparent TFTs. It is expected that the field effective mobility and on current/off current of ZnO-based TFTs would be similar to or higher than that of a-Si based TFTs if proper process conditions were found.

Other techniques of depositing ZnO have been explored in TFTs and Transparent TFTs[6-7]. Recently ZnO based TFTs with peak incremental mobilities as high as ~25 cm^2/Vs have been reported[6]. Also, a TTFT was fabricated utilizing zinc oxide by pulsed laser deposition (PLD)[8]. PLD deposited zinc oxide yielded TFTs with peak incremental mobilities of ~1 cm^2/Vs. In general, ZnO thin films for the channel layer of TFTs are deposited by RF magnetron sputtering methods. On the other hand, we studied ZnO thin films deposited with DC magnetron sputtering using ZnO ceramics target for the channel layer of TFTs.

In this paper, we include the structural, electrical, and chemi-physical properties of intrinsic ZnO thin films deposited by DC magnetron sputtering. And then, we explain how we did that in order to use ZnO thin films as an active channel layer of TFT. Finally, we describe the construction and characteristics of bottom-gate-type TFT.

2. Experimental

Intrinsic ZnO thin films were prepared on SiO_2/p-Si substrate using DC magnetron sputtering. The target used in this study was sintered stoichometric ZnO (99.999 %, purity) ceramic. The SiO_2/p-Si substrates were ultrasonically cleaned in acetone and methanol and rinsed in deionized water for 10 minutes each. The sputtering was performed in an argon atmosphere with oxygen partial pressure ranging from 0 % to 40 %. The substrate temperature was about 100 ℃ and plasma discharge power density was 0.5 W/cm^2.

The structural, electrical, and chemi-physical properties of intrinsic ZnO thin films were characterized with various analysis tools. A high-resolution X-ray diffractometer (HR-XRD, Bruker Discover) was used to investigate the crystallinity and crystal orientation. The surface roughness and morphology were examined by atomic force microscopy (AFM, Seiko Instrument, SPA-400) and field emission scanning electron microscopy (FESEM, Hitachi, S-48000). The electrical properties of films including carrier concentration, carrier mobility, and resistivity were measured by Hall Effect system (Ecopia, HMS-3000). The chemical binding structures in the films were investigated by X-ray photoemission spectroscopy (XPS, SIGMA PROBE, ThermoVG) and the elemental composition in the films were investigated by Rutherford back scattering (RBS, NEC 53DH-2).

After the analysis of structural, electrical, and chemi-physical properties of ZnO thin films, we fabricated a TFT cell with a ZnO channel layer. The entire device was fabricated on a heavily doped p-type silicon substrate with thermal silicon dioxide as the gate insulator. Intrinsic ZnO thin film as the active channel layer was fabricated by DC magnetron sputtering and Al or indium tin oxide (ITO) thin films were used for the source and drain electrodes. For I-V measurements on the TFT, large ohmic contacts for gate electrodes were made on the back side of the p-Si by applying sliver (Ag) paste. All electrical characterizations were carried out with a semiconductor parameter analyzer (HP 4155, Agilent Technologies) at room temperature.

3. Results and discussion

3.1 Structural properties

From the result of XRD analysis, the intrinsic ZnO thin films were highly oriented to (002) directions independent of oxygen partial pressures. We could define that the diffraction peak intensities of ZnO thin films increase as the oxygen partial pressures increases. Fig. 1 shows the surface images and roughness of ZnO thin films deposited with various oxygen partial pressures. As it can be seen from Fig. 1, when the oxygen partial pressure was 15 % (O_2 / $Ar+O_2$), the surface morphology was more smooth than other ZnO films deposited at different conditions of oxygen partial pressures. The reason may be that the proper oxygen pressure enhanced the crystallinity of ZnO thin films. In other words, additional oxygen gas decreased the defects in ZnO thin films such as oxygen vacancies.

3.2 Electrical properties

The electrical properties of ZnO thin films were obtained using Hall Effect measurement at 77 K. From Fig. 2, it can be seen that the resistivity and carrier concentration slightly decreases with increasing oxygen partial pressures. These results are generally considered as decreasing oxygen partial pressure allows oxygen vacancies to act like donors. For above reasons, the conductivity of ZnO thin films was diminished and resistivities of ZnO thin films were so high (about ~10^5 Ω-cm). Consequently, with enough oxygen gas injected, the deposited ZnO thin films became like an insulator.

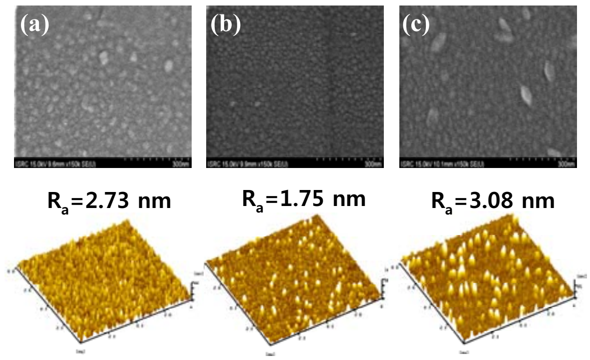

Fig. 1. Surface morphology and roughness of ZnO thin films deposited with various oxygen partial pressures ; (a) 0 % (b) 15 % (c) 40 %

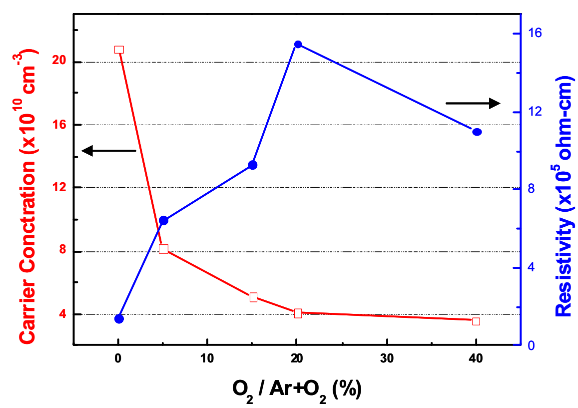

Fig. 2. Carrier concentration (n_e) and resistivity (ρ) of ZnO thin films deposited with various oxygen pressures ranged from 0 % to 40 %

3.3 Chemi-physical properties

The chemical binding states of zinc and oxygen in ZnO thin films have been investigated using XPS analysis. The intensities of the photoemission are indicated for binding energies of oxygen 1s in Fig. 3. The O_I peak is assignable to the related peak with oxygen vacancies in ZnO_{1-x} matrix. On the other hand, O_{II} peak means the stochiometric oxygen within the ZnO matrix[9]. From Fig. 4, it can be seen that atomic percentage related to the stoichiometric oxygen at 15 % was the highest value compared with other conditions of oxygen partial pressure. So, the ZnO thin film deposited at oxygen partial pressure of 15 % has a higher probability of having a nearly stoichiometric chemical binding state. There is some relation between electrical properties and XPS results.

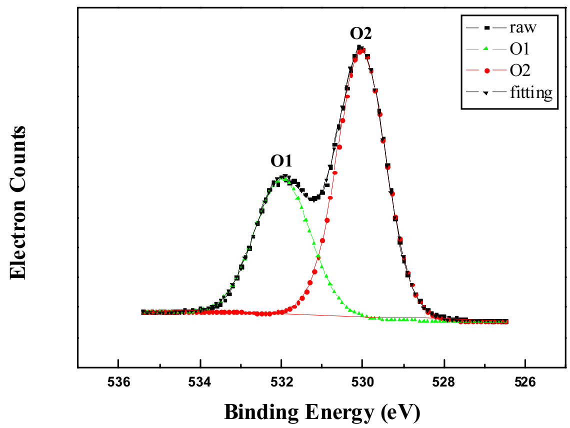

Fig. 3. O1s spectrum on the surface of ZnO thin film deposited at oxygen partial pressure 0 %. ; O_I and O_{II} peaks denote that oxygen vacancy within ZnO_{1-x} matrix and stoichiometric oxygen within ZnO matrix, respectively.

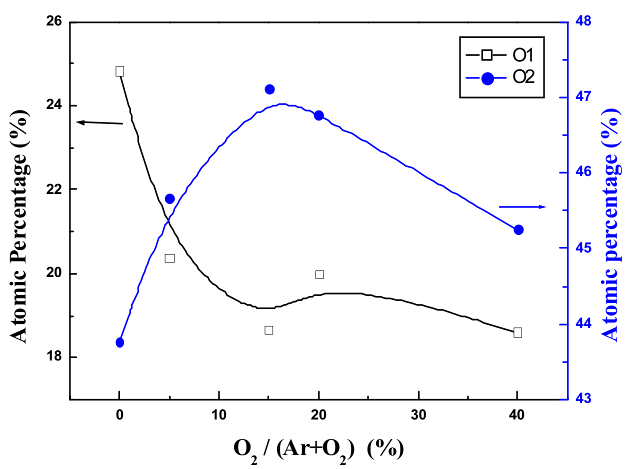

Fig. 4. Variations of O_I and O_{II} peaks in oxygen O1s of ZnO thin films with various oxygen partial pressures

The elemental composition of ZnO thin films were analyzed by RBS. The composition ratio of zinc and oxygen in films are listed in table 1. It can be suggested that three O_2 / Ar+O_2 ratio regions, namely, 0-10 % (region I : oxygen deficient region), 15-20% (region II : nearly stoichiometric region), and 20~40 % (region III : excessive oxygen region) exist. As the oxygen partial pressure is increased up to 10 % in region I, ZnO thin films are formed as oxygen deficient non-stoichiometric states because of the natural properties of ZnO. However, ZnO thin films were deposited with nearly stoichiometric states due to decreasing oxygen vacancies in films at up to 15 %. In region III, we thought to be a non-stoichiometric as oxygen excessive state, based on the fact that ZnO thin films deposited in a more oxygen atmosphere than it was needed. From these facts we can conclude that ZnO thin film deposited at oxygen partial pressure 15 % is a good alternative material for the active channel layer.

Table 1. Elemental composition ratio of zinc and oxygen atoms in ZnO thin films deposited with various oxygen partial pressures by RBS analysis

Oxygen partial pressure (O_2 / Ar+O_2)	Composition Ratio Zn	Composition Ratio O
0 %	1.00	0.96
15 %	1.00	1.00
40 %	1.00	1.01

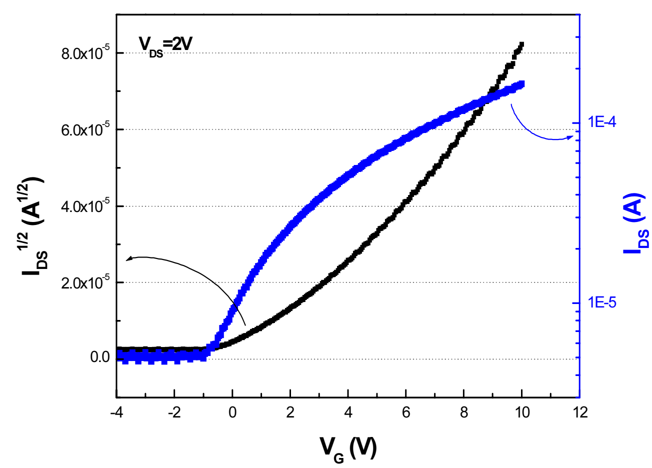

Fig. 5. Typical ZnO-based TFT transfer characteristics with the channel layer deposited by DC magnetron sputtering

3.4 ZnO-based TFTs fabrications

Next, we fabricated TFTs device which has a bottom gate structure with ZnO thin films as active channel layer. Fig. 5 exhibits the plots of the square root of I_D vs. the gate voltage, $\sqrt{I_D} - V_G$ and $\ln I_D - V_G$, respectively, obtained from TFTs fabricated with the ZnO channel layer deposited at oxygen partial pressure 15 %. The field effective mobility was calculated by taking the slopes of $\sqrt{I_D} - V_G$ curves in Fig. 5 based on the mobility-estimation equation in the I_D-saturation regime where we used a fixed V_{DS}=2 V. The field effect mobility (μ_{sat}) of 1.8 cm^2/Vs and threshold voltage (V_{th}) of -0.7 V were obtained. Our

TFTs operates as an n-channel depletion mode device since a negative gate voltage is required to induce a channel and channel conductivity increase with increasing negative gate voltage bias.

4. Summary

From the experimental results the following conclusions can be drawn:

ZnO thin films deposited by DC magnetron sputtering were highly oriented in (002) directions, independent of oxygen partial pressures. When a film was deposited at oxygen partial 15 %, it had more smooth surface morphology and lower RMS roughness than other films. ZnO thin films deposited at oxygen partial 15 % has the higher probability of having a nearly stoichiometric chemical binding state. There is some relation between XPS and RBS analysis results. TFTs fabricated with ZnO thin films as active channel layer operates as an n-channel depletion mode. And our TFTs device was obtained the $_{sat}$ of 1.8 cm^2/Vs and V_{th} of -0.7 V. Although our TFTs device has a lower field effective mobility than other reported ZnO-based TFTs, it is a work worthy of close attention because our ZnO thin films as active channel layer were deposited by DC magnetron sputtering method using ZnO ceramic target. However, there remains some uncertainty as to the above conclusion.

5. References

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