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Analysis of Hump Characteristics in Thin-Film Transistors with ZnO Channels Deposited by Sputtering at Various Oxygen Partial Pressures.

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***Abstract*— Electrical properties of thin-film transistors with ZnO channels which was deposited by rf magnetron sputtering at various oxygen partial pressures [*p(O₂)*] were investigated. Negative shift of turn-on voltage with "hump" was observed, and donor-like traps were generated at intermediate energy levels from conduction band when the ZnO channel was deposited at the *p(O₂)* below a critical pressure. Thermal desorption spectroscopy study revealed that the donor-like traps were generated when the ZnO film changed from O-rich to Zn-rich condition. The Zn related native defects would be possible origin of the donor-like traps generated intermediate energy levels in the ZnO TFTs.**

***Index Terms*—Zinc oxide, Thin film transistors, Trap density, Sputtering, Hump characteristics, Intrinsic defects, Thermal Desorption Spectroscopy**

I. INTRODUCTION

Recently, high mobility thin-film transistors (TFTs) applying for large-area electronic device have received considerable attention for next generation flat panel displays. Significant progress has been made in oxide TFTs during last few years.[1-13] It has been verified that the ZnO TFTs has a higher mobility than amorphous silicon TFTs.[8-11]

Up to now, several deposition methods have been used for preparing oxide semiconductor channels for TFTs, such as pulsed laser deposition[1,2,6] atomic layer deposition[10,11], and direct current (dc) or radio frequency (rf) sputtering.[4,5,7-9] Among those methods, the sputtering is one promising method for depositing oxide semiconductors over a large-area substrate at low temperature.

In intrinsic oxide semiconductors, electrical resistivity of the films strongly depend on partial pressure of oxygen [*p(O₂)*] during the sputtering.[4,7] For sputtered ZnO films, an abrupt transition from semiconductor to insulator occurred as the *p(O₂)* exceeds a critical pressure.[4] Hence, it is necessary to choose appropriate *p(O₂)* for ZnO TFT in order to obtain superior switching properties such as low leakage current and high on/off current ratio.

In this letter, the effects of the *p(O₂)* in ZnO sputtering on the electrical properties and the trap density of the ZnO TFTs were investigated.

II. EXPERIMENTAL PROCEDURE

Bottom-gate TFTs with the ZnO channels which were deposited by rf magnetron sputtering at various *p(O₂)* were fabricated on a glass substrate. Figure 1 shows a schematic cross section of the ZnO TFTs. There was a 200-nm-thick SiNx passivation layer on the TFT.

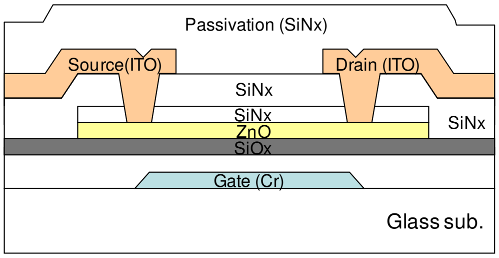

Fig. 1 Schematic cross section view of the ZnO TFT.

A SiOx/SiNx (50/100 nm) stacked gate insulator was deposited on a chromium (Cr) gate electrode at 350 °C by conventional plasma-enhanced chemical vapor deposition (PECVD). Then, a 40-nm-thick ZnO film served for active channel was deposited at 150 °C with a mixture gas of O_2 and Ar as working gas by rf magnetron sputtering. Deposition pressure was maintained at 1.0 Pa, and the *p(O₂)* was varied from 0.17 to 0.75 Pa by controlling O_2/Ar flow rate ratio (Ar= 10 sccm). The rf power density applying for ZnO target was set at 2.3 W/cm^2. From X-ray diffraction (XRD) analysis, all ZnO films deposited on glass substrates showed polycrystalline form with a preferred orientation of (002) c-axis perpendicular to the substrate.[14] Detailed fabrication process of the ZnO TFT was reported previously.[9,13]

Channel width (W) and length (L) of the ZnO TFTs were 50 and 20 μm, respectively. Before electrical measurements, the ZnO TFTs were annealed in N_2 ambient for 3 hours. The annealing temperature was adjusted for different ZnO TFTs (330, 360, and 375 °C for the *p(O₂)* of 0.17, 0.33, and 0.5~0.75 Pa) in order to obtain appropriate on-current of the TFTs. Transfer characteristics were measured by a semiconductor parameter analyzer at a drain voltage (Vds) of 0.1 V.

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III. RESULTS AND DISCUSSION

Figure 2(a) shows the transfer characteristics of the TFTs with the ZnO channels deposited at various $p(O_2)$. As shown in Fig. 2(a), the on-current of all TFTs was almost unchanged, indicating that the field effect mobility of all TFTs was almost the same. The transfer characteristics of the ZnO TFTs were little changed when $p(O_2)$ varied in the range of 0.50-0.75 Pa; however, a negative shift of the turn-on voltage (V_{on}) with the "hump" was observed from the TFTs with the ZnO channels deposited at the $p(O_2)$ of 0.33 and 0.17 Pa. In this study, V_{on} was defined as the gate voltage (Vgs) at when a drain current increased to 0.1 pA. The V_{on} was around -1 V in the $p(O_2)$ of 0.50~0.75 Pa; however, it shifted to -2.8 and -5.4 V when the $p(O_2)$ decreased to 0.33 and 0.17 Pa, respectively.

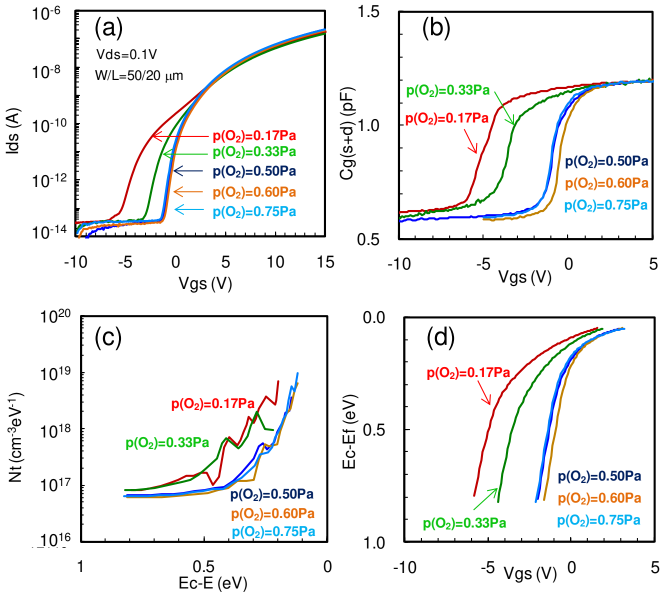

Fig. 2 (a)Transfer characteristics, (b) low-frequency (1 Hz) C-V characteristics, and (c) energy distribution of traps of the TFTs with the ZnO channels deposited at various $p(O_2)$. (d) Fermi level (E_F) at a channel/gate insulator surface as a function of a gate voltage (Vgs).

In order to investigate the origin of the negative V_{on} shifts with the "hump" characteristics, energy distributions of the traps were extracted directly from the TFTs using low-frequency (1 Hz) capacitance-to-voltage (CV) measurements as shown in Fig. 2(b). Extraction method of the traps was as follows; firstly, the surface potential was determined from the CV measurements. Secondly, the potential profile in the entire channel layer was calculated by applying Poisson's equation and assuming trap densities. Finally, the trap densities were extracted by the fitting of the calculated potential profile to the measured surface potential. [15]

Figure 2(c) shows the trap densities of the ZnO TFTs with various $p(O_2)$ as a function of energy from conduction band (E_C-E). In the $p(O_2)$ of 0.50-0.75 Pa, the energy distribution of traps was almost unchanged. However, the densities of traps were found to increase when the ZnO channels were deposited at the $p(O_2)$ of 0.33 and 0.17 Pa.

The effects of acceptor-like and donor-like traps on electrical properties of amorphous InGaZnO TFT which has a similar band-gap of the ZnO were numerically analyzed using two-dimensional (2D) device simulation. [16,17] Considering the acceptor-like traps, the tail states affect subthreshold swing (S) and on-current without the V_{on} shift, and the deep states have the effect of the V_{on} shift (positive V_{on} shift with increasing the deep trap density) without degradation of the S value and the on-current.[16] Thus it would be difficult to reproduce the negative V_{on} shift with the "hump" by adjusting the density and energy distribution of the acceptor-like traps. By contrast, 2D device simulation result indicated that similar negative V_{on} shift with the "hump" was occurred when the donor-like traps existed at the intermediate energy level (0.5 eV) from E_C.[17] It was also reported that shallow donor-trap existed at 0.1 eV from E_C induced the negative transfer curves shift without degradation of the S valus, while the deep donor-trap existed at 1.0 eV from E_C didn't affect the TFT performance.

Figure 2(d) shows the relationship between the (E_C- E_F) at a channel/gate insulator surface and the Vgs. The (E_C-E_F) of the TFTs at the Vgs=V_{on} changed from 0.42~0.48 eV ($p(O_2)$= 0.50~0.75 Pa) to 0.64 eV ($p(O_2)$=0.17 Pa).

Transfer characteristics were determined by the relative position of the E_F at Vgs=V_{on} and the energy levels of the traps. Considering the donor-like traps, the traps existed below the E_F at V_{on} didn't affect the TFT performance because the traps were neutralized. In contrast, when the traps existed above the E_F at V_{on}, the traps influenced the subthreshold swing because the E_F moved below to above the energy levels of the traps. When the E_F further moved toward the Ec, the donor-like traps existed below the E_F were neutralized, resulting at the transfer curves in the positive Vgs region almost unchanged as shown in Fig. 2(a). Hence the distribution of increased donor-like traps existed above the E_F at the V_{on} played an important role in determining the V_{on} and the hump of the ZnO TFT.

In order to investigate the origin of the donor-like traps formed at low $p(O_2)$, thermal desorption spectroscopy (TDS) measurement was carried out for the ZnO films deposited at the $p(O_2)$ of 0.33, 0.60, and 0.75 Pa.

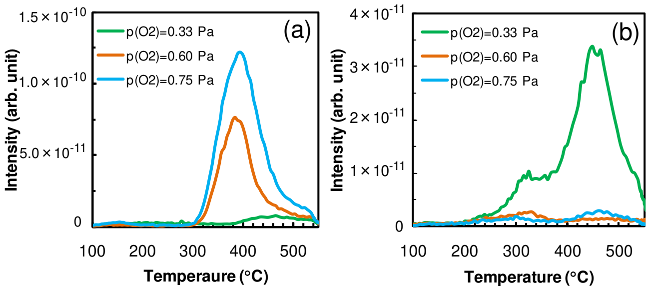

Fig. 4 TDS spectra of (a) O_2^+ (m/z of 32) and (b) Zn^+ (m/z of 64) from the ZnO films deposited at the $p(O_2)$ of 0.33, 0.60, and 0.75 Pa.

Figure 4 shows TDS spectra of the mass fragments (m/z) of (a) 32 and (b) 64 from the ZnO films deposited at the $p(O_2)$ of 0.33, 0.60, and 0.75 Pa. The m/z of 32 and 64 correspond to the O_2^+ and Zn^+ desorption from the ZnO films, respectively.

As shown in Fig. 4(a), a rapid increase of O_2^+ was observed from the films deposited at the $p(O_2)$ of 0.60 and 0.75 Pa when the temperature exceeded 300 °C; however, it disappeared rapidly from the film deposited at the $p(O_2)$ of 0.33 Pa. In contrast, Zn desorption was only observed from the film deposited at the $p(O_2)$ of 0.33 Pa as shown in Fig. 4(b).

It was found that desorption elements from the ZnO films drastically changed from the $p(O_2)$ of 0.60 to 0.33 Pa. This result indicated that the ZnO films were changed from O-rich to Zn-rich condition when the $p(O_2)$ decreased from 0.60 to 0.33 Pa. With the ZnO films changing from O-rich to Zn-rich condition, the ZnO TFTs showed negative V_{on} shift with the "hump" due to the increase of free carriers contributed from ionization of the donor-like traps existed at intermediate energy levels from the E_C.

According to the computational studies of the formation energies of native point defects in ZnO, oxygen vacancy (V_O) and zinc vacancy (V_{Zn}) are abundant defects in O-rich n-type ZnO.[18,19] When the film changed from O-rich to Zn-rich, the formation energies of donor type defects of zinc interstitial (Zn_i^{2+}) and zinc antisite (Zn_O^{2+}) decreased, whereas that of acceptor type defect of V_{Zn}^{2-} increased. Although the V_O has the lowest formation energy among the donor-type defects in n-type Zn-rich ZnO, the charge state of the V_O^0 is more preferable than that of the V_O^{2+}.[19]

According to the analysis of the ZnO TFT characteristics, generated traps were donor-like traps. However, the reported donor level of the V_O is deeper than the mid-gap[19,20], whereas that of the Zn_i^+ is ~0.5 eV from the E_C.[20] Hence, zinc related native defects such as the Zn_i^{2+} and/or Zn_O^{2+} would be a possible origin of the donor-like traps existed at intermediate energy levels from the E_C in the ZnO TFTs when the ZnO channel was deposited at the $p(O_2)$ below a critical pressure.

IV. CONCLUSION

Electrical properties of the TFTs with the ZnO channels deposited by rf magnetron sputtering at various $p(O_2)$ were investigated. Negative shift of the V_{on} with the "hump" was observed from the TFTs when the ZnO channel was deposited at the $p(O_2)$ below a critical pressure. The energy distribution of traps in the ZnO TFTs revealed that the origin of the negative V_{on} shift with the "hump" of the ZnO TFTs was the donor-like traps existed at intermediate energy levels from the E_C. These donor-like traps were generated when the ZnO film was changed from O-rich to Zn-rich condition by changing the $p(O_2)$ during the ZnO sputtering. The Zn related native defects would be a possible origin of the donor-like traps existed at intermediate energy levels in the ZnO TFTs when the ZnO channels were deposited at pressures below the critical $p(O_2)$.

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