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Hysteresis-Free Like, High Mobility p-Channel Tin Monoxide Thin-Film Transistor

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ABSTRACT

We demonstrate high mobility p-channel tin monoxide (SnO) thin-film transistors with hysteresis free-like behavior. Intermediate alumina encapsulation in the middle of two postdeposition annealing processes significantly facilitates crystal growth, enabling considerable intertwining between crystals. Here, we report a simple method crystallizing the SnO thin-film.

1 Introduction

Since the invention of amorphous indium gallium zinc oxide (a-IGZO) in 2004, amorphous oxide semiconductor (AOS) family, such as IGZO, indium gallium oxide (IGO), and indium gallium tin oxide (IGTO) *etc.*, has been studied due to their fascinating characteristics such as high mobility (μ_{FE}), extremely low off-current, and great uniformity *etc.* [1,2] Benefiting from these properties, organic light-emitting diodes (OLED) display backplanes which consist of AOS thin-film transistors (TFTs) were practically demonstrated. However, the energetic bombardment which occurs during deposition of indium tin oxide (ITO) thin-film on an organic hole injection layer deteriorates electrical characteristics of inverted OLED stacks. In this respect, it could be a breakthrough to develop high-performance p-type oxide semiconductors. However, valence band (*VB*) maximum is strongly localized by oxygen 2p orbitals in the oxide system, which hinders the development of high-performance p-type oxide semiconductors to date.

Tin monoxide (SnO) is one of a few p-type oxide semiconductor candidates. [3] It draws significant attention due to its several characteristics such as moderate μ_{FE} and large optical bandgap. For this reason, it has been considerably studied to improve its electrical characteristics with various approaches. [3-5] Nonetheless, μ_{FE} of p-channel SnO TFTs still stays at the level of a few cm^2/Vs, which indicates a necessity to increase the μ_{FE}. Large hysteresis is also a severe hindrance and its origin in the p-channel SnO TFTs, which should be investigated for its potential applications.

In this study, we report an effect of intermediate encapsulation on p-channel SnO TFTs. Of particular interest is our finding that the encapsulation in the middle of two postdeposition annealing (PDA) prevents a complete oxidation and expedites a significant growth of crystals in the corresponding SnO thin-films. Benefiting from this improved crystallization, the resultant TFTs exhibit high mobility, hysteresis free-like behavior with maximum μ_{FE} of 15.8 cm^2/Vs and hysteresis of 0.1 V *etc.*

2 Experiment

Aluminum oxide (Al_2O_3)/hafnium zirconium oxide (HZO) gate dielectric stack was deposited using plasma-enhanced atomic layer deposition (PEALD) process. Then, 20-nm-thick p-type SnO thin-film was deposited on the gate dielectric stack using reactive sputtering. The thin-films were subjected to first PDA (PDA-1) at 100 or 250 °C for 1 hour. Subsequently, ITO thin-films were deposited for source/drain (S/D) electrodes using the sputtering. Note that the patterning was defined using metal shadow masks, and width/length of the patterned channel were 500/100 μm. Furthermore, Al_2O_3 encapsulation layer was deposited on top of the channel layer using the PEALD, followed by second PDA (PDA-2) at 250 °C for 1 hour. Figure 1 shows a schematic of p-channel SnO TFTs and its fabrication procedure.

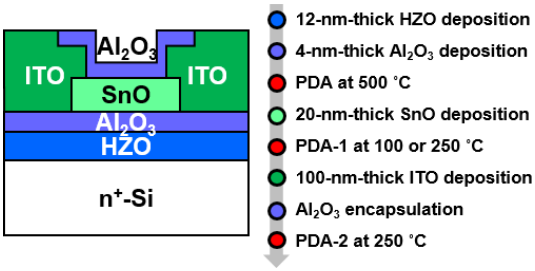

Figure 1. A schematic of p-channel SnO TFT and its fabrication procedure.

3 Results

Crystalline structure of SnO thin-films fabricated through different fabrication procedures were investigated through grazing incidence X-ray diffraction (GIXRD) as shown in Figure 2a. SnO thin-films with PDA-1 at 100 °C show tetragonal Sn phase (JCPDS card No. 04-0673), which could come from the low PDA temperature not enough to effectively oxidize the thin-film. With the temperature of PDA-1 increasing up to 250 °C, the crystalline structure is completely changed to tetragonal SnO phase (JCPDS card No. 06-0395). However, Al_2O_3 encapsulation effectively prevents the complete oxidation of SnO thin-films even after PDA-2 at 250 °C, which leads to the formation of a mixed structure of tetragonal Sn and SnO phases in the encapsulated thin-films with PDA-1 and PDA-2 at 100 and 250 °C, respectively. Note that SnO thin-films with PDA-1 at 250 °C have tetragonal SnO phase regardless of the intermediate encapsulation.

High-resolution transmission electron microscopy (HRTEM) was also conduced to investigate nanoscale differences in the crystalline structure of SnO thin-films (Figure 2b-d). As a result, the encapsulated SnO thin-film with PDA-1 and PDA-2 at 100 and 250 °C, respectively, has the improved surface roughness and crystallinity compared to the other SnO thin-films. Notably, the size of each crystal is significantly enlarged in the corresponding postdeposition condition.

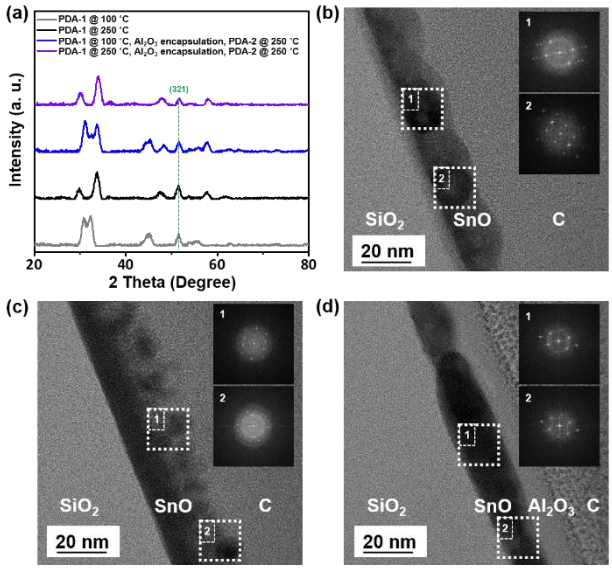

Figure 2. (a) GIXRD patterns of SnO thin-films. (b-d) HRTEM images of SnO thin-films: (b) PDA-1 at 100 °C; (c) PDA-1 at 250 °C; (d) PDA-2 at 250 °C after PDA-1 at 100 °C and subsequent encapsulation.

Then, electrical characteristics of SnO TFTs were examined (Figure 3). SnO TFT with PDA-1 at 100 °C shows the metallic behavior without switching capability. As the temperature of PDA-1 increases to 250 °C, it is changed to semiconducting characteristics with device performances including a current modulation ratio ($I_{ON/OFF}$) of 8.1 × 10^1 and a μ_{FE} of 1.7 cm^2/Vs *etc*. Surprisingly, the encapsulation considerably improves the device performances of TFT with PDA-1 and PDA-2 at 100 and 250 °C, where an $I_{ON/OFF}$ of 3.4 × 10^3, a subthreshold swing (*SS*) of 0.6 V/dec, a record-breaking μ_{FE} of 14.6 cm^2/Vs and a negligible hysteresis of 0.1 V *etc*. are revealed. This significant enhancement can be attributed to the considerable improvement in the crystal quality. Meanwhile, encapsulated SnO TFT with both PDA-1 and PDA-2 at 250 °C exhibits the conventional device performances with a μ_{FE} of 1.8 cm^2/Vs and a negligible hysteresis of 1.0 V *etc*. Given that the best hysteresis is obtained in the thin-film with the best surface property and crystal quality, bulk defects in SnO thin-films can be a possible origin of the hysteresis.

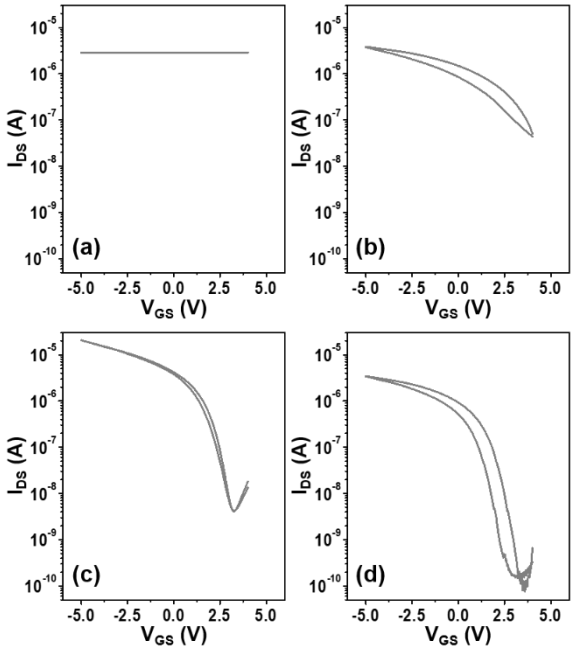

Figure 3. Transfer characteristics of SnO TFTs: (a) PDA-1 at 100 ˚C; (b) PDA-1 at 250 ˚C; (c) PDA-2 at 250 ˚C after PDA-1 at 100 ˚C and subsequent encapsulation; (d) PDA-2 at 250 ˚C after PDA-1 at 250 ˚C and subsequent encapsulation.

4 Conclusions

In this study, we demonstrate the hysteresis free-like, high mobility p-channel SnO TFT using the low temperature PDA-1 and subsequent encapsulation. The significant enhancement in the device performances could be attributed to the improvement in both the crystal quality and surface property by the proposed fabrication method.

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