AMD1-4L
(Late-News Paper)
Invited

Control of Switching Behavior through Oxygen Vacancy Modulation in p-Channel Tin Monoxide Thin-Film Transistor

Taikyu Kim[1], and Jae Kyeong Jeong[1,*]

*jkjeong1@hanyang.ac.kr
[1]Department of Electronic Engineering, Hanyang University, Seoul 04763, Republic of Korea
Keywords: tin monoxide, oxide semiconductor, p-channel transistor, ambipolar behavior

ABSTRACT

We demonstrate an oxygen vacancy (V_O)-mediated electrical characteristic transition in a p-channel tin monoxide (SnO) transistor. Only p-channel characteristic in SnO transistor can be switched to an ambipolar characteristics by increasing V_O near back-channel, which suggests that the V_O at the back-channel can be a possible origin for the ambipolar behavior in the SnO transistors.

1 Introduction

Since Nomura *et al*. reported fabrication of an amorphous indium gallium zinc oxide (*a*-IGZO) in 2004, amorphous oxide semiconductor (AOS) family has been studied considerably owing to their intriguing characteristics including a moderate mobility, low off-current, and good uniformity *etc.* [1] It leads to the successful implementation of AOSs to display back-planes for organic light-emitting diodes (OLED) television. However, the ITO thin-film deposited on top of an organic hole injection layer deteriorates the performance of the inverted OLED stacks by the energetic bombardment, forcing normal OLED stacks with the relatively inferior gray scale representation to be used. In this regard, it can be one of the effective solutions to develop high-performance p-channel oxide transistor. However, ionic bonding innately localizes a valence band (*VB*) edge in the oxide system, which strongly hinders the development of p-type oxide semiconductor with the high mobility.

Tin monoxide (SnO) has been considered one of the most promising p-type oxide semiconductors because of its moderate mobility and great transparency, drawing an enormous attention to implement its high-performance transistor applications. [2-4] However, a clear understanding of several critical issues observed in their transistors, such as high off-current and ambipolar characteristic *etc.*, is still lacking. Amongst, the ambipolar characteristic has not been controlled even if it is frequently revealed in the SnO transistors, necessitating the elucidation of the origin of ambipolar characteristic.

In this study, we suggest an oxygen vacancy (V_O)-rich region in the SnO back-channel as a plausible origin of ambipolar characteristic in the p-channel SnO transistors. It was demonstrated by modulating an oxygen partial pressure in plasma (O_{PP}) during the fabrication of Al_2O_3 passivation layer using plasma-enhanced atomic layer deposition (PEALD). With the O_{PP} increasing from 2.5 to 20%, the volume of compensated V_O increases, which causes to the transition of electrical characteristics from the ambipolar to the p-channel only.

2 Experiment

The p-type SnO thin-film was deposited through magnetron reactive sputtering at room temperature on top of a thermally grown 90-nm-thick SiO_2/Si wafer. Post-deposition annealing (PDA) process was subsequently conducted at 200 °C for 1 hour in ambient air. Then, the ITO thin-film was deposited as source/drain electrodes through the sputtering at room temperature, followed by the deposition of Al_2O_3 passivation layer using the PEALD at 150 °C. Finally, the PDA was performed at 250 °C for 1 hour in ambient air. Figure 1 shows a schematic diagram of fabrication procedure for p-channel SnO transistors.

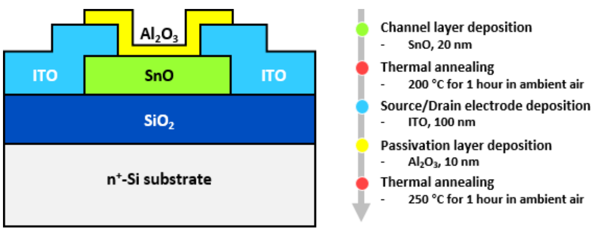

Figure 1. Schematic diagram and fabrication procedure for SnO transistor with a Al_2O_3 passivation layer.

3 Results and discussions

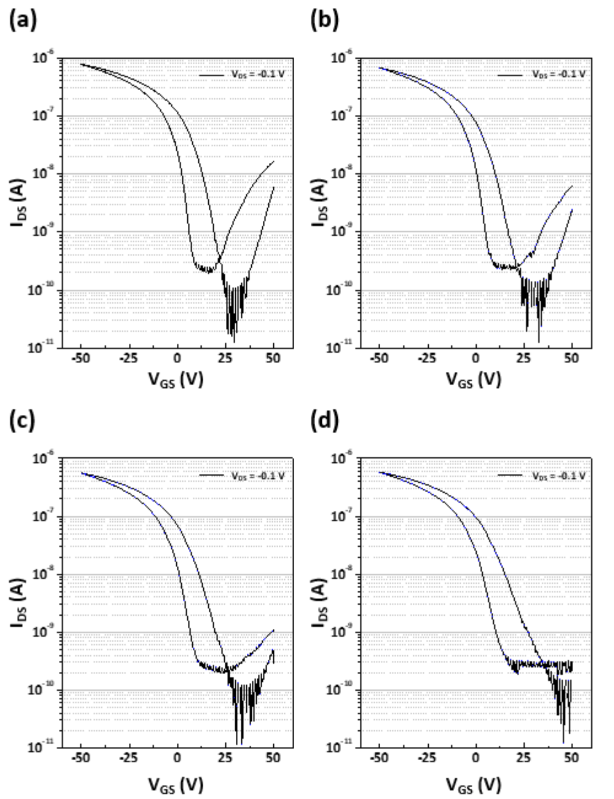

Figure 2. Representative transfer characteristics of the SnO transistors depending on the O_{PP}: (a) O_{PP} = 2.5%, (b) O_{PP} = 5%, (c) O_{PP} = 10%, and (d) O_{PP} = 20%.

Figure 2 shows representative transfer characteristics of SnO transistors depending on the O_{PP}, where it is demonstrated that the electrical characteristic is changed from the ambipolar to the p-channel only as the O_{PP} increases from 2.5 to 20%. It would be attributed to the generation of V_O by adsorption of trimethylaluminum (TMA) on the SnO layer. The TMA precursor can absorb the oxygen from the SnO layer underneath owing to its strong oxidation power, which creates the V_O at the SnO back-channel. The created V_O will be diminished by the supply of oxygen, because the increased O_{PP} accompanies the higher oxidation potential. These results are consistently confirmed in output characteristics of SnO transistors as shown in **Figure 3**. The device performances are summarized in **Table 1**.

Table 1. Device performance of the SnO transistors depending on the O_{PP}.

	O_{PP} = 2.5%	O_{PP} = 5%	O_{PP} = 10%	O_{PP} = 20%
μ_{FE} (cm^2/Vs)	1.0	0.9	0.8	0.8
$I_{P\_ON/OFF}$	5.0×10^4	4.6×10^4	3.9×10^4	3.1×10^4
$I_{N\_ON/OFF}$	2.7×10^2	1.2×10^2	0.6×10^2	NA

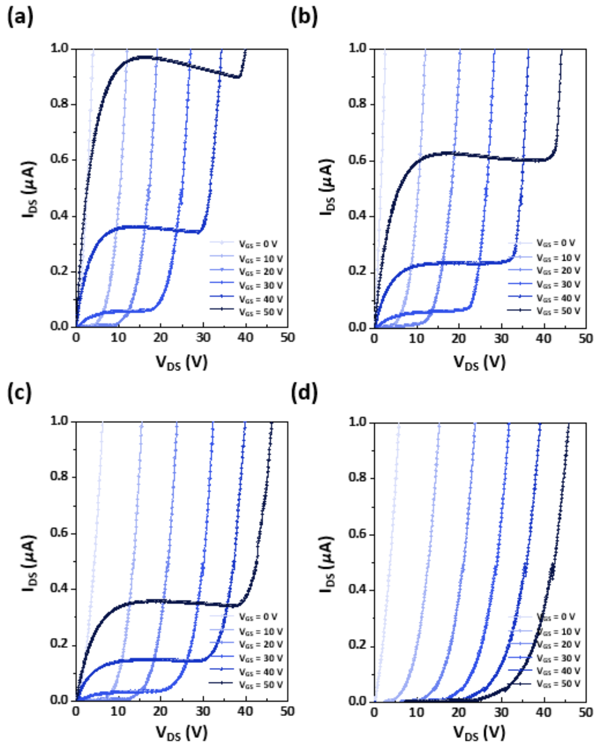

Figure 3. Representative output characteristics of the SnO transistors depending on the O_{PP} at positive V_{GS} and V_{DS}: (a) O_{PP} = 2.5%, (b) O_{PP} = 5%, (c) O_{PP} = 10%, and (d) O_{PP} = 20%.

The evolution of concentration of V_O is investigated through X-ray photoelectron spectroscopy (XPS) analysis. **Figure 4(a)** shows Sn *3d*$_{5/2}$ peaks of the SnO thin-films with the different O_{PP}, where it is clearly observed that Sn^0 decreases from 16.0 to 10.4% and Sn^{4+} increases from 11.2 to 20.5% with the increasing O_{PP} from 2.5 to 20%. It is noteworthy that the high O_{PP} can provide the SnO back-channel with the sufficient oxygen and reduce the concentration of V_O, further oxidizing the excess Sn cations and accompanying the increase in the oxidation states of Sn. The decreasing trend of V_O can be also supported by X-ray reflectometry (XRR), which shows the increasing trend of mass density at the SnO/Al_2O_3 interface from 1.5 to 2.9 g/cm^3 (**Figure 4(b)**), implying that the volume of V_O decreases with the increasing O_{PP}.

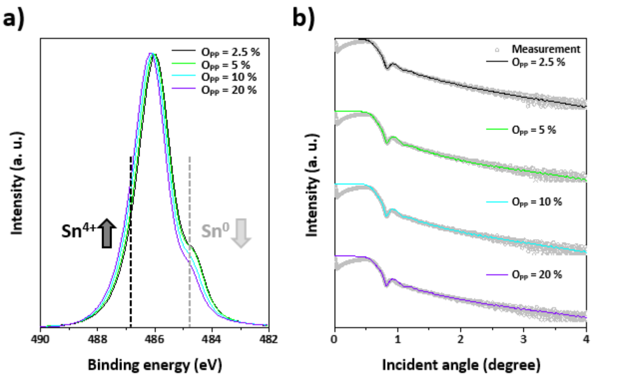

Figure 4. Analyses on the SnO thin-films depending on the O_{PP}: (a) Sn $3d_{5/2}$ peaks of XPS. (b) XRR results.

4 Conclusions

This study empirically demonstrates that the ambipolar characteristic is effectively regulated in the p-channel SnO transistors by modulating the O_{PP} during the Al_2O_3 encapsulation layer deposition, which presents the facile method to improve/suppress the ambipolar characteristics. It is concluded that the V_O at the SnO back-channel can be a plausible origin of ambipolar characteristics.

References

[1] K. Nomura, H. Ohta, A. Takgi, T. Kamiya, M. Hirano, H. Hosono, *Nature* **2004**, 432, 488.

[2] T. Kim, B. Yoo, Y. Youn, M. Lee, A. Song, K.-B. Chung, S. Han, J. K. Jeong, *ACS Appl. Mater. Interfaces* **2019**, 11, 40214-40221.

[3] S. Yim, T. Kim, B. Yoo, H. Xu, Y. Youn, S. Han, J. K. Jeong, *ACS Appl. Mater. Interfaces* **2019**, 11, 47025-47036.

[4] T. Kim, J.-K. Kim, B. Yoo, H. Xu, S. Yim, S.-H. Kim, H.-Y. Yu, J. K. Jeong, *J. Mater. Chem. C* **2020** 8, 201.