Applied Physics Letters

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Cite as: Appl. Phys. Lett. **93**, 142111 (2008); https://doi.org/10.1063/1.2998612
Submitted: 28 July 2008 . Accepted: 20 September 2008 . Published Online: 10 October 2008

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Transparent Al–Zn–Sn–O thin film transistors prepared at low temperature

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(Received 28 July 2008; accepted 20 September 2008; published online 10 October 2008)

We have fabricated transparent bottom gate thin film transistors (TFTs) using Al-doped zinc tin oxide (AZTO) as active layers. The AZTO active layer was deposited by rf magnetron sputtering at room temperature. The AZTO TFT showed good TFT performance without postannealing. The field effect mobility and the subthreshold swing were improved by postannealing below 180 °C. The AZTO TFT exhibited a field effect mobility (μ_{FET}) of 10.1 cm^2/V s, a turn-on voltage (V_{on}) of 0.4 V, a subthreshold swing (S/S) of 0.6 V/decade, and an on/off ratio (I_{on}/I_{off}) of 10^9.
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Flexible and transparent displays based on organic light emitting diodes (OLEDs) have attracted interest because they are considered to create new applications of electronics. The reliable transparent thin film transistor (TFT) showing good electrical performance is indispensable for the displays and should be manufactured at low temperature. In recent times, flat panel display televisions demand high resolution and large size. As the display size and resolution increase, the TFT back plane with good uniformity, low cost, and high stability is required.[1] Conventional amorphous silicon TFT can be fabricated with high uniformity and low cost; however, its mobility and bias stability are poor. Low temperature polysilicon TFT has disadvantages for large size production due to relatively poor uniformity and high cost.[2] For these reasons, oxide TFTs are considered as a prominent candidate for the driving device of active-matrix OLED.[3] Transparent oxide TFTs using ZnO,[4] In–Zn–O,[5,6] Zn–Sn–O,[7,8] and In–Ga–Zn–O [9,10] as an active channel have been widely studied. Most oxide TFTs require high temperature (>200 °C) processing to present good electrical performance. Several studies concerning oxide TFTs processed at low temperature (<150 °C) were reported; however the electrical performances were relatively poor.[11] In order to use plastic substrates for flexible displays, processing temperature lower than 180 °C for all manufacturing processes is desirable.

We have fabricated inverse coplanar type bottom gate TFTs with the Al-doped zinc tin oxide (AZTO) active layer sputtered at room temperature. The schematic diagram of the AZTO TFT structure is shown in Fig. 1. A 100×100 mm^2 alkaline-free glass was used as a substrate after the ultrasonic cleaning with acetone, isopropyl alcohol, and de-ionized water in sequence. Gate and source/drain electrodes were constituted with 150 nm thick indium tin oxide. A gate insulator of Al_2O_3 was formed by atomic layer deposition method at 150 °C and its thickness was 185 nm. An AZTO layer was formed by cosputtering of an Al_2O_3–ZnO (Al_2O_3, 2 wt %) target and a SnO_2 target (ANP Co.) with a rf magnetron sputter. The sputtering was performed in the atmosphere of Ar and O_2 mixed gas with a chamber pressure of 0.2 Pa. The thicknesses of the AZTO active layers were 25 ± 3 nm. All patterning processes were performed with the photolithographic method and wet etching process. Postannealing was performed in vacuum using electric ovens. The electrical characteristics of the TFTs were measured with a semiconductor parameter analyzer (Agilent B1500A). X-ray diffraction (XRD) spectra of the AZTO films were recorded with a Rigaku RU-200BH diffractometer using Cu Kα radiation. The chemical composition of the AZTO thin film was analyzed by the Auger electron spectroscopy method.

The AZTO films were transparent and the transparency of the AZTO thin films (100 nm thick) was $89\pm1\%$ at 550 nm. The AZTO thin film deposited by sputtering at room temperature was amorphous. Figure 2 shows the XRD spectra of AZTO thin films having a composition of about 4 mol % of AlO_x, 66 mol % of ZnO, and 30 mol % of SnO_2 before and after annealing. There was no diffraction peak in the crystalline phase in the XRD spectra even after the 300 °C annealing. Thus, the AZTO active layer on the TFT was considered as a very stable amorphous oxide material.

Figure 3 shows the transfer characteristics of the bottom gate AZTO TFT ($W/L=40$ $\mu m/20$ μm) with the active layer deposited at room temperature. There was no heat treatment on the active layer because it was deposited in the final process. The AZTO TFT showed a μ_{FET} of 1.9 cm^2/V s, a V_{on} of near 2.0 V, and a I_{on}/I_{off} of more than 10^7. The subthreshold swing (S/S) was relatively large and the off-current level was below 10^{-12} A. Figure 4 shows the transfer characteristics of the AZTO TFTs at 150 and 180 °C annealed in vacuum. The 150 °C annealed TFT exhibited a μ_{FET} of

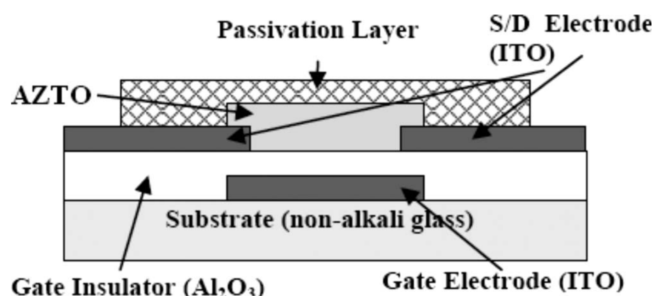

FIG. 1. Schematic diagram of bottom gate AZTO TFT structure.

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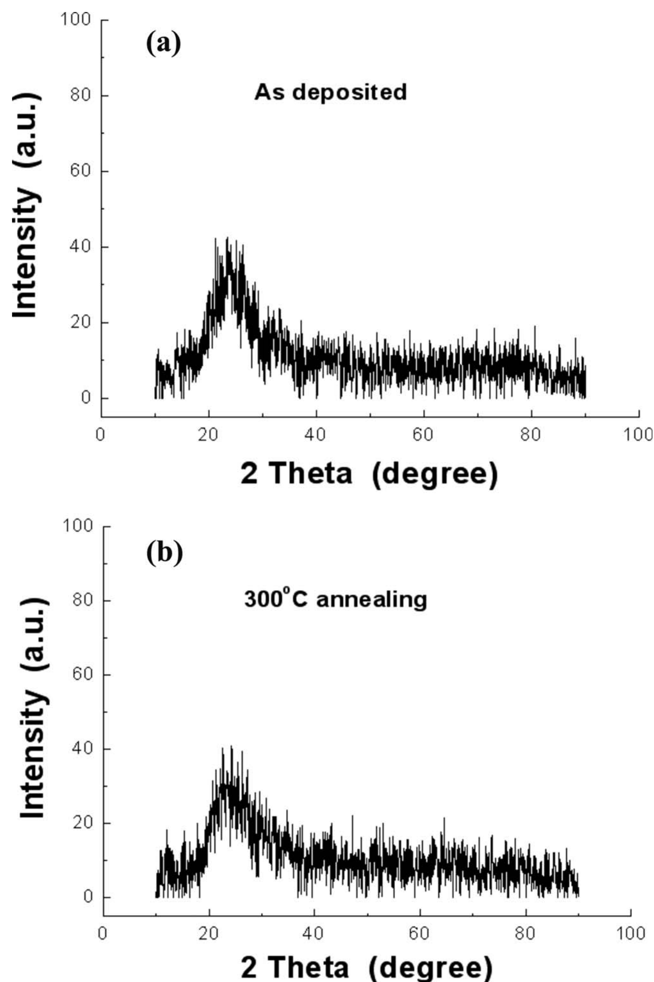

FIG. 2. XRD spectra of (a) AZTO thin film deposited at room temperature and (b) annealed at 300 °C.

6.2 cm^2/V s, a V_{on} of 0.9 V, a I_{on}/I_{off} of about 10^9, and a S/S of 0.60 V/decade. The 180 °C annealed TFT exhibited a μ_{FET} of 10.1 cm^2/V s, a V_{on} of 0.9 V, a I_{on}/I_{off} of more than 10^9, and a S/S of 0.58 V/decade. It can be seen that the mobility increased by increasing the annealing temperature. The S/S and the I_{on}/I_{off} were sufficiently improved considering the application to active matrix displays just by postannealing at 150 °C. The V_{on} shifted to near 0 V by low temperature annealing. Figure 5 shows the transfer characteristics of the bottom gate AZTO TFT (W/L =40 μm/20 μm), which is composed of about 5 mol % of AlO_x, 79 mol % of ZnO, and 16 mol % of SnO_2 with and without passivation layer. The passivation was performed with polyimide polymer by spin coating and baking method. The V_{on} was shifted by gate bias field as shown in Fig. 5. The field effect mobility was not degraded by the passivation. The V_{on} shift, the S/S, and the long-term reliability were improved by the polyimide passivation. The threshold voltage shift of the polyimide passivated TFT was 0.8 V after 30 days.

The mobility changes with SnO_2 content and O_2/Ar ratio in sputtering chamber are shown in Fig. 6. The mobilities in Figs. 6(a) and 6(b) were measured for the AZTO TFTs with the composition of xSn(1-x)$(Al_{0.06}Zn_{0.94})O_y$ and $0.05AlOx0.71ZnO0.24SnO_2$, respectively. The mobility increased with SnO_2 content and the mobility change was large until 16 mol % of SnO_2; from then, the mobility increment became slow. Below 10 mol % of SnO_2, the AZTO did not show the field effect transistor characteristics. The mobility increased with decreasing O_2/Ar ratio, which is supposed to originate from the increase in carrier concentration related to oxygen deficiency.[12]

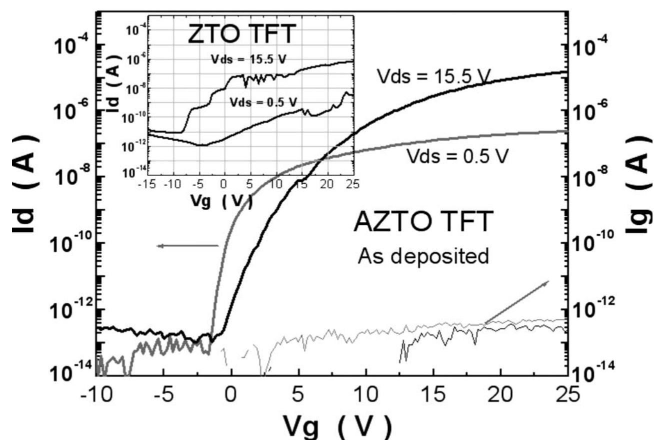

FIG. 3. Transfer characteristics of AZTO TFT with the active layer deposited at room temperature (I_d-V_g characteristics of ZTO TFT are shown in the small box).

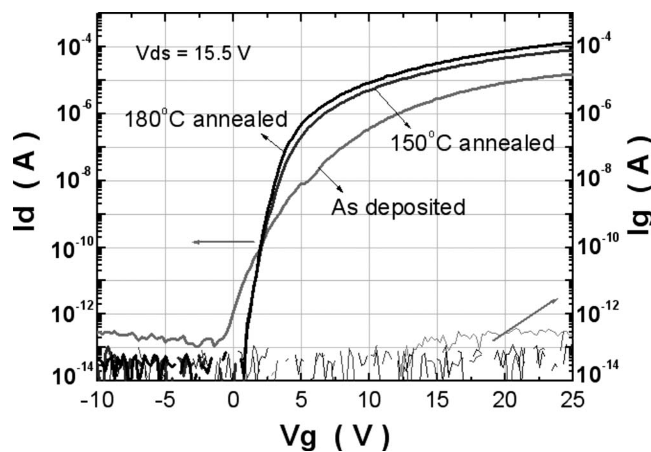

FIG. 4. Transfer characteristics of AZTO TFT without heat treatment, annealed at 150 °C, and 180 °C in vacuum for 1 h.

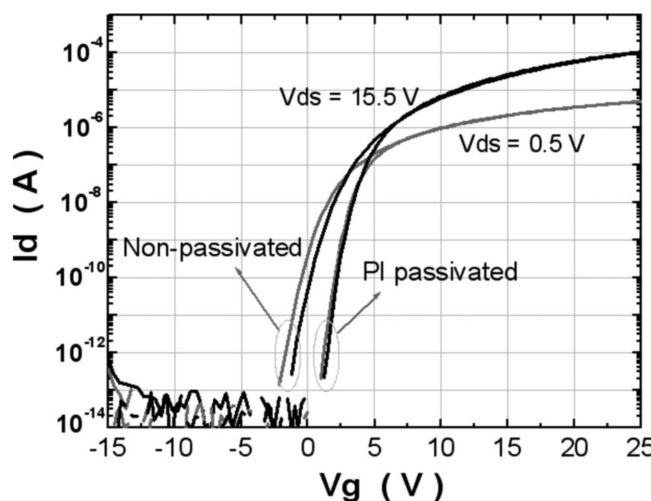

FIG. 5. Transfer characteristics of nonpassivated AZTO TFT annealed at 180 °C in vacuum for 1 h and polyimide passivated AZTO TFT.

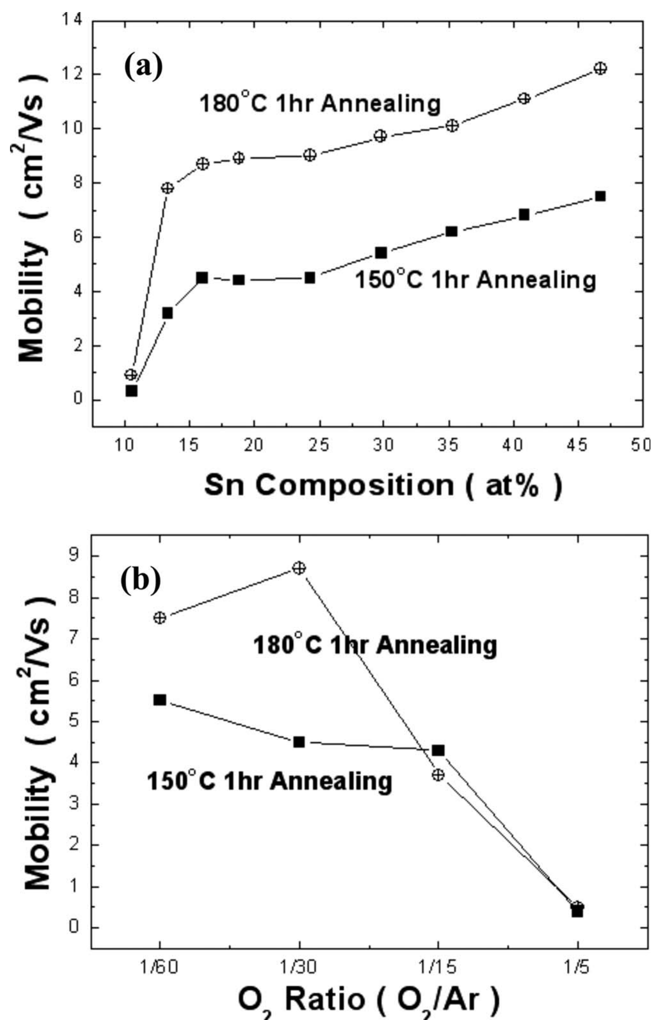

FIG. 6. The field effect mobility change with (a) SnO_2 content in AZTO active layer and (b) O_2/Ar ratio of the sputtering chamber.

Amorphous oxides composed of heavy-metal cations with $(n\text{-}1)d^{10}ns^0(n\geq 4)$ electronic configurations show high electron mobilities because ns^0 $(n\geq 4)$ orbitals overlap between adjacent orbitals. The large diameter and spherical symmetry of the ns^0 orbitals lead to a high degree of overlap and conduction band dispersion.[7,12] In the AZTO thin films, Sn^{4+} and Zn^{2+} are such heavy-metal cations. As a result of the mobility dependence on SnO_2 content, Sn^{4+} is supposed to control the field effect mobility rather than Zn^{2+} because the $5s^0$ orbital of Sn^{4+} is larger than the $4s^0$ orbital of Zn^{2+}. Al^{3+} is not the heavy-metal cation; thus, the addition of AlO_x is considered to scarcely enhance the electron transport. The mobilities of the AZTO TFTs annealed at 180 °C are similar to those of Zn–Sn–O TFTs annealed at 300 °C.[7] However, the AZTO TFTs showed relatively good transfer characteristics without high temperature annealing, while Zn–Sn–O TFT showed very poor transistor characteristics before annealing as shown in Fig. 3. The active layer of the Zn–Sn–O TFT was prepared with the same sputtering condition as the AZTO TFT. The electron transport properties of the as-deposited films fabricated at an inadequate condition are known to be improved by thermal annealing, while those of the films fabricated at optimized condition are scarcely changed by annealing.[13] The highest level by thermal annealing is almost the same as that of the films deposited at the optimized condition.[13] It is considered that the addition of AlO_x makes the optimization of the Zn–Sn–O film easy even at room temperature. Therefore, AlO_x was supposed to enhance the electrical characteristics of the AZTO TFT processed at low temperature.

We have manufactured transparent oxide TFTs with the AZTO active layer, which showed good electrical performance even with the room temperature deposition and annealing below 180 °C. The room temperature deposition and the low temperature process are significant advantages for flexible electronics. The addition of AlO_x to Zn–Sn–O is supposed to enhance the electrical characteristics of the TFT processed at low temperature. AZTO TFT is considered to be a prominent candidate as a driving device for flexible and transparent displays.

This work was supported by IT R&D program of Ministry of Knowledge Economy (Grant No. 2006-S079-02, smart window with transparent electronic devices).

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