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Transparent Al–In–Zn–O Oxide semiconducting films with various in composition for thin-film transistor applications

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Abstract

Al–In–Zn–O thin-film transistors were fabricated. To examine the effect of In composition, we adopted a co-sputtering method using Al–Zn–O and In_2O_3 targets. The sputtering power of In_2O_3 was varied to 200, 150, and 50 W. The mobility and turn-on voltage of each device were 27.8 $cm^2V^{-1}s^{-1}$ and -4.2 V, 4.5 $cm^2V^{-1}s^{-1}$ and -3.5 V, 0.7 $cm^2V^{-1}s^{-1}$ and -3 V, respectively. We also investigated instabilities under negative gate bias stress (NBS) and negative bias illumination stress (NBIS). While the NBS was not influenced by the In contents, the NBIS characteristics were optimized for the device with In_2O_3 sputtering at 150 W.

Keywords: Thin film transistors; Oxide semiconductor; Al–In–Zn–O

1. Introduction

Oxide thin-film transistors (TFTs) have been vigorously researched and developed for various promising applications that demand good uniformity in device behaviors, high carrier mobility, and low temperature process compatibility [1,2]. Many factors affect the oxide TFT performance, including the fabrication methods, device structures, and material composition of the semiconducting active channels. Among them, the constituent elements and composition of a channel material have a great impact on its electrical characteristics. So far, various materials of oxide semiconductors, such as ZnO [3], In–Zn–O (IZO) [4], In–Ga–Zn–O (IGZO) [5,6], Al–Zn–Sn–O (AZTO) [7], and Al–In–Zn–Sn–O [8], have been intensively studied. In the case of IGZO, it is generally accepted that In, Ga, and Zn have distinct roles, to form the electron pathways, suppress carrier generation, and stabilize atomic networks, respectively. The Sn element in the AZTO active layer could be a mobility enhancer [7]. Meanwhile, the Hf [9] and Si [10] were confirmed to act as carrier suppressors. In designing the channel composition for the oxide TFT, two major concerns must be considered, in order to find a compromise between moderate carrier mobility and excellent device reliabilities under bias and illumination stress conditions. Although we know that In plays a large role in increasing the carrier mobility, an excessive addition of In might deteriorate the stability of device characteristics [11]. Especially for oxide TFT, it is very important to guarantee photo-induced stability, due to its high transparency to the visible light: the oxide channel inevitably experiences light illuminations from the backlight unit of liquid crystal display or from natural light. Consequently, studies of new material compositions are needed in order to realize highly functional and highly stabilized oxide TFTs for promising applications in the near future.

In this work, we propose a new composition of Al–In–Zn–O (AIZO) as an active channel material for the oxide TFT, in which Al and In are expected to act as suitable carrier suppressor and enhancer, respectively. We evaluated the device characteristics of the fabricated TFTs using AIZO channels while the In concentrations in the AIZO were varied. The electrical stabilities and light responses of the fabricated AIZO TFTs were also investigated.

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2. Material and methods

We fabricated AIZO TFTs with bottom-gate-bottom-contact structure on a glass substrate. The 150 nm thick In–Sn–O (ITO) electrodes were prepared as source/drain and gate electrodes by the sputtering method. They were annealed in vacuum at 200 °C in order to reduce their resistance. A 176 nm thick Al_2O_3 gate insulator layer was grown by means of atomic layer deposition (ALD) at 150 °C using trimethylaluminum (TMA) as an Al and H_2O as an oxygen precursor. The AIZO layers were deposited by the co-sputtering method using an AZO (2 wt% Al) and an In_2O_3 target, in which the sputtering power of the In_2O_3 target was varied to 200, 150, and 50 W in order to verify the effects of the In contents on the AIZO channels. The sputtering power of the AZO target was fixed at 200 W. The thicknesses of the AIZO with different compositions were controlled to be 20 nm. The deposition rates under different power conditions and the corresponding film thicknesses were measured using a surface profiler. The detailed deposition conditions of AIZO layer are given in Table 1. As shown in Fig. 1(a) and (b), The compositional ratio of AIZO channel layers was analyzed by Auger Electron Spectroscopy (AES), in which the relative In contents were estimated to be approximately 5.5 (200 W): 3.5 (100 W): 1 (50 W) by integrating the In etch profiles of each condition. Although this was only a relative comparison between the conditions, it was obvious that the In composition of the prepared AIZO channels could be controlled by the sputtering power for the In_2O_3 target. Considering that oxide TFTs are highly sensitive to the environmental condition, a passivation layer was adopted to prevent the adsorption and desorption of oxygen and water molecules at the back channel. The 40 nm thick Al_2O_3 layer was grown at 150 °C by the ALD method using the same precursors as for the gate insulator. All the patterning processes for the device fabrications were performed by using conventional photolithography and the wet etching method with a diluted hydrofluoric acid-based etchant. Finally, all devices were annealed at 250 °C in ambient air. A schematic diagram of the fabricated AIZO is shown in Fig. 1(c). The electrical performances of the AIZO TFTs were measured by using a semiconductor parameter analyzer (Agilent, B1500A) in a dark box. The defined gate channel width (W) and length (L) of the evaluated devices were 40 μm and 20 μm, respectively.

3. Results and discussion

Fig. 2(a) shows the drain current (I_{DS})–gate voltage (V_{GS}) transfer characteristics of the fabricated AIZO TFTs with various In composition ratios, which were measured for forward and reverse sweeps in V_{GS} at a drain voltage (V_{DS}) of 15.5 V. All devices exhibited a sufficiently low off-current (I_{off}) level and a negligible hysteresis in I_{DS}. When the sputtering power of In_2O_3 was varied to 200, 150, and 50 W, the saturation mobility (μ_{sat}) and turn-on voltage (V_{on}) of each controlled device were estimated to be approximately 27.8 $cm^2\,V^{-1}\,s^{-1}$ and −4.2 V, 4.5 $cm^2\,V^{-1}\,s^{-1}$ and −3.5 V, and 0.7 $cm^2\,V^{-1}\,s^{-1}$, and −3.0 V, respectively. The V_{on} was defined as the voltage where the I_{DS} approached 1 pA from the off state in the transfer curves. The (μ_{sat}) was calculated with the following equation:

$$I_{DS}=\frac{W}{2L}\mu_{sat}C_{ox}(V_{GS}-V_{TH})^2$$

(C_{ox} and V_{TH} correspond to the capacitance of Al_2O_3 gate insulator and the threshold voltage, respectively.)

The subthreshold swing (S.S.) and the ratio of on current (I_{on}) and off-current (I_{off}) were 0.51 V/decade and 2.01×10^9 (In_2O_3 200 W), 0.69 V/decade and 1.67×10^8 (In_2O_3 150 W), 0.63 V/decade and 3.80×10^7 (In_2O_3 50 W), respectively. As summarized in Fig. 2(b), the electrical characteristics of the AIZO TFTs were confirmed to be dependent on the sputtering power of In_2O_3. With the increase in In contents of the AIZO active channels, the saturation mobility and I_{on}/I_{off} ratio were enhanced and V_{on} was shifted in the negative direction. For the TFT with a sputtering power of 200 W, the transfer curve is distorted; this appears to be very closely related to the relatively higher amounts of In content. These trends are in good agreement with the previous results for IZO TFTs that the higher In contents incorporated in the oxide active channel can enhance the carrier mobility and shift the V_{on} in the negative direction [11]. From these obtained characteristics, the proposed AIZO TFTs showed promising operation, and that their operational behaviors could be controlled by modifying the In contents.

The second goal of this work is to verify the device reliabilities of the AIZO TFTs, which were severely evaluated under negative gate bias stress conditions with and without an illumination source. First, for the negative bias stress (NBS) tests, a V_{GS} of = −20 V

Table 1
The detailed deposition conditions of AIZO channel layer. The calculated In_2O_3 thickness ratio of each deposition condition was about 2.6 (In_2O_3 200 W):2.25 (In_2O_3 150 W):1 (In_2O_3 50 W).

Co-deposition power	Deposition-rate (Å/s)	Thickness ratio (Å) (estimated)	Deposition time (s)/total thickness (Å) (estimated)
AZO (200 W): In_2O_3 (200 W)	0.52:0.47	105.04:94.94	202/199.98
AZO (200 W): In_2O_3 (150 W)	0.52:0.36	118.56:82.08	228/200.64
AZO (200 W): In_2O_3 (50 W)	0.52:0.12	162.76:36.56	313/200.32