Effects of Active Layer Thickness on the Electrical Characteristics and Stability of High-Mobility Amorphous Indium–Gallium–Tin Oxide Thin-Film Transistors

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Abstract: Herein, we investigated the effects of active layer thickness ($t_S$) on the electrical characteristics and stability of high-mobility indium–gallium–tin oxide (IGTO) thin-film transistors (TFTs). IGTO TFTs, with $t_S$ values of 7 nm, 15 nm, 25 nm, 35 nm, and 50 nm, were prepared for this analysis. The drain current was only slightly modulated by the gate-to-source voltage, in the case of the IGTO TFT with $t_S = 50$ nm. Under positive bias stress (PBS), the electrical stability of the IGTO TFTs with a $t_S$ less than 35 nm improved as the $t_S$ increased. However, the negative bias illumination stress (NBIS) stability of these IGTO TFTs deteriorated as the $t_S$ increased. To explain these phenomena, we compared the O1s spectra of IGTO thin films with different $t_S$ values, acquired using X-ray photoelectron spectroscopy. The characterization results revealed that the better PBS stability, and the low NBIS stability, of the IGTO TFTs with thicker active layers were mainly due to a decrease in the number of hydroxyl groups and an increase in the number of oxygen vacancies in the IGTO thin films with an increase in $t_S$, respectively. Among the IGTO TFTs with different $t_S$, the IGTO TFT with a 15 nm thick active layer exhibited the best electrical characteristics with a field-effect mobility ($\mu_{FE}$) of 26.5 cm$^2$/V·s, a subthreshold swing (SS) of 0.16 V/dec, and a threshold voltage ($V_{TH}$) of 0.3 V. Moreover, the device exhibited robust stability under PBS ($\Delta V_{TH} = 0.9$ V) and NBIS ($\Delta V_{TH} = −1.87$ V).

Keywords: IGTO TFT; active layer thickness; positive bias stress stability; negative bias illumination stress stability

1. Introduction

Amorphous indium–gallium–zinc oxide (IGZO) thin-film transistors (TFTs) were reported for the first time by Nomura et al. in 2004; since, they have attracted significant attention because of their excellent electrical properties, low process temperature, large-area uniformity, and low fabrication cost [1–5]. Currently, IGZO TFTs are being widely used as a backplane for large-area active-matrix flat-panel displays, such as organic light-emitting diode (OLED) displays and liquid-crystal displays (LCD) [6–8]. The recent development of low-temperature polycrystalline oxide technology is expected to further expand the application range of IGZO TFTs in the field of displays [7,8]. However, the relatively low field-effect mobility of IGZO TFTs ($\mu_{FE} = −10$ cm$^2$/V·s) still hinders their application in the backplane of ultra-high-resolution and high-frame-rate displays [9,10]. This is because the OLED pixels require a high current to emit light. Therefore, the study presents a new low-voltage driving OLED pixel circuit with high-mobility amorphous oxide TFTs as the driving device with high resolution [11]. To date, various oxide semiconductors have been studied as active materials for high-mobility oxide TFTs [12–14]. Among them, IGTO has recently attracted considerable attention as a promising active material for next-generation high-mobility oxide TFTs. The In$^{3+}$ and Sn$^{4+}$ ions have almost similar electronic
structures. They have a small effective electron mass due to the 5 s orbital overlapping structure, leading to a highly conductive path for electron carriers, and remarkably high mobility [15,16]. Furthermore, the IGTO TFTs exhibit excellent electrical characteristics, even at low annealing temperatures (below 200 °C) [17–19].

For oxide TFTs, active layer thickness ($t_S$) is an important parameter that strongly affects the electrical performance and stability of these TFTs. To date, extensive research has been performed to determine the effects of $t_S$ on the electrical characteristics and stability of oxide TFTs comprising different active materials. However, previous studies have reported different results for the effects of $t_S$ on the electrical characteristics and stability of oxide TFTs according to the type of active material and fabrication process conditions. For example, Cho et al. [20] and Yang et al. [21] reported that the positive bias stress (PBS) stability of indium–zinc-oxide and IGZO TFTs deteriorated with an increase in $t_S$, respectively. Nevertheless, Lee et al. [22] and Li et al. [23] observed an improvement in the PBS stability of IGZO TFTs with an increase in $t_S$. These results imply that investigating the effects of $t_S$ on the electrical performance and stability of IGTO TFTs is extremely necessary to determine the optimal $t_S$ for IGTO TFTs. In this study, we examined the effects of $t_S$ on the electrical characteristics and stability of IGTO TFTs. IGTO TFTs, with the $t_S$ values of 7 nm, 15 nm, 25 nm, 35 nm, and 50 nm, were prepared for this analysis. A systematic study was conducted to investigate the physical mechanisms responsible for the observed effects of $t_S$ on the electrical performance and PBS/NBIS stability of IGTO TFTs.

2. Materials and Methods

Figure 1a,b shows the schematic and top-view optical image of the fabricated IGTO TFTs, respectively. The IGTO TFTs were constructed on a heavily doped p-type Si wafer (resistivity < 0.005 $\Omega$·cm) covered by 100-nm thick thermally grown SiO$_2$. The heavily doped p-type Si wafer was used as a substrate and a gate electrode. Thermally grown SiO$_2$ was used as a gate dielectric. IGTO active layers with the thicknesses of 7 nm, 15 nm, 25 nm, 35 nm, and 52 nm were deposited on the substrate by direct current magnetron sputtering under the following conditions: working pressure, 3.0 mTorr, Ar/O$_2$; gas mixing ratio, 21/9 sccm; sputtering power, 150 W; and chuck temperature, room temperature (RT). Then, a 100-nm thick indium–tin-oxide layer was deposited on the IGTO active layer-coated substrate to prepare source and drain electrodes of the TFTs. Subsequently, a 30-nm thick Al$_2$O$_3$ thin film was deposited as a passivation layer on top of the resulting substrate using radio frequency magnetron sputtering at RT. Finally, the IGTO TFTs were thermally annealed on a hot plate at 200 °C for 2 h in ambient air.

![Figure 1. (a) Schematic and (b) top-view optical image of the fabricated IGTO TFTs.](image)

The active, source/drain electrodes, and passivation layers were patterned using photolithography and a lift-off process. Electrical characteristics and stability of the IGTO TFTs were measured using a semiconductor parameter analyzer (4156C, Agilent Technologies, Santa Clara, CA, USA) at RT in ambient air. Crystalline structure of the IGTO thin films was analyzed using X-ray diffraction (XRD, New D8-Advance, Bruker-AXS, Wisconsin, USA) with CuK$\alpha$ radiation ($\lambda = 0.15406$ nm). Chemical properties of the IGTO thin films with different $t_S$ were examined using X-ray photoelectron spectroscopy (XPS, K-alpha+,...
TFTs were measured using a semiconductor parameter analyzer (4156C, Agilent). The negatively shifted V_{TH} and the large SS for the thick active oxide TFTs have been mainly attributed to the reduced surface roughness scattering in the oxide semiconductor. As the carrier transport layer is farther from the surface of the thick film, the effect of the surface roughness on the carrier mobility is weaker in the thick film, compared with the thin film.

3. Results and Discussion

Figure 2 shows the XRD patterns of a 35-nm thick IGTO thin film fabricated on an aluminosilicate glass substrate. The XRD pattern demonstrates only halo peaks at approximately 23° and 45°, originating from the glass substrate [24]. The results shown in Figure 2 indicate that the IGTO thin film has an amorphous phase, which is consistent with the results of previous studies [17].

![Figure 2. XRD pattern of the 35-nm thick IGTO thin film formed on the aluminosilicate glass substrate.](image)

Figure 3 shows a semi-logarithmic scale plot of transfer curves for the IGTO TFTs (width/length (W/L) = 500 µm/500 µm), with the t_S of 7, 15, 25, 35, and 50 nm. Herein, the drain current (I_D) of all of the IGTO TFTs was evaluated by varying the gate-to-source voltage (V_{GS}) from −20 to 20 V at a fixed drain-to-source voltage (V_{DS}) of 1 V. Figure 3 shows that the I_D of the IGTO TFT with a t_S of 50 nm is slightly modulated by V_{GS}; therefore, the electrical characteristics and stability of only the IGTO TFTs with the t_S of 7, 15, 25, and 35 nm were examined in this study. Table 1 presents the electrical parameters of the IGTO TFTs with the t_S of 7, 15, 25, and 35 nm. The \( \mu_{FE} \) was calculated using the maximum value of transconductance, and the \( V_{TH} \) was determined as the V_{GS} value causing \( I_D = W/L \times 10^{-8} \) (A) at a V_{DS} of 1 V. The subthreshold swing (SS) was extracted as the d(V_{GS})/d(log I_D) value in the range of \( 10^{-10} \) A < I_D < \( 10^{-9} \) A. The \( V_{TH} \) decreased and the SS and the off-current (I_{OFF}) increased with an increase in t_S (Figure 3 and Table 1). The IGTO TFT with the t_S of 7 nm exhibited a significantly smaller \( \mu_{FE} \) than those of the IGTO TFTs with thicker active layers. However, the \( \mu_{FE} \) of the IGTO TFTs with a t_S larger than 15 nm only slightly increased with an increase in t_S. The results shown in Figure 3 and Table 1 are consistent with those reported in previous studies for oxide TFTs, and they demonstrate that t_S significantly affects the transfer characteristics of IGTO TFTs [25]. The negatively shifted \( V_{TH} \) and the large SS for the thick active oxide TFTs have been mainly attributed to the large number of free electrons within the oxide semiconductor and the higher sheet trap density in the active layer, respectively [26–28]. The increase in I_{OFF} with an increase in t_S was considered to be due to enhanced bulk conduction through the back-active layer [27]. The increase in \( \mu_{FE} \) with an increase in t_S has been primarily ascribed to the reduced surface roughness scattering in the oxide semiconductor.
4e depicts the 
illumination using a white light-emitting diode (LED, wavelength 420–780 nm) backplane 
in Table 1. Electrical parameters of IGTO TFTs with the 
for the IGTO TFT with the 
with a luminance of 2000 lux. For every IGTO TFT, the transfer curves shifted in the 
of 7, 15, 25, and 35 nm. For every IGTO TFT, the transfer curves shifted in the positive direction with an 
was noticed for the IGTO TFT with the 
whereas the smallest magnitude of 
threshold voltage (Vth) for the IGTO TFTs 
was observed for the IGTO TFT with the 
0.7 V after stress for 3000 s), whereas the smallest ΔVth was noticed for the IGTO TFT with the 
Vth for the IGTO TFTs 
with different tS under negative bias illumination stress (NBIS) at different stress times. Clearly, the magnitude of ΔVth for the fabricated IGTO TFTs decreased with an increase in tS under PBS (Figure 4).

Figure 5a–d shows the time dependence of the transfer curves for the IGTO TFTs with 
7, 15, 25, and 35 nm, respectively, at a VOV (VOV = Vgs – VTH) of 20 V and a VDS of 0 V. For every IGTO TFT, the transfer curves shifted in the negative direction with an increase in the stress time. The largest magnitude of ΔVTH was obtained for the IGTO TFT with the tS of 35 nm (ΔVTH = −11.2 V after stress for 3000 s), whereas the smallest magnitude of ΔVTH was achieved for the IGTO TFT with the tS of 7 nm (ΔVTH = −0.6 V after stress for 3000 s). Figure 5e depicts the ΔVTH for the IGTO TFTs 
with different tS under negative bias illumination stress (NBIS) at different stress times. The magnitude of ΔVTH for the fabricated IGTO TFTs increased with an increase in tS under NBIS (Figure 5).
The magnitude of $\Delta V_{TH}$ for the fabricated IGTO TFTs increased with an increase in $t_s$ under NBIS (Figure 5).

**Figure 4.** Time dependence of the transfer curves for IGTO TFTs with the $t_s$ of (a) 7 nm, (b) 15 nm, (c) 25 nm, and (d) 35 nm at a constant $V_{OV}$ of 20 V; (e) $\Delta V_{TH}$ for the IGTO TFTs with different $t_s$ under PBS at different stress times.
Figure 4. Time dependence of the transfer curves for IGTO TFTs with the $t_S$ of (a) 7 nm, (b) 15 nm, (c) 25 nm, and (d) 35 nm at a constant $V_{OV}$ of 20 V; (e) $\Delta V_{TH}$ for the IGTO TFTs with different $t_S$ under PBS at different stress times.

Figure 5. Time dependence of the transfer curves for the IGTO TFTs with the $t_S$ of (a) 7 nm, (b) 15 nm, (c) 25 nm, and (d) 35 nm at a constant $V_{OV}$ of $-20$ V under illumination using a light-emitting diode backplane unit with a luminance of 2000 lux; (e) $\Delta V_{TH}$ for the IGTO TFTs with different $t_S$ under NBIS at different stress times.
To investigate the physical mechanisms responsible for the effects of $t_S$ on the PBS and NBIS stability of IGTO TFTs (Figures 4 and 5), we characterized the O1s spectra of the IGTO thin films with different $t_S$ obtained using XPS. Figure 6a–d shows the XPS O1s spectra of 7, 15, 25, and 35-nm thick IGTO thin films located near the IGTO/SiO$_2$ interface. The XPS O1s spectra were resolved into three sub-peaks originating from fully coordinated metal ions (metal–oxygen lattice ($O_{\text{latt}}$)), oxygen vacancies ($O_{\text{Vac}}$), and impurity-related oxygen ($O_{\text{Imp}}$). The XPS peak positions assigned to these sub-peaks were 530.0 eV ($O_{\text{latt}}$), 531.0 eV ($O_{\text{Vac}}$), and 532.5 eV ($O_{\text{Imp}}$), respectively [14,17]. Figure 7 shows the relative peak area ratios of $O_{\text{latt}}$, $O_{\text{Vac}}$, and $O_{\text{Imp}}$ for the IGTO thin films with different $t_S$, located near the IGTO/SiO$_2$ interface. The relative peak area ratio of $O_{\text{Imp}}$ was highest for the 7-nm thick IGTO thin film, and decreased with an increase in $t_S$ (Figure 7). In previously reported studies on IGZO or IGTO TFTs, $O_{\text{Imp}}$ was mainly ascribed to the O bond in the hydroxyl group (OH) [17]. The OH creates acceptor-like trap states close to the conduction band (CB) edge and accelerates the electron trapping process under PBS because of its polar nature [17,31–34]. Considering this, the lower PBS stability of the IGTO TFTs with thinner active layers can be ascribed to the high concentration of OH in the channel layer. It has been reported that a thicker active layer can isolate the channel from ambient factors, including H$_2$O molecules, even after the passivation layer is deposited on the active layer [35]. Effective self-passivation from H$_2$O molecules in the air is the most probable reason for the better PBS stability of the IGTO TFTs with thicker active layers (Figure 7).

![Figure 6](image_url)

**Figure 6.** XPS O1s spectra of the (a) 7-nm, (b) 15-nm, (c) 25-nm, and (d) 35-nm thick IGTO thin films located near the IGTO/SiO$_2$ interface.
films located near the IGTO/SiO$_2$ interface. Therefore, the concentration located near the IGTO/SiO$_2$ interface.

The experimental results shown in Figures 4 and 5 indicate that it is necessary to consider the trade-off between the PBS stability and the low NBIS stability of the IGTO TFTs. From the transfer characteristics and PBS/NBIS stability of the IGTO TFTs with different $t_S$, it can be concluded that 15 nm is the optimal $t_S$ for IGTO TFTs. From the transfer characteristics and PBS/NBIS stability of the IGTO TFTs with different $t_S$, it can be concluded that 15 nm is the optimal $t_S$ for IGTO TFTs, leading to the best electrical characteristics ($\mu_{FE}$: 26.5 cm$^2$/V·s; SS: 0.16 V/dec; and $V_{TH}$: 0.3 V), and decent PBS and NBIS stability of IGTO TFTs.

**4. Conclusions**

In this study, we examined the effects of $t_S$ on the transfer characteristics and stability of high-mobility amorphous IGTO TFTs with $t_S$ values of 7, 15, 25, 35, and 50 nm. The obtained results showed that with an increase in $t_S$, $V_{TH}$ shifted in the negative direction, and the SS and $\mu_{FE}$ of the fabricated IGTO TFTs increased. Clearly, the PBS stability of the IGTO TFTs improved as the $t_S$ increased. However, the NBIS stability of the IGTO TFTs deteriorated with an increase in $t_S$. The XPS characterization results revealed that the better PBS stability and the low NBIS stability of the IGTO TFTs with thicker active layers were mainly owing to the decrease in the concentration of OH and the increase in the number of $O_{Vac}$ in the IGTO, with an increase in $t_S$. We found that the optimum thickness of the active layer for the IGTO TFTs is approximately 15 nm, which results in a positive $V_{TH}$, an acceptably high $\mu_{FE}$, and decent PBS and NBIS stability of the IGTO TFTs.

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