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Effects of Yttrium Doping on a-IGZO Thin Films for Use as a Channel Layer in Thin-Film Transistors

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Abstract: Amorphous In−Ga−Zn−O (a-IGZO) has been studied as a channel layer in thin-film transistors (TFTs). To improve the bias-induced instability of a-IGZO TFTs, we introduced yttrium with high bond enthalpy by magnetron co-sputtering system. The Y-doped a-IGZO (a-IGZO:Y) films show relatively lower carrier concentration and higher Hall mobility, which is due to the suppression of oxygen vacancies caused by Y doping. The a-IGZO:Y showed a relatively higher transmittance in the visible light region compared to non-doped IGZO, which could be due to the decrease of shallow defect levels caused by oxygen vacancy in the band gap. The a-IGZO without Y doping showed dramatic changes in electrical properties as times progressed (over 240 h); however, the a-IGZO:Y showed no significant changes. The a-IGZO:Y TFTs demonstrated a more stable driving mode as exhibited in the positive gate bias stress test even though the values of V_{TH} and SS were slightly degraded.

Keywords: TFT channel layer; amorphous transparent conductive oxide semiconductor; magnetron sputtering; change with time; indium−gallium−zinc−oxide

1. Introduction

Oxide semiconductors have recently drawn attention as channel layer materials in various optoelectronic devices, such as active-matrix organic light-emitting diodes (AM-OLEDs) and flexible displays [1–6]. Compared to conventional amorphous/polysilicon thin film transistors (TFTs), oxide TFTs have several advantages including their low processing temperature and cost, transparency (wideband gap, >3.1 eV), and good electrical properties (e.g., field-effect mobility) [4,7]. In particular, amorphous indium−gallium−zinc−oxide (a-IGZO), an oxide semiconductor, is believed to be suitable for use as the channel layer in TFTs [2,3,8–13]. Despite the amorphous structure, an a-IGZO TFT shows high mobility (~10 cm^2 V^{-1} s^{-1}) compared to a-Si:H (~1 cm^2 V^{-1} s^{-1}) due to the conduction band minimum, which is made of spherically extended s-orbitals of the constituent metals [8,9,11,12]. ZnO-based semiconductors, even those deposited at room temperature, have a polycrystalline structure with columnar grains. Devices fabricated from these materials suffer from problems associated with the grain boundaries, such as nonuniformity of the electrical performance over large areas, instability in response to the atmosphere due to gas adsorption/desorption, and roughness of the film surface [7,14]. The stability of ZnO-based TFT devices remains as one of the most important and critical issues. Therefore, several studies have been performed on ZnO-based TFTs in an attempt to understand the deterioration of the bias-induced instabilities [14,15]. However, studies have rarely been conducted on

a-IGZO doping [10,16,17]. It was proposed that the reliability of ZnO-based TFTs, with positive gate bias stress and negative bias temperature stresses under illumination, is influenced by the ambient gas or charge-trapping of electrons, or photon-induced holes, at the interface between the gate insulator and the semiconductor [7,14,18]. In particular, it is widely known that the electrical performance characteristics of ZnO-based TFTs are strongly dependent on the oxygen gas content. The reason why is due to low bond enthalpy between Zn and O (159 kJ/mol). The existence of oxygen vacancies in the a-IGZO thin films affects the stability of a-IGZO TFTs under bias stress, which occurs largely due to thermally activated creation of ionized oxygen vacancies during device operation [17,19].

In this study, yttrium oxide (Y_2O_3) was selected as a dopant of the a-IGZO thin films to suppress the oxygen vacancies with a low electronegativity (1.22), standard electrode potential (−2.372 V), and high Y–O bond enthalpy value (719.6 kJ/mol) [4,16,17,20]. This paper discusses the effect of the addition of Y_2O_3 in a-IGZO thin films and its influence on the stability of a-IGZO TFTs.

2. Experimental Details

The IGZO (In_2O_3:Ga_2O_3:ZnO = 1:1:1) and Y_2O_3 targets were used as sputtering sources. A radio frequency (RF) power supply was used to vary the RF power to the Y_2O_3 target from 0 to 110 W and to control the dc power supplied to the IGZO target. To guarantee high reproducibility of the film characteristics, the base pressure was maintained at 1×10^{-5} Torr. Deposition of the a-IGZO and Y_2O_3 films was carried out in pure Ar gas (purity of 99.9995%) at a total gas pressure of 0.7 Pa onto non-alkali, glass substrates (Corning 2000, Samsung Corning Precision Glass, Seoul, Korea). The thicknesses of the a-IGZO and Y_2O_3-doped a-IGZO thin films were constant at approximately 50 ± 3 nm.

The thickness of the film was measured using a reflectometer (ST2000-DLXn, K-MAC, Daejeon, Korea). The electrical properties were estimated from the Hall Effect measurements (HMS-3000, Ecopia, Gyeonggi, Korea) at room temperature. The transmittance of the films was measured within the range of 200–1100 nm using a spectrophotometer (UV-Vis 1800, Shimadzu, Kyoto, Japan). In addition, the associated surface morphologies were observed through atomic force microscopy (AFM, XE-120, PSIA Corp., Fremont, CA, USA).

The schematic cross-section of the a-IGZO:Y TFTs is shown in Figure 1. The a-IGZO:Y TFTs employ an inverted staggered, bottom-gate structure. The fabrication process is as follows: To use a gate electrode layer, n-type silicon wafers, with a resistance less than 0.005 Ω cm, were used. A 150-nm-thick SiO_2 layer on the silicon wafers served as the insulating layer. To form a gate electrode for the gate contact, the SiO_2 layer was wet-etched by a buffered oxide etch (BOE) for approximately 3.5 min. Subsequently, ultrasonic cleaning was performed for 5 min using trichloroethylene, acetone, methanol, and de-ionized water to remove impurities on the wafer surface. Toremove residual moisture, the surface was treated with dry nitrogen gas and dried on a hot plate at 100 °C for 5 min. Finally, a-IGZO and Y-doped a-IGZO (a-IGZO:Y) layers were deposited by magnetron co-sputtering with a shadow mask. After deposition, an aluminum layer was deposited by e-beam evaporation to form the source and drain electrodes. Evaporation for the Al electrodes was carried out at a base pressure of 2.3×10^{-8} Pa, resulting in a channel with a length of 100 μm, a width of 1000 μm and a thickness of 100 nm. The electrical properties of the oxide TFTs were measured using a semiconductor parameter analyzer (EL423, Elecs Co., Ltd., Uttarakhand, India).

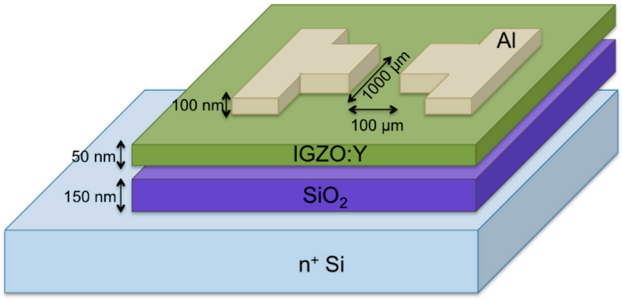

Figure 1. Device structure of the yttrium-doped amorphous In−Ga−Zn−O (a-IGZO) thin-film transistors (TFTs).

3. Results and Discussion

Figure 2 shows the electrical properties of the a-IGZO:Y films as a function of the RF power applied to the Y_2O_3 target. Generally, an increase in the carrier concentration results in a decrease in the Hall mobility due to scattering effects. However, the data show that the carrier concentration and the Hall mobility are proportional. These data can be explained by Adler's percolation conduction model [19,21]. The model assumes that carrier transport is controlled by the existence of potential barriers in the conduction band.

As shown in Figure 2, the a-IGZO:Y films showed the lowest resistivity with RF power 50 W (applied to the Y_2O_3 target). The low resistivity can be attributed to the increased carrier concentration and Hall mobility. These results can also be explained by the effects of Y_2O_3 doping. In the case of lower Y-dopant content, the Y-dopant is activated electrically because carrier generation is dominated mainly by substitution of Y^{3+} ions into the Zn^{2+} sites [17,22]. However, the resistivity increased with increasing RF power from 50 to 110 W. These data suggest that the easily-ionized yttrium is bonded with O^{2-} due to the low standard-electrode potential of the Y-dopant. This is believed to be due to the reduction of the carrier concentration by inhibiting oxygen vacancy formation [8,9].

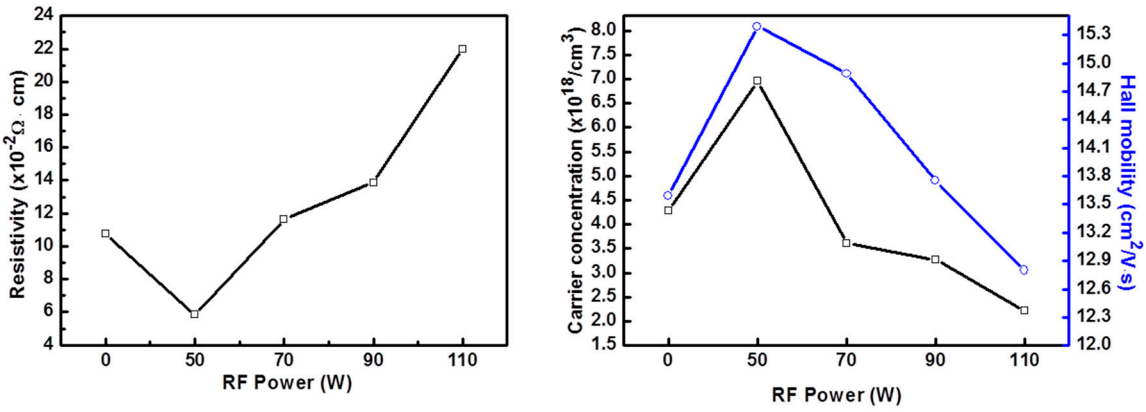

Figure 2. Electrical properties (resistivity, carrier concentration, and Hall mobility) of the yttrium-doped a-IGZO (a-IGZO:Y) films as a function of radio frequency (RF) power (0–110 W).

Figure 3 shows the transmittance of the a-IGZO:Y thin films as a function of the RF power (0–110 W) applied to the Y_2O_3 target. The a-IGZO:Y films had a relatively high transmittance compared to that of the undoped, IGZO thin films. In the case of the a-IGZO:Y films, there was no significant change in the transmittance when the RF power was increased from 50 to 110 W. The Y^{3+} ions combine preferentially with oxygen anions, which can lead to the suppression of oxygen vacancies. The oxygen vacancies act as shallow defect levels between the band gaps [17,22]. As a result, the number of oxygen vacancies can be decreased by increasing the RF power.

To observe changes in the films over time, they were exposed to room temperature, ambient air for 10 days. Figure 4 shows the electrical properties of the a-IGZO:Y thin films, as a function of the RF power (0–110 W), after being exposed to ambient air for 10 days (240 h). Consequently, the resistivity of the undoped a-IGZO thin films had a relatively higher change than that of the a-IGZO:Y thin films after 10 days (240 h), which is attributed to decrease in carrier concentration. This means that a-IGZO showed still low electrical stability due to exhaustion of oxygen vacancy. This suggests that the change over time, observed in all the thin films, is dominated by suppressed oxygen vacancies due to the higher Y–O bond enthalpy (719.6 kJ/mol). As a result, it was confirmed that a-IGZO:Y films prepared at 70 W showed high electrical stability, and there was no significant change after 10 days. Therefore, we selected a-IGZO:Y film as a channel layer for TFTs.

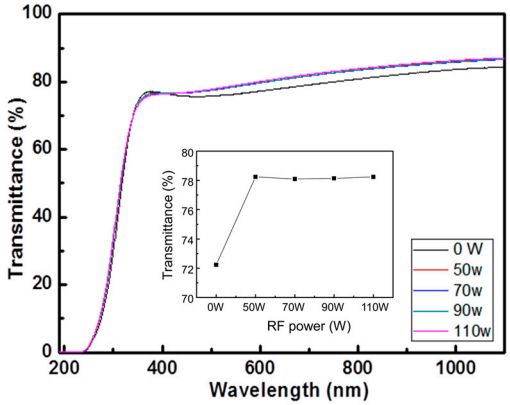

Figure 3. Transmittance of the a-IGZO:Y thin films as a function of the RF power (0–110 W). Inset shows transmittance of thin films at 550 nm.

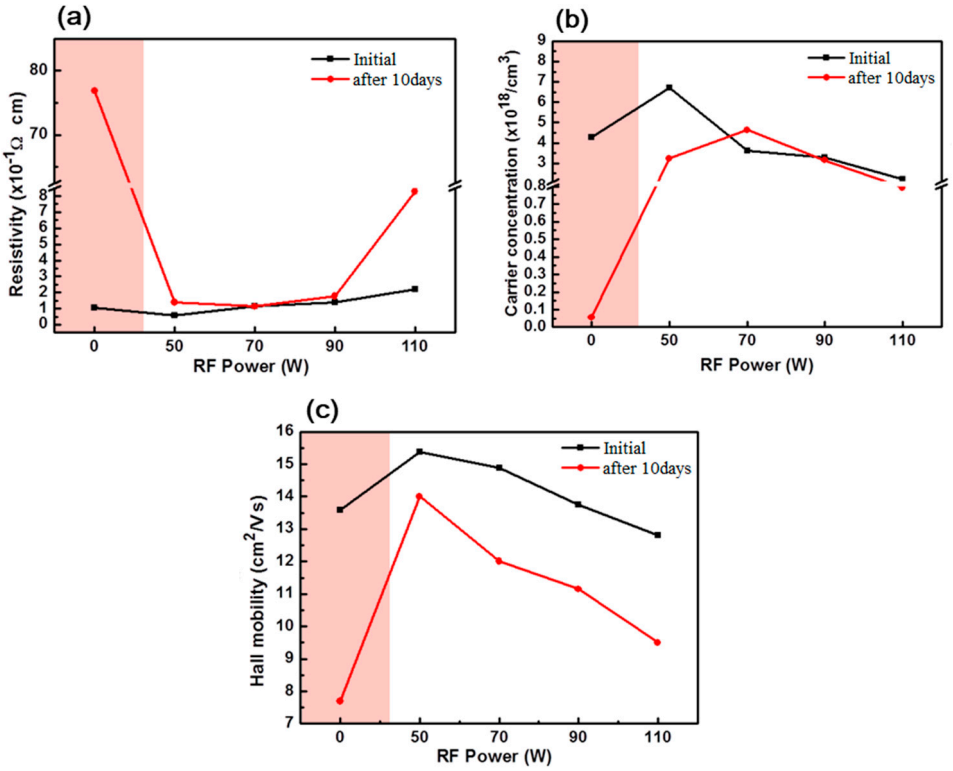

Figure 4. Electrical properties of the a-IGZO:Y films as a function of the RF power (0–110 W) at the initial state and after exposure to ambient air for 10 days (240 h): (**a**) resistivity; (**b**) carrier concentration; and (**c**) Hall mobility.

Figure 5 shows the I_{DS}–V_{DS} performance characteristics of the a-IGZO and a-IGZO:Y TFTs. The I_{DS}–V_{DS} performance characteristics were measured by varying the source-drain voltage in the range of 0–40 V while applying the V_G voltage in nine steps from 0 to 40 V with a 5-V sweep. In the case of the a-IGZO TFTs, the maximum current in the I_{DS}–V_{DS} curve was 9.99 × 10^{-4} A. Compared to the a-IGZO TFTs, the a-IGZO:Y TFTs displayed a lower maximum (9.03 × 10^{-4} A). This is likely due to the decreased carrier concentration caused by inhibiting the formation of oxygen vacancies due to the strengthening of the Y–O bond enthalpy (719.6 kJ/mol). In the case of a-IGZO TFT thin films, the amplification is enhanced, and the saturation was not stable at high voltage with a rapid increase of current. On the other hand, in the case of a-IGZO:Y TFT thin films, they showed stable saturation and amplification that indicating that the $I_{DS}-V_{DS}$ characteristics are stable.

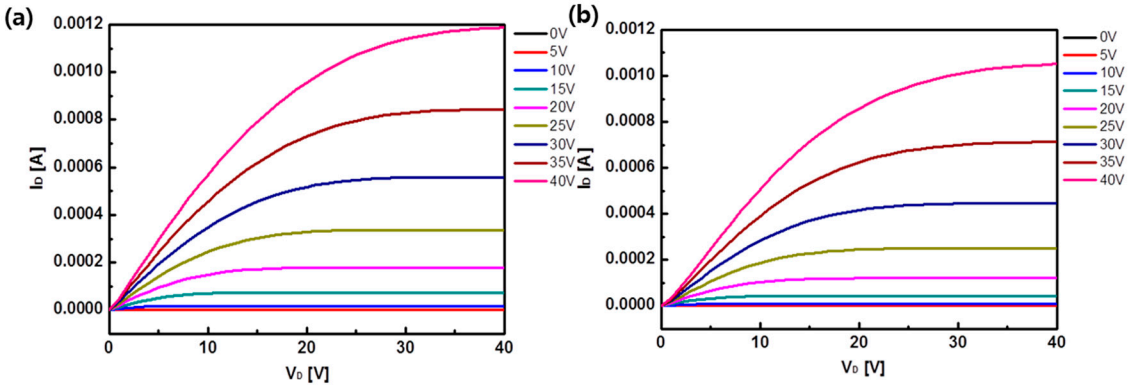

Figure 5. I_{DS}–V_{DS} characteristics of the (**a**) a-IGZO and (**b**) a-IGZO:Y TFTs.

Figure 6 shows the transfer characteristics of the a-IGZO and a-IGZO:Y TFTs. In the case of the I_{DS}–V_G characteristics, the drain current was measured at varying V_G (−40 to +40 V), while the V_{DS} in the saturation region was fixed. Saturation mobility (μ_{sat}) can be calculated using the following Equation (1):

$$I_D = \left(\frac{C_{ox} W \mu_{sat}}{2L}\right)(V_G - V_{TH})^2, \quad V_D > V_{D\_sat} - V_{TH} \tag{1}$$

where W, is the channel width, L is channel length, and C_{OX} is the capacitance per unit area of the gate-insulating layer. The value of the threshold voltage (V_{TH}), mobility (μ_{sat}), subthreshold slope (SS) and the current flicker ratio ($I_{on/off}$ ratio) were obtained from the data in Table 1. The characteristic parameters of the device are summarized in Table 1.

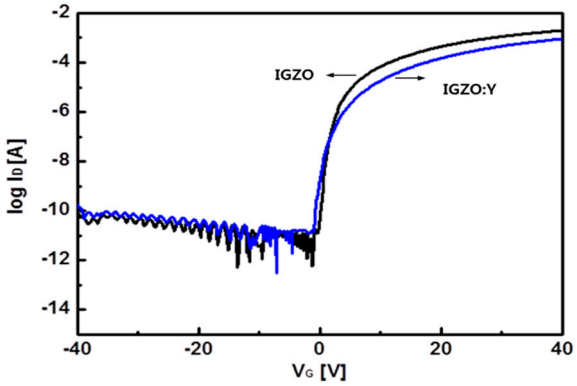

Figure 6. I_{DS}–V_G transfer characteristics of the a-IGZO and a-IGZO:Y TFTs.

Table 1. Summary of the extracted electrical characteristics of amorphous In−Ga−Zn−O (a-IGZO) and yttrium -doped a-IGZO (a-IGZO:Y).

Sample	V_{TH} (V)	μ_{sat} (cm^2 V^{-1} S^{-1})	$I_{on/off}$ Ratio	SS (V/dec)
a-IGZO TFT	3.2	10.5	5×10^9	0.43
a-IGZO:Y TFT	4.6	9.8	9×10^9	0.52

V_{TH} was obtained in the linear region of the transfer-characteristic curve and was found to increase due to the yttrium doping. As is evident from the shift of V_{TH} from 3.2 to 4.6 V and the increased SS value, the characteristics of the device seem to have been degraded. However, the current flicker ratio, which is important for the switching characteristics of the device, is increased with doping. The mobility is reduced, which is thought to be due to scattering from increased impurities in the film caused by the addition of the Y-dopant [13]. Moreover, the SS value increased to a small extent, which is a result of trapping in the thin film due to the addition of impurities. It is possible to confirm the influence of the Y-dopant on carrier suppression, and the result would indicate that the carrier amount and the trap density of the thin film can be controlled by the level of dopant.

Figure 7 shows the transfer characteristics of the TFTs with a positive gate bias stress. For the positive gate bias stress measurements, the TFTs were held at 10 V and changes in I_D–V_G curves measured at intervals of 10 min over the course of 1 h. Generally, the device is damaged by the deterioration of the gate oxide film due to the stress caused by the continuous voltage, or current, applied to the gate. In addition, a trapping phenomenon occurs due to the accumulation of charges between the channel layers and an injection phenomenon occurs in the insulating film so that the threshold voltage is increased by a decreased number of electrons [23]. As a result of the stress analysis in Figure 7b, it was confirmed that the threshold voltage shift of the a-IGZO:Y device is small and the stability at the off current is excellent. Therefore, the stable threshold voltage of the a-IGZO:Y device is considered to be influenced by the oxygen vacancy suppression caused by the yttrium doping. This observation suggests that the a-IGZO:Y thin films may be better suited for use in TFT devices when compared to a pure a-IGZO thin film.

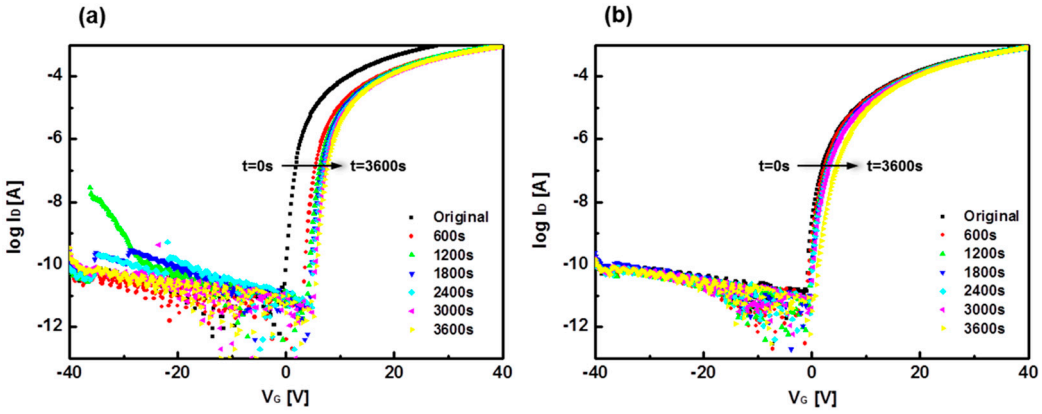

Figure 7. Transfer characteristics of (**a**) a-IGZO and (**b**) a-IGZO:Y TFTs with positive gate bias stress.

4. Conclusions

To improve the driving stability of a-IGZO TFTs, yttrium-doped a-IGZO thin films were prepared by magnetron co-sputtering. The electrical characteristics of the a-IGZO:Y thin film revealed an optimal condition for carrier concentration and Hall mobility when the RF power applied to the Y_2O_3 target was 70 W. The increased values of V_{TH} and SS, with yttrium doping, indicate that the device characteristics have been slightly degraded. In addition, the current flicker ratio, which is important for the switching characteristics of the device, was shown to increase. The yttrium-doped devices demonstrated a more stable driving mode as exhibited in the positive gate bias stress test. Through

yttrium doping of a-IGZO, we were able to achieve the goal of carrier control and electrical stability. It is believed that this work will provide an opportunity to make a stable TFT device.

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Conflicts of Interest: The authors declare no conflict of interest.

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