Crystallized IGTO as a Transparent Electrode for Replacing Conventional S/D Metal Electrodes in Transparent Displays

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Abstract

Transparent electrodes were fabricated by crystallizing IGTO thin films at 400°C. The IGTO transparent electrodes exhibited high mobility of 21.3 cm²/V·s and contact resistance comparable to that of conventional metal electrodes. These results demonstrate the potential of IGTO transparent electrodes to replace non-transparent metal electrodes.

Author Keywords

Transparent Display; Oxide Semiconductor; IGTO Crystallization; Transparent Electrode; Contact Resistance

1. Introduction

Recently, transparent displays have garnered significant attention both aesthetically and commercially. These displays consist of transparent and non-transparent regions, with the ongoing challenge of minimizing the non-transparent areas. Typically, the non-transparent regions are occupied by Thin-Film Transistors (TFTs) rather than OLED pixels, and metals such as Al, Ti, and Mo are commonly used as source and drain (S/D) electrodes, which are not transparent. Replacing these non-transparent metal electrodes with transparent electrodes that offer comparable electrical characteristics could enable the development of transparent displays with significantly higher transmittance.

In this study, Indium Gallium Tin Oxide (IGTO) oxide, which has been extensively studied as a channel layer, was crystallized and utilized as an electrode material. Unlike Indium Gallium Zinc Oxide (IGZO) and other oxides, IGTO achieves crystallization at much lower temperatures. This property is believed to enhance its electrical characteristics, demonstrating the potential of IGTO as a replacement for non-transparent metallic S/D electrodes.

2. Experimental

In this experiment, a Bottom Gate, Top Contact structure was employed. First, a 4-inch P^{++} silicon wafer, heavily doped with boron, was used as the gate electrode. On top of this, 150 nm of $SiO_2$was deposited via thermal oxidation, serving as the gate insulator. Second, the channel layer was formed using IGZO (In:Ga: Zn = 1:1:1 at%) deposited by RF plasma sputtering. The sputtering conditions for the deposition were RF power of 100 W, a process pressure of 3 mTorr, and process gas flows of 30 sccm Ar and 8 sccm O_2, resulting in a 15 nm-thick film. The channel layer was patterned on the wafer using a 2 cm by 2 cm metal mask made of Invar as a shadow mask (W/L = 500/300 μm). Finally, IGTO (In:Ga: Sn = 7:1:2 at%) was deposited as the source/drain electrodes using DC plasma sputtering. The sputtering conditions for the electrode deposition were DC power of 100 W, a process pressure of 2 mTorr, and a process gas flow of 30 sccm Ar with 0 sccm O_2, resulting in a 50 nm-thick film. After all depositions, the devices were annealed in a box furnace at 400°C for 1 hour in ambient atmosphere. Similar to the previous method, the channel layer was formed using IGZO (In:Ga: Zn = 1:1:1 at%) deposited by RF plasma sputtering. Additionally, ITO was deposited using an E-beam evaporator to obtain a thickness of 70 nm. The ITO deposition was carried out using DC plasma sputtering with the following conditions: DC power of 100 W, a process pressure of 2 mTorr, and gas flows of 30 sccm Ar and 0 sccm O_2, resulting in a 50 nm-thick film. The crystal structure was investigated using X-ray diffraction (XRD) and composition of the IGTO films, while X-ray photoelectron spectroscopy (XPS) was employed to examine the compositional ratios and perform surface analysis of the oxides. Lastly, UV-Vis spectroscopy was utilized to assess the transparency.

3. Results and Discussion

3.1 IGTO Electrode

Among oxide semiconductors similar to IGTO, IGZO is the most widely used as a channel layer. Significantly, IGZO does not crystallize even after annealing at temperatures ranging from 600°C to 700°C and retains its semiconductor properties [1]. However, as shown in Figure 1, devices with IGTO deposited as the channel layer undergo significant metallization above 350°C. Based on these findings, I explored the potential application of IGTO as an S/D transparent electrode instead of a channel layer. IGZO was deposited as the channel layer, and IGTO was sputtered as the S/D electrode under the same process conditions previously used for IGTO as the channel layer (R_O = 50%), replacing ITO. Here, Ro refers to the oxygen flow ratio, defined as $O_2/(Ar + O_2)$. As shown in Figure 2, the transistor transfer curve, indicating the I_{on}/I_{off} characteristics, started to form at an annealing temperature of 300°C, with the best performance observed at 400°C. This improvement is attributed to post-sputtering annealing. However, when the annealing temperature exceeded 400°C, excessive heat caused an increase in both on-current and the off-current, leading to degraded performance.

3.2 IGTO Optimazation

Based on the above experimental results, the potential of IGTO as a transparent S/D electrode has been demonstrated. To maximize the conductivity of IGTO electrodes, the oxygen flow ratio, one of the key process parameters, was optimized. The sputtering process conditions were fixed as follows: a process pressure of 2 mTorr, a DC plasma power of 100 W, a film thickness of 50 nm, and an Ar gas flow rate of 30 sccm. IGTO films were deposited while varying the oxygen flow ratio. The results of the oxygen flow ratio optimization experiment, as shown in Figure 3, demonstrate that decreasing the oxygen flow leads to an increase in mobility and the on/off ratio. In addition, Vth and SS decreased. Devices fabricated under the optimized process conditions exhibited the best electrical characteristics, with a mobility of 21.3 cm²/V·s, a sub-threshold swing of 0.75 V/decade, and an on/off ratio of 5.22×10^7.

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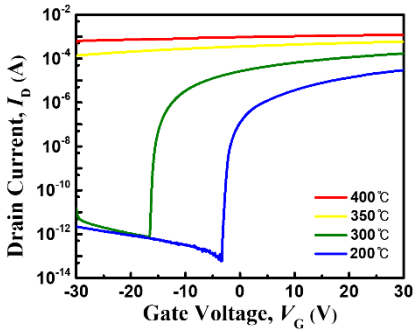

Figure 1. Transfer curve of the IGTO channel layer device at different annealing temperatures.

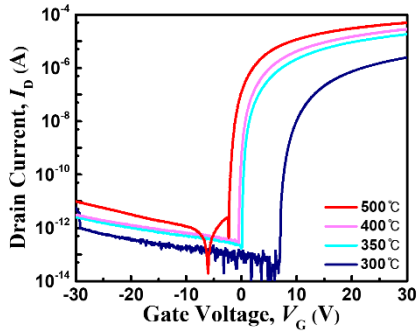

Figure 2. Transfer curve of the device with IGTO as S/D electrode at different annealing temperatures.

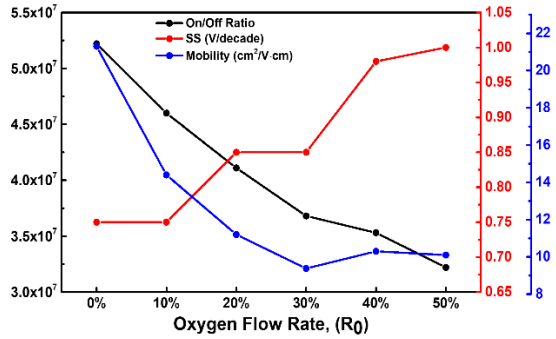

Figure 3. Electrical characteristic parameters of the device with IGTO S/D electrodes at different oxygen flow ratios.

3.3 IGTO Crystalization

Typically, as the oxygen flow ratio increases during the sputtering deposition of oxide films, the electrical conductivity of the films tends to decrease. This is because a decrease in the oxygen flow ratio results in an increased amount of Ar gas, which leads to more collisions between the Ar gas and the covalent bonds between the oxygen ions and metal ions in the oxide layer during the sputtering process, causing these bonds to break. As a result, oxygen atoms are separated, creating more oxygen vacancies, which significantly reduce the resistance of the film [2]. However, a comparison of the XPS spectra of IGTO films with Ro = 0% and Ro = 50% reveals a completely opposite trend. On the contrary, the IGTO film with the lowest oxygen flow ratio (RO = 0%) exhibits significantly fewer oxygen vacancies. Figures 4(a) and 4(b) illustrate the XPS spectra of IGTO films deposited at R_O = 0% and R_O = 50%, respectively. The O1s spectra of the IGTO films, shown in Figures 4(a) and 4(b), are deconvoluted into peaks corresponding to binding energies of 529.8 eV (O_I), 530.8 eV (O_{II}), and 531.9 eV (O_{III}), which represent different chemical states of oxygen in the films [3]. The O_{II} peak of the R_O = 0% IGTO films was reduced by 26.8% compared to that of the R_O = 50% IGTO film. In contrast, the O_I peak of the R_O = 0% IGTO films showed a dramatic increase compared to the corresponding peak of the R_O = 50% IGTO films. Additionally, the total sum of the raw data peaks is significantly higher for the R_O = 0% IGTO films compared to the R_O = 50% IGTO films. The area ratio of the O_{II} to O_I peaks provides an additional indicator of the relative amount of oxygen defects in the IGTO film [4]. The O_{II}/O_I ratio for the R_O = 0% IGTO films is 0.317, while for the R_O = 50% IGTO films, it increases to 0.538. The R_O = 0% IGTO films exhibit a much lower value. This indicates a reduction in oxygen vacancy density and a significant increase in the number of stable M-O bonds. Finally, the O_{III} peak is also smaller for R_O = 0% IGTO films compared to R_O = 50% IGTO films. The O_{III} peak is associated with electron traps, and its reduction suggests a decrease in trap states. As a result, the higher conductivity of the R_O = 0% IGTO films is due to the effects of crystallization [5].

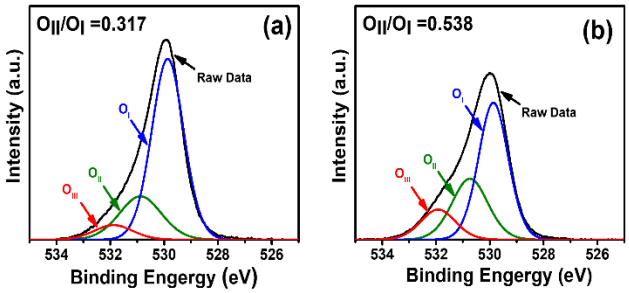

Figure 4. O1s XPS spectra: (a) R_O=0% IGTO films, (b) R_O=50% IGTO films.

To confirm the crystallization of IGTO films, the GI-XRD patterns of IGTO films with R_O = 0% and R_O = 50% were compared. Figure 5 shows the GI-XRD patterns of the IGTO films. As seen in Figure 5, R_O = 0% IGTO films clearly underwent crystallization, with a peak observed in the XRD spectrum. However, for the R_O = 50% IGTO films, the material remains in an amorphous state. This difference in crystallization is responsible for the variations in electrical characteristics. The crystallization leads to a reduction in oxygen vacancies and an improvement in crystallinity. As the oxygen vacancies decrease, the structural stability increases, and conductivity can also improve. Additionally, the stabilization of the crystal arrangement results in a reduction in resistance [6].

Additionally, the variation in the degree of crystallization of R_O = 0% IGTO thin films with annealing temperature was investigated. Figure 6 presents the GI-XRD patterns of R_O = 0% IGTO thin films annealed at various temperatures. Peaks were observed only in the sample annealed at 400°C, while no noticeable peaks appeared at lower temperatures. Analysis of these peaks revealed that the 211, 222, 400, 440, and 622 peaks correspond to In_2O_3, indicating a significant influence of indium on the crystallization of IGTO. These results confirm that crystallization of IGTO

begins at approximately 400°C, with the most pronounced crystallization occurring at this temperature.

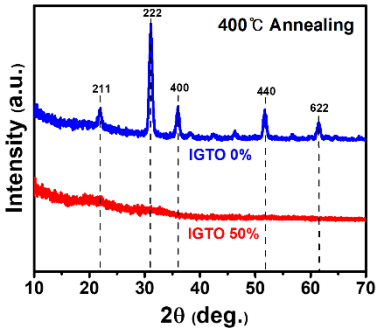

Figure 5. GI-XRD patterns of Ro = 0% and Ro = 50% IGTO films after annealing at 400°C.

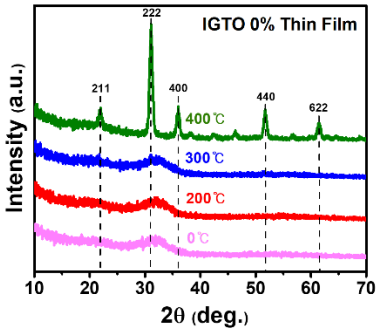

Figure 6. GI-XRD patterns of Ro=0% IGTO films at different annealing temperatures.

3.4 Electrical Characteristics

The electrical characteristics of devices using IGTO, deposited under optimized conditions as the S/D transparent electrode on an IGZO channel layer, were measured. Additionally, the electrical characteristics of Al electrodes, which are most commonly used as S/D electrodes in display panels, and ITO electrodes, currently the most widely used transparent electrodes, were compared. Figure 7(a) and (b) illustrate the transfer curves of IGTO, ITO, and Al electrodes. In general, IGTO electrodes exhibit significantly lower off-current across the entire off-state region. The IGTO electrode shows minimal leakage current even at very low gate voltage. Furthermore, in the on-state region, the IGTO electrode device shows higher on-current compared to the ITO electrode device. When comparing the Al electrode device with the IGTO electrode device, the on-current is slightly lower in the low gate voltage region, but as the gate voltage increases, they become more similar. This difference is expected to be influenced by the Ga atoms in IGTO. Compared to Sn atoms, Ga atoms have a stronger ability to bind with oxygen vacancies, thereby reducing the oxygen vacancies [7].

Table 1 shows the detailed electrical characteristic parameters of the three electrodes. The IGTO electrode device exhibits the highest mobility of 21.3 $cm^2/V{\cdot}s$ and the best on/off ratio of 5.22×10^7. In summary, when IGTO is used as the S/D electrode, it demonstrates superior electrical characteristics compared to the most common transparent electrode, ITO, and shows electrical characteristics similar to those of the most widely used S/D electrode, Al.

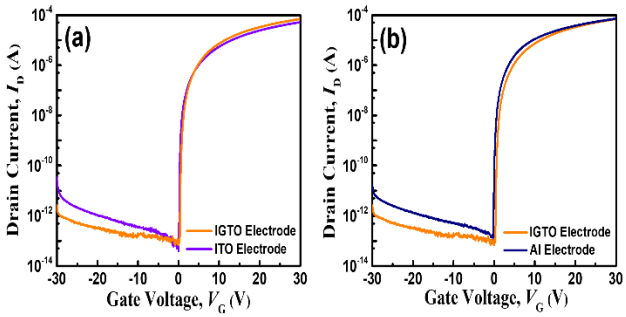

Figure 7. Comparison of transfer curves: (a) devices with IGTO and ITO as S/D electrodes, (b) devices with IGTO and Al as S/D electrodes.

Table 1. Electrical characteristics parameters of devices with IGTO, ITO, and Al as S/D electrodes.

Electrode	IGTO	Al	ITO
Mobility ($cm^2/V{\cdot}s$)	21.3	19.5	19.1
V_{th} (V)	1.3	0.7	0.9
SS (V/decade)	0.75	0.5	0.86
On/Off Ratio	5.22×10^7	3.54×10^7	2.37×10^7

Figure 8 shows the contact resistance between the three electrodes and the IGZO channel layer. The X-axis in Figure 8 shows the channel length (200 ~ 400 nm), while the Y-axis shows the total resistance. The total resistance was obtained from the output curve of each device. The process is as follows: for each channel length, the output curve was obtained for V_G values ranging from 0.1V to 2V. Then, V_D was fixed at 0.1V, and the slope at each V_G (0.8V, 1V, 1.2V, 1.4V, 1.6V, 1.8V, 2V) was calculated to extract the total resistance. Finally, the total resistance versus channel length was plotted, and linear fitting was performed. The intersection points of each line were considered as the contact resistance. To compare the contact resistance, the final value should be obtained by multiplying the resistance by the channel width (W). However, since all devices have the same channel width of 500 μm, only the resistance values were compared relatively. The contact resistance of the IGTO electrode is approximately 0.85 MΩ, which is significantly lower than the 1.23 MΩ contact resistance of the ITO electrode. It also shows a value very similar to the 0.79 MΩ contact resistance of the Al metal electrode. The extracted contact resistance from the graph is in line with previously reported values (tens to hundreds of kΩ) for contact resistance [8]. Thus, it can be concluded that when IGTO electrodes are deposited along with the IGZO channel, the contact resistance is superior to that of the commonly used transparent electrode ITO and similar to that of metal electrodes.

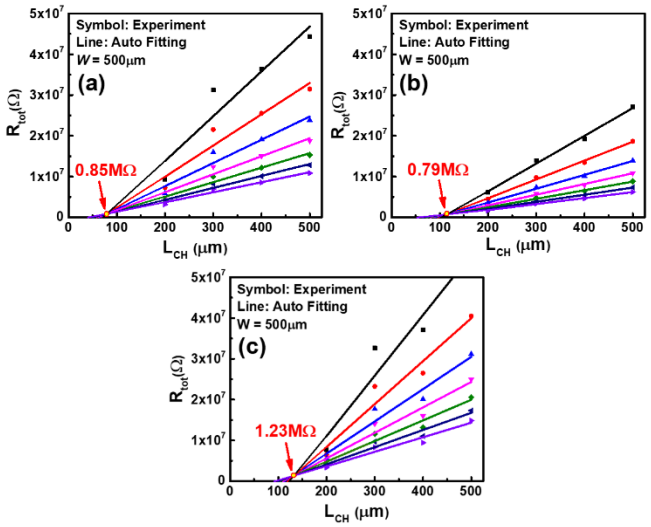

Figure 8. Graph of total resistance versus channel length with linear fitting: (a) device with IGTO as S/D electrodes, (b) device with Al as S/D electrodes, and (c) device with ITO as S/D electrodes.

3.5 Optical Characteristics

Figure 9 shows the optical transmittance graph measured using a UV-Vis spectrometer. Immediately after IGTO films deposition, the optical transmittance in the 350 nm region was measured to be as low as approximately 51.8%. However, the transmittance significantly increased after annealing at 400°C. Even after the deposition of not only IGTO but also the IGZO channel layer and SiO2 insulating layer, the transmittance remained very stable and high, reaching around 80.5% in the 350 nm region. Additionally, after annealing, the absorption edge exhibited a blue shift(shift to the left). This shift is because of the enhancement in the crystallization of IGTO from thermal decomposition and atomic rearrangement [9]. Typically, when metals such as Al are used as S/D electrodes, the transmittance is below 10%. However, by using IGTO as a transparent S/D electrode, a very high transmittance of up to 81.9% in the visible light range can still be achieved, even after annealing at 400°C.

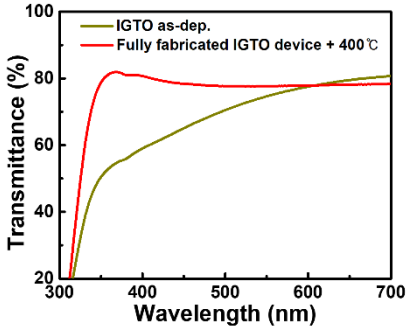

Figure 9. Optical transmittance versus wavelength graph for reference IGTO film and fully processed IGTO device after 400°C annealing.

4. Summary

In summary, the properties of crystallized IGTO were evaluated when used as a transparent S/D electrode, Instead of as a channel layer. Unlike other oxide semiconductors, IGTO undergoes crystallization and becomes electrode-like at annealing temperatures above 350°C. The crystallization was confirmed through GI-XRD and XPS analysis. It was observed that, IGTO at R_O=0% exhibited the clearest crystallization and the best properties, including a mobility of 21.3 $cm^2/V \cdot s$, a sub-threshold swing of 0.75 V/decade, and an on/off ratio of 5.22×10^7. Electrical characteristics and contact resistance measured from the I-V curve show that IGTO performs similarly to the Al metal electrode. After annealing at 400°C, IGTO maintains an exceptionally high transmittance in the visible range, ranging from 78.2% to 81.9%. As a result, the use of IGTO as an S/D transparent electrode demonstrates the potential for high-performance transparent TFTs. This could contribute to the development of transparent display panels with significantly higher transmittance.

5. References

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