Performance improvement of thin-film transistors with In$_2$O$_3$ channel engineering

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**ABSTRACT**

Thin-film transistors (TFTs) with bilayer channels were used to improve the field-effect mobility and bias stress stability of the TFTs. Homogeneous structures were fabricated by the combination of a carrier deficient layer made of In$_2$O$_3$ thin film annealed in oxygen atmosphere (InO:A) and an electron injection layer made of In$_2$O$_3$ thin film annealed in air (InO:A). Compared with the InO:A/InO:A TFT with only air annealing, the field-effect mobility of InO:A/InO:A TFT with two-step annealing process was improved from 0.04 to 5.11 cm$^2$/Vs, the on/off current ratio was ameliorated from 4.6 × 10$^5$ to 7.6 × 10$^5$ A, while the $V_{th}$ is decreased from 12.5 to 4.7 V under the positive bias stressing (PBS). It is confirmed that the excessive oxygen vacancies are produced by annealing the thin film in the air. The electrical performance of the InO:A/InO:A TFTs with two-step annealing process is greatly improved due to the formation of a low defect state and high carrier concentration electron transport layer, through the combination of the carrier transport layer and the carrier injection layer. These optimized electrical properties indicate an important step toward achieving transparent, high performance, and low-temperature metal oxides TFTs.

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1. Introduction

Metal oxide semiconductors (MOS) based thin-film transistors (TFTs) exhibit excellent electrical characteristics including high carrier mobility, high optical transparency, and simple synthesis process [1,2]. These advantages made MOS a pivotal position for the applications in transparent electronics, flexible electronics, logic devices and neuromorphic networks [3–5]. Among the MOS, In$_2$O$_3$ received considerable attention because of its high carrier mobility, high transmittance in the visible region and a direct band gap of 3.75 eV [6–8]. Nevertheless, In$_2$O$_3$ TFT limited mobility and stability at low temperatures is still a challenging problem to meet with ultra-high-definition displays or flexible displays of the latest demand, particularly for solution treated metal oxide TFT [9–11]. Up to now, great efforts have been devoted to improve the electrical performance of the TFTs based on solution-processed In$_2$O$_3$ thin film, including defect doping [5,8], plasma treatment [6,12], oxygen atmosphere annealing [13], and so forth. Among them, In$_2$O$_3$ with appropriate doping has shown improved stability but engendered unwanted mobility scarification due to the formation of scattering centers and the reduction of the carrier concentration [9]. Oxygen atmosphere annealing has also been reported to improve the stability of In$_2$O$_3$ TFT by reducing oxygen vacancies [13], which relies on the existence of defect states, such as oxygen vacancies and organic residues [14]. However, it would also induce an inevitable reduction in carrier concentration when the oxygen vacancies are reduced, because the carriers are mainly originated from the donor-state oxygen vacancies [14,15]. To overcome the inevitable trade-off among the device stability and its carrier concentration and mobility, a device structure with proper design has been reported to obtain channels with both high carrier concentration and low defect states. So far, TFT devices with dual-channel structures such as IGO/GIZO [16], ZTO/ITO [17], and IGO/IZO [18] have been fabricated and exhibit excellent electrical properties. However, in these dual-channel TFTs, element doping is introduced into the channel layer to adjust the defect state, which inevitably forms scattering centers, resulting in a decrease in the mobility of the carrier transport layer.

In this work, the TFTs with rationally designed two-step annealing process were proposed. The channels combined an In$_2$O$_3$ carrier transport layer annealed in oxygen atmosphere (InO:A) and an electron injection layer fabricated by air annealing (InO:A). At the same time, the TFTs with bilayer channel structures composed of InO:A/InO:A and InO:A/InO:O device were constructed and tested for comparison. Due to the separation of the injection layer and the transport layer, the TFT with bilayer channel of InO:A/InO:A exhibits significantly higher stability, and the mobility at low temperature is also increased.
2. Experiment

The TFT with bilayer channels adopts a bottom gate and top contact device structure. A thickness of 100 nm thermally grown SiO₂ layer was used as the dielectric layer and p-type Si substrate was used as the gate electrode. To form a dual channel of the TFT devices, In₂O₃ semiconductor layers were prepared by dissolving 0.3 g of indium nitrate hydrate (In(NO₃)₃·xH₂O, 99.9%, Aladdin) into 10 mL 2-methoxyethanol (2-ME, 99.8%, Aladdin). The precursor was constantly stirred for 12 h at room temperature to form the uniform sol–gel solution. In order to fabricate the TFT with a bilayer channel, 0.1 M In₂O₃ precursor solution was firstly spin-coated on the SiO₂/Si substrate at 500 rpm for 3 s and 5000 rpm for 30 s, respectively. The sample was baked at 150°C for 15 min and subsequently annealed at 280°C for 2 h in an oxygen atmosphere. Subsequently, an electron injection layer was prepared by repeating the above-mentioned spin coating steps and finally annealed in air at 280°C for 2 h. Finally, Al source and drain electrodes were thermally evaporated by the shadow mask evaporation on In₂O₃ thin films. In this work, the channel length and width of these devices are, respectively, 100 and 1000 µm.

3. Results and discussion

Figure 1(a) shows the transfer characteristics of the TFTs based on In₂O₃ thin films with various channel configurations (InO:O/InO:A, InO:O/InO:O and InO:A/InO:O), and the key electrical parameters of the TFTs were extracted and are listed in Table 1. The output curves of the TFTs based on InO:O/InO:A are shown in Figure 1(b), which exhibit a clear pinch off and apparent current saturation behavior. Without observation of any current congestion, the ohmic contacts between the film and the electrodes are verified. It can be seen from Table 1 that the electrical properties of the TFTs based on InO:O/InO:A have been greatly improved compared with InO:A/InO:A and InO:O/InO:O, including high on-state current, carrier mobility, and low subthreshold swing (SS) value.

In order to explain these phenomena, the mechanism explanation diagram is proposed and shown in Figure 1(c). As previously reported, due to the reduction of oxygen vacancies and organic residues for the thin film annealed in oxygen atmosphere, a dense MOS can be obtained [19,20]. The increase of the metal-oxide lattice is helpful for the electron transfer from the valence band to the conduction band, with the special 4d¹⁰5s° electron configuration as electron transport pathways [21]. As a result, the carrier

![Figure 1](image-url)

Figure 1. (a) Transfer characteristics of TFTs based on In₂O₃ with various channel configurations (InO:O/InO:A, InO:O/InO:O and InO:A/InO:O) (b) Output characteristics of TFTs based on In₂O₃/In₂O₃-A. (c) TFT device structure and mechanism explanation diagram of TFTs based on In₂O₃/In₂O₃-A.
trapping and scattering can be reduced by using InO:O as a carrier transport layer. As the gate voltage is applied, more carriers can be injected into the electron transport layer due to the excessive carrier concentration in the injection layer. Therefore, the formation of carrier transport channel with high carrier concentration and low defect density can be expected, which leads to the increased $\mu_{FE}$ and decreased SS value for the TFTs based on InO:O/InO:A [16, 22]. When InO:A thin film is used as a carrier transport layer, the mobility of TFTs based on InO:A/InO:A is decreased due to the trapping of the carriers, as indicated in Figure 1(a). Compared with the TFTs based on InO:A/InO:A, an increase in $\mu_{FE}$ and a smaller SS value of TFTs based on InO:O/InO:O are obtained, due to the decrease in the defects in the transport layer [20]. However, the on-state current and the field-effect mobility of TFTs based on InO:O/InO:O are low compared to the TFTs based on InO:O/InO:A channels. This is due to the lack of electron injection layer and the low carrier concentration in the carrier transport layer.

In order to verify the chemical compositions of the In$_2$O$_3$ thin films annealed in different atmospheres, X-ray photoelectron spectroscopy (XPS) investigations were performed, and the results are shown in Figure 2.

Table 1. Electrical parameters of TFTs based on bilayer channels of InO:A/InO:A, InO:O/InO:O, and InO:O/InO:A.

| Sample           | $I_{on}$ | $I_{off}/I_{on}$ | SS [V dec$^{-1}$] | $\mu_{FE}$ [cm$^2$/V s] |
|------------------|---------|------------------|-------------------|------------------------|
| InO:O/InO:A      | 2.4 × 10$^{-5}$ | 4.6 × 10$^{-4}$ | 0.75              | 0.04                   |
| InO:O/InO:A      | 1.9 × 10$^{-4}$ | 1.0 × 10$^{-3}$ | 0.22              | 0.98                   |
| InO:O/InO:A      | 8.2 × 10$^{-4}$ | 7.6 × 10$^{-3}$ | 0.08              | 5.11                   |

O1s spectrum of the In$_2$O$_3$ thin films can be divided into three peaks located at 529.6, 531.5 and 532.3 eV, respectively. The dominant peak represents the oxygen bond of metal oxide (O$_i$), which is located at 529.6 eV. The peak at 531.5 eV is related to the oxygen vacancies (O$_{\delta}$) and the peak centered at 532.3 eV indicates the remaining of hydroxide (O$_{\delta}$). It is found that the atomic percentage of V$_{\delta}$ (O$_{\delta}$) in the In$_2$O$_3$ film annealed in O$_2$ is decreased from 45.9% to 42.3%, the OH bond is decreased from 7.5% to 5.5%, and the M-O bond is increased from 46.6% to 52.2%. This result demonstrates that dense MOS can be obtained by annealing in an oxygen atmosphere, due to the reduction of the oxygen vacancies and the organic residues. This result is consistent with the electrical performance of the TFTs depicted in Figure 1(a).

Notably, it has been reported in some studies that the peak at 531.5 eV is assigned to the C-O related species [23–25]. It is assumed that the C-O related species are mainly originated from the absorption and diffusion of carbon contamination, and the incomplete conversion of the oxide. The surface and interior XPS survey scans of the In$_2$O$_3$ thin films annealed in various atmospheres (air or oxygen) are measured and shown in Figure 3(a–d), respectively. The amount of the atoms at various positions of the thin film annealed in different atmospheres are listed in Table 2, and a small amount of carbon can be detected in the thin films.

Figure 4(a,b) show the surface and interior C1s XPS spectra of In$_2$O$_3$ film annealed in air, and Figure 4(c,d) show the surface and interior C1s XPS...
spectra of \( \text{In}_2\text{O}_3 \) film annealed in oxygen. For the \( \text{In}_2\text{O}_3 \) film annealed in oxygen, the atomic content of carbon is 17.04\% on the surface and 5.94\% in the interior of the thin film. For the \( \text{In}_2\text{O}_3 \) film annealed in the air, the atomic content of carbon is 20.74\% on the surface and 7.85\% in the interior of the thin film. The large content of C1s on the surface of the thin film indicates that C-O bond exists on the surface is largely due to the carbon contamination, while the content of C1s in the thin film is not negligible (5.94\% and 7.85\%). The result indicates that the peak at 531.5 eV can be due to contributions from the bond of C-O and oxygen vacancies, which exist in the \( \text{In}_2\text{O}_3 \) thin film fabricated by the sol-gel method and annealed at low temperature. In the literature, the carbon-related impurities are responsible for the negative bias stress stability of the TFT [23,24]. As depicted in Figure 5, the TFT based on \( \text{InO}:\text{O}/\text{InO}:\text{A} \) exhibits good stability under negative bias stress (NBS) condition. This demonstrates that the C-O bond-related impurities exhibit a small effect on the device performance, and the \( V_O \) are dominant in determining the electrical performance of the device.

In order to further study the stability of the TFT devices, the positive bias stress (PBS) tests were also carried out by applying a \( V_{GS} \) of +30 V for 1000 s. Figure 6(a,b) show the transfer characteristics of the TFTs based on \( \text{InO}:\text{O}/\text{InO}:\text{A} \) and \( \text{InO}:\text{A}/\text{InO}:\text{A} \), respectively, as a function of PBS time. It can be found that all the transfer curves for the TFTs based on \( \text{InO}:\text{O}/\text{InO}:\text{A} \) and \( \text{InO}:\text{A}/\text{InO}:\text{A} \) are positively shifted under PBS. This is due to the fact that the carriers are trapped by the trap state at the dielectric/channel interface and/or in the carrier transport layer [26]. With the positive voltage applied, the carriers are induced at the interface between the dielectric and the channel layer, and then captured by the traps [22]. As the carrier concentration in the channel layer is decreased, the trapped electrons could partially screen the electric field [26]. This results in a positive shift of the threshold
voltage, which can be observed from the transfer characteristics of the TFTs. After being stressed for 1000 s, the $V_{TH}$ shift of the TFT based on InO:O/InO:A is 4.4 V, which is evidently smaller than that based on InO:A/InO:A (12.5 V). This is attributed to the formation of a carrier transport layer with low defect density and high carrier concentration.

4. Conclusion

In summary, the TFT based on the InO:O and InO:A with a two-step annealing process was integrated and compared. Due to the formation of the electron injection layer (InO:A) and the transport layer (InO:O), the field-effect mobility and the stability of the TFT based on InO:O/InO:A channels are improved compared to that based on InO:A/InO:A. The field-effect mobility is improved from 0.04 to 5.11 cm$^2$/Vs and the $V_{TH}$ shift is decreased from 12.5 to 4.7 V under the PBS tests for 1000 s. The high-performance TFTs with proper channel engineering provide a new route for flexible devices fabricated by low-temperature solution processes.

Disclosure statement

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