Effects of Source/Drain Electrodes on the Performance of InSnO Thin-Film Transistors

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Abstract: Oxide thin-film transistors (TFTs) are of increasing interest in the field of advanced displays. In this work, we explore Al, InSnO (ITO), Ti, and Mo as source/drain electrodes of ITO TFTs. A comparison study is conducted on the electrical properties of ITO TFTs with the four categories of source/drain electrodes. Interestingly, the ITO TFT with an Al source/drain electrode exhibits better device performance, such as a field-effect mobility ($\mu_{FE}$) of 26.45 cm$^2$/Vs, a reasonable turn-on voltage ($V_{ON}$) of 2.7 V, and a steep subthreshold swing (SS) of 201.50 mV/decade. The contact properties of ITO TFTs are further analyzed, and the results show that the device with an Al electrode exhibits lower contact resistance than the other devices. However, the devices with the four electrode materials all reveal excellent stability under negative bias illumination stress (NBIS) with $|\Delta V_{TH}| < 1$ V. This work paves the way for the practical applications of ITO TFTs in next-generation displays.

Keywords: InSnO (ITO); thin-film transistors (TFTs); contact resistance; source/drain electrodes; bias stress stability

1. Introduction

Oxide thin-film transistors (TFTs) are promising candidates for next-generation transparent and flexible displays due to their high transmittance, high mobility, low cost, and low temperature process [1–5]. Among all kinds of oxide semiconductor materials, InGaZnO (IGZO) is the most represented category and has been studied extensively in recent years [6–10]. However, the typical mobility of IGZO TFTs is only around 10 cm$^2$/Vs, which is not high enough to satisfy the increasing demands of next-generation displays with ultra-fast frame rates and ultra-high resolutions. Therefore, other novel oxide materials, such as InSnO (ITO), InZnO (IZO), ZnON, AlZnO (AZO), and ZnSnO (ZTO), that exhibit high carrier mobility have been extensively investigated recently to replace IGZO [11–15].

It is known that the contact resistance between the channel layer and source/drain electrode is a bottleneck factor on the performance of oxide TFTs, which is responsible for limiting the transconductance (hence the device mobility) [16–19]. However, as the display size and resolution increase, the reduction of RC load of display is in urgent need, which also requires low-resistance metals for the source/drain electrodes of oxide TFTs [20]. Therefore, exploration of suitable source/drain electrode materials is necessary to realize the practical applications of oxide TFTs in large-area and advanced displays. Much research has been carried out regarding low-resistance source/drain electrodes on the performance of oxide TFTs [21–26]. According to previous reports, conducting materials such as Al, ITO, Ti, and Mo are commonly used as source/drain electrodes since they are more likely to form ohmic contacts, which is beneficial to achieve high-performance oxide TFTs.

ITO is well-known as a transparent conductive material and has been widely used in display applications for transparent electrodes. Recently, utilization of ITO as a channel material has been a research hotspot in the field of oxide TFTs due to its great potential...
to achieve high mobility \([11,27,28]\). In our previous work, ITO was investigated as a channel layer of TFTs, and excellent electrical characteristics were obtained \([29]\). However, our previous studies did not investigate source/drain electrode materials of ITO TFTs. Therefore, in this work we investigate source/drain electrode materials, exploring Al, ITO, Ti, and Mo as source/drain electrodes. The results demonstrate that the device with an Al source/drain electrode exhibits the best performance with a high field-effect mobility \((\mu_{FE})\) of 26.45 \(\text{cm}^2/\text{Vs}\), a reasonable turn-on voltage \((V_{ON})\) of 2.7 V, and a steep subthreshold swing \((SS)\) of 201.50 mV/decade. We hope that our work can accelerate the practical applications of ITO TFTs in next-generation displays.

2. Experimental Methods

As shown in Figure 1, bottom-gate top-contact ITO TFTs were fabricated in this work. A heavily-doped n-type Si wafer was used as both the substrate and gate electrode. Firstly, the Si wafer was ultrasonic cleaned in acetone, alcohol, and deionized water for five minutes, respectively. Subsequently, a bi-layer gate insulator (\(\text{HfO}_2/\text{Al}_2\text{O}_3\)) was prepared. 30 nm thick \(\text{HfO}_2\) was deposited using a radio-frequency (RF) magnetron sputter (Beijing Jinshengweina, JR-2B) in an \(\text{Ar}/\text{O}_2 = 90/10\) atmosphere at room temperature, and 10 nm thick \(\text{Al}_2\text{O}_3\) was deposited using an ALD system (MEZ, M-150) at 100 °C. The precursors used for deposition of \(\text{Al}_2\text{O}_3\) were trimethylaluminum and deionized water. Afterwards, 5 nm thick ITO channel layer was sputtered in an \(\text{Ar}/\text{O}_2\) atmosphere with an 80/20 ratio at room temperature. Finally, four kinds of source/drain electrodes were sputtered at room temperature, including Al, ITO, Ti, and Mo. The devices were patterned using conventional photolithography (SUSS, MJB4) and a lift-off process.

Channel dimensions of the ITO TFTs were 100 \(\mu\text{m} \times 100 \mu\text{m}\). The size of the S/D electrode was 60 \(\mu\text{m} \times 100 \mu\text{m}\). Thermal annealing was performed after source/drain electrode deposition under vacuum at 100 °C for 1 h. The electrical characteristics were evaluated using an Agilent B1500A semiconductor device analyzer. The interface properties of the S/D electrode and ITO channel were examined using transmission electron microscopy (TEM, FEI Tecnai F20).

![Schematic device structure of ITO TFTs.](image)

3. Results and Discussion

To determine the effects of the electrode materials on the electrical properties of the ITO TFTs, typical transfer curves were firstly measured, as shown in Figure 2a–d. The gate bias was applied from −10 to 10 V with drain voltages of 0.1 and 10 V. The gate leakage current \((I_{GS})\) is also provided in Figure 2. For all devices, \(I_{GS}\) is lower than 100 pA, which is negligible compared to \(I_D\). To analyze the samples quantitively, we extracted some important parameters, as listed in Table 1. The \(\mu_{FE}\) is the linear mobility and is determined by the maximum transconductance \((g_{m})\) at a drain voltage of 0.1 V. It is calculated using Equations (1) and (2).
\[
g_m = \frac{\partial I_D}{\partial V_G} \quad (1)
\]

\[
\mu_{FE} = \frac{g_m L}{W C_{OX} V_D} \quad (2)
\]

\(C_{OX}\) is the gate insulator capacitance per unit area, \(L\) is the channel length, and \(W\) is the channel width [30]. \(V_{ON}\) is defined as the gate voltage that induced a drain current of 1 nA. SS is estimated using Equation (3) [31].

\[
SS = \left[\frac{\partial \log(I_D)}{\partial V_G}\right]^{-1} \quad (3)
\]

Notably, the device with an Al source/drain electrode after annealing revealed better electrical properties than the other devices, showing a high \(\mu_{FE}\) of 26.45 cm²/Vs, a reasonable \(V_{ON}\) of 2.7 V, and a steep SS of 201.50 mV/decade. The excellent electrical performance of the ITO TFT with an Al source/drain electrode is comparable to our previous work [29], which demonstrates the feasibility of ITO materials for TFTs. The above results illustrate that Al is a suitable electrode material for ITO TFTs.

Figure 2. Transfer curves of annealed ITO TFTs with (a) Al, (b) ITO, (c) Ti, and (d) Mo source/drain electrodes.

\(g_m\) as a function of \(V_G\) was also extracted and is shown in Figure 3. The four devices reach a maximum \(g_m\) (hence \(\mu_{FE}\)) at a close \(V_G\), while the device with an Al electrode exhibits a larger maximum \(g_m\) (hence \(\mu_{FE}\)) than the other devices. The presence of a maximum \(g_m\) (hence \(\mu_{FE}\)) can be attributed to the material properties of the channel layer. Since ITO is amorphous, the trap density is low and a large \(\mu_{FE}\) can be achieved when the small potential barriers associated with structural disorder are surpassed, where \(\mu_{FE}\) is maximum. As \(V_G\) increases, the conductive channel is drawn closer to the ITO/Al₂O₃ interface, which contributes to increased scattering effects resulting in a decrease of \(\mu_{FE}\) [1].
Figure 4 shows the output curves of annealed ITO TFTs with the four different source/drain electrode materials. The device with an Al electrode (Figure 4a) exhibits the largest output current with a distinct linear and saturation region, which is consistent with transfer curves. The device with an ITO electrode (Figure 4b) exhibits a lower output current than the device with an Al electrode. For the devices with Ti and Mo electrodes (Figure 4c,d), the saturation current presents a trend that increases first and then decreases with drain voltage, which may be caused by the large vacancies, traps, and interface charges between the channel layer and the source/drain electrodes. In addition, there is a jitter of the saturation current in Figure 4c,d. Therefore, the output characteristics also demonstrate that Al is a suitable electrode material for ITO TFTs.

Table 1. Electrical parameters of ITO TFTs, including $\mu_{FE}$, SS, and $V_{ON}$.

| Source/Drain | $\mu_{FE}$ (cm$^2$/Vs) | SS (mV/Decade) | $V_{ON}$ (V) |
|--------------|------------------------|----------------|--------------|
| Al           | 26.45                  | 201.50         | 2.7          |
| ITO          | 20.83                  | 108.70         | 3.9          |
| Ti           | 12.46                  | 179.00         | 4.5          |
| Mo           | 7.99                   | 113.39         | 5.3          |
Here, \( r_{ch} \) is the channel resistance per unit channel length. Figure 5 shows the \( R_T \) as a function of the channel length (L) at various gate voltages for the ITO TFTs with different source/drain electrode materials. Considering that the lines related to \( V_G \) of 6 V and 7 V in all Figures (Figure 5a–d) show better linearity, we used those two lines for linear fitting to obtain the value of \( R_{SD} \), as shown in the insets in Figure 5a–d. After applying linear fitting, the width-normalized contact resistance (\( R_{SD} \times W \)) of the TFTs with Al, ITO, Ti, and Mo electrodes were calculated to be 109.4, 165.8, 207.3, and 411.7 k\( \Omega \)·\( \mu \)m, respectively. Of note, the \( R_{SD} \) presents transfer and output curves with a consistent trend. The contact property indicates that ideal ohmic contact can be readily formed between the ITO channel layer and Al electrode. However, a comparison with recent reports of oxide TFTs with different source/drain electrodes is exhibited in Table 2. Our ITO TFT with an Al source/drain electrode shows competitive characteristics.
Previous studies have reported that the contact resistance of the source/drain electrode and channel layer decreases with the decreasing work function of the source/drain electrode. The electrode with the lower work function is more likely to form ohmic contact. It was previously reported that the work functions of Al, ITO, Ti, and Mo are 4.28 eV, 4.32 eV, 4.33 eV, and 4.60 eV, respectively [32,33]. Therefore, the ITO TFT with an Al source/drain electrode shows the best performance possibly due to its low work function.

For further evaluating the contact property between the ITO channel layer and different source/drain electrode materials, the transmission line method (TLM) was utilized to extract contact resistance ($R_{SD}$) [34]. The total resistance ($R_T$) was defined as the sum of channel resistance ($R_{ch}$) and $R_{SD}$ at $V_D = 0.1$ V by the following equation:

$$R_T = \frac{V_D}{I_D} = R_{ch} + R_{SD} = r_{ch}L + R_{SD}$$  (4)

### Table 2. Summary of recent reports for major electrical parameters of oxide TFTs with different source/drain electrodes.

| Source/Drain | Channel | $R_{SD} \times W$ (kΩ·µm) | $\mu_F$ (cm²/Vs) | SS (mV/Decade) | $V_{ON}$ (V) |
|-------------|---------|---------------------------|------------------|----------------|----------------|
| Al [35]     | IGZO    | >500                      | 8.1              | 1000.09        | 2.5            |
| ITO [25]    | IGZO    | 704                       | 9.1              | 704            | ~0             |
| ITO [36]    | STO     | /                         | 5.6              | 300            | ~2             |
| Cu/Ti [37]  | IGZO    | 3200                      | 18.8             | /              | ~2             |
| Cu [34]     | IGZO    | 120                       | 6.3              | /              | ~2             |
| Cu/ITO [38] | IGZO    | 18                        | 11.5             | 200            | 1.5            |
| Mo [39]     | IZTO    | /                         | 35.25            | 210            | ~0.58          |
| Au [40]     | IAZO    | /                         | 20.57            | 550            | ~0             |
| CuCrZr [41] | NdIZO   | 84.5                      | 32.1             | 160            | ~0             |
| Al [this work] | ITO | 109.4                      | 26.45            | 201.50         | 2.7            |

To achieve a more in-depth study on various metal electrodes and their effects on electrical performance, TEM measurements of the electrodes/ITO interface were performed, as shown in Figure 6a–d. All samples were annealed under vacuum at 100 °C for 1 h, which is the same annealing condition for the devices. There was no evidence of an interfacial reaction between the electrodes and ITO for ITO, Ti, and Mo even though the samples were annealed after metal deposition. However, an aluminum oxide (AlOₓ) layer was formed at the interface between the ITO and Al. As shown in Table 1 and Figure 5, the TFT with an Al electrode exhibits better electrical properties and lower $R_{SD}$. This can be attributed to the electron transfer from AlOₓ to ITO that would occur at the initial interface since the electronegativities of In and Sn are slightly larger than that of Al [23,42]. This induces an increase in carrier density on the ITO surface, leading to the reduced $R_{SD}$ between the Al and ITO.

As TFTs are almost inevitably exposed to visible light originating from the underlying backlight unit in a working AMLCD panel or the self-emitting radiation in AMOLED products, the stability of the TFTs with the four categories of source/drain electrodes under negative bias illumination stress (NBIS) was measured, as shown in Figure 7. For NBIS tests, the devices were stressed under a negative gate bias ($V_{GS} = -4$ V, $V_{DS} = 0$ V) as well as a photoillumination (white light with a photointensity of 4000 Lux). It can be seen that all devices show comparable and excellent stability under NBIS with $|\Delta V_{TH}| < 1$ V.
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Figure 6. TEM images of the interfacial microstructures between ITO and the metal electrodes: (a) Al, (b) ITO, (c) Ti, and (d) Mo.

Figure 7. Cont.
4. Conclusions

In conclusion, ITO TFTs with Al, ITO, Ti, and Mo source/drain electrodes were fabricated in this work. The results show that the ITO TFT with an Al electrode exhibits better device performance than the other devices. The major electrical properties of the device with an Al source/drain electrode are a $\mu_{FE}$ of 26.45 cm$^2$/V·s, a $V_{ON}$ of 2.7 V, and a SS of 201.50 mV/decade. However, the devices with the four electrode materials all reveal excellent stability under NBIS with $|\Delta V_{TH}| < 1$ V. All the results indicate that ITO TFTs with an Al source/drain electrode have great potential in future display applications.

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Figure 7. NBIS time-evolutions of the transfer curves for the ITO TFTs with (a) Al, (b) ITO, (c) Ti, and (d) Mo source/drain electrodes.
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