Contact Performance and Thermal Stability Improvement of Amorphous InGaZnO Thin-Film Transistors by Using a Buffer/Cu/Buffer Source/Drain Electrode Structure

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Abstract. This paper discussed the contact characteristics and thermal stability of a-IGZO TFTs with various kinds of buffer/Cu/buffer electrode structure. The work found that the a-IGZO TFTs with Cu electrode and Mo/Cu/Mo electrode show worse thermal stability than these with ITO/Cu/ITO electrode. The work speculates that the contact performance deterioration after post-anneal was due to Cu oxidation and an interface separation between Mo and Cu, respectively. The work used the G-function method to discuss the contact performance of a-IGZO TFTs with the different kinds of S/D electrodes. The a-IGZO TFT with an ITO/Cu/ITO electrode shows a smaller contact resistance than the other TFTs and had an ohmic contact between the a-IGZO and ITO. In terms of thermal stability and contact performance, ITO/Cu/ITO electrode is a better choice than Mo/Cu/Mo electrode.

1. Introduction

In the LCD industry, hydrogenated amorphous silicon thin film transistors (a-Si:H TFTs) are used as driving and switch units on a backplane [1]. As LCD technology develops to larger size and higher resolution, the a-Si:H TFT backplane becomes the bottleneck because of its low mobility. Hence, amorphous InGaZnO thin-film transistor (a-IGZO TFT) technology has received wide attention because it has high mobility (>10 cm²/Vs) and large area uniformity at the same time [1]. On the other hand, in the application of large panels, the resistance of metal wire and parasitic capacitance will cause a delay in the driving signal. Therefore, copper wires are required in large LCD TVs, especially in those with sizes over 65 inches [2, 3]. In large-size and high-resolution LCD TVs, manufacturers are developing oxide TFT backplane technology with copper electrodes.

W.S. Kim et al. fabricated an a-IGZO TFTs with a Cu source/drain (S/D) electrode, and the field-effect mobility (μFE) was 9.64 cm²/Vs [4]. Yim J. R. et al and Ka J found that copper electrodes diffuse into the channel during a post-annealing process [5, 6]. M. J. Zhao et al observed a similar phenomenon in amorphous InZnO TFTs [7]. Therefore, Mo, Ti, Ta, Ni, Mn and their alloys are used as buffer layers to block the diffusion of copper [8, 9]. The deposition of the SiOₓ passivation layer easily causes Cu oxidation and increases its resistance. Therefore, a buffer/copper/buffer structure is needed to avoid copper oxidation. In addition, high-temperature post-annealing is required in generating oxide thin film transistors, so the contact characteristics after annealing are very important. However, few papers have discussed the thermal stability and contact characteristics of a-IGZO TFTs with a layered buffer/Cu/buffer electrode. In this study, we observed that ITO/Cu/ITO source/drain...
electrodes had better thermal stability than Mo/Cu/Mo source/drain electrodes. Through SEM testing, we found that the interface separation between Mo and Cu was caused during annealing, which resulted in an increase in contact resistance and deterioration of device performance. Using the G-function method, we found that the contact resistance of the ITO electrode was smaller than that of the Mo electrode and that ohmic contact was formed between ITO and IGZO.

2. Experiment
The fabrication process is shown in figure 1. Bottom gate a-IGZO TFTs were fabricated on Si wafers with 100-nm-thick thermal SiO$_2$ as the dielectric layer. First, we used acetone and alcohol to clean the substrate. Second, the channel layer was deposited by RF sputtering in Ar/O$_2$ atmosphere with a film thickness of approximately 60 nm. The a-IGZO layer was patterned by using a shadow mask. Before the S/D was deposited, the IGZO layer was annealed at 350 °C in a N$_2$ atmosphere for 1 h. Then, the layered buffer/Cu/buffer structure was subsequently deposited as S/D electrodes. The S/D electrodes were patterned by lift-off process. Finally, some TFTs were annealed in an N$_2$ environment at temperatures of 180 °C or 350 °C. Electrical tests were carried out by using an Agilent B1500A semiconductor device analyser.

![Figure 1](image1.png)

Figure 1. The fabrication process of a-IGZO TFTs.

3. Results and Discussion
To study the effect of the buffer layer material on the thermal stability of electrodes, we prepared a-IGZO TFTs with a copper electrode, a Mo/Cu/Mo electrode, and an ITO/Cu/ITO electrode. The transfer curves and output curves of a-IGZO TFTs with the various kinds of S/D electrodes are shown in figure 2. The un-annealed a-IGZO TFTs with the Cu S/D electrode shows good transfer curves (the black line of figure 2a). However, the output characteristic is relatively poor, as shown in the black line of figure 2d. As the post-annealing temperature rises to 180 °C or even 350 °C, the performance of a-IGZO TFT with the Cu S/D electrode rapidly deteriorates, as shown in the black lines of figures 2e and 2f. The a-IGZO TFT with the Mo/Cu/Mo electrode maintains good electrical properties after being annealed at 180 °C, as shown in the red line of figures 2d and 2e. However, after annealing at 350 °C, the field-effect mobility decreases from 10 cm$^2$/Vs to 2 cm$^2$/Vs. Compared with the other two kinds of devices, the a-IGZO TFT with the ITO/Cu/ITO electrode has the best electrical characteristics after thermal annealing. The mobility of the device with the ITO/Cu/ITO electrode is higher than that of the device with the Mo/Cu/Mo electrode and can reach 10 cm$^2$/Vs without annealing or annealing at 350 °C. This indicates that the devices with ITO/Cu/ITO electrode structures have better thermal stability.

Cross sections of a-IGZO TFTs with the various kinds of S/D electrode layers under scanning electron microscopy (SEM) are shown in figure 3. We found that the copper electrode was directly separated from IGZO, the Mo/Cu/Mo electrode had some bumps, and the ITO/Cu/ITO electrode had a flat surface. When the temperature reaches a certain level, copper thin films are easily separated from IGZO because of their high expansion coefficient. The gap between Cu and IGZO increases the contact resistance, which results in the deterioration of the transfer curve and the output curve. As shown in figure 3b, there is no bulging gap between the Mo/Cu/Mo electrodes and IGZO, but hills and bulging still exist. The expansion coefficient of Mo itself is one third of that of Cu, which can alleviate the expansion stress of the copper layer to a certain extent. These bumps result in a decrease in the $\mu_{FE}$
and output current of the device after 350 °C annealing (figure 2f). The ITO/Cu/ITO electrode annealed at 350 °C has no bulging or folding on its surface (figure 3c), which shows that the ITO/Cu/ITO has better structural thermal stability than the other electrodes.

Figure 2. $I_{DS}$-$V_G$ curves of a-IGZO TFTs with the various kinds of S/D electrodes: (a) without annealing, (b) with 180 °C annealing and (c) 350 °C annealing. Output curves of a-IGZO TFTs with the various kinds of S/D electrodes: (d) without annealing, (e) with 180 °C annealing and (f) 350 °C annealing.

Figure 3. SEM image of a-IGZO TFT with the various kinds of S/D electrodes after 350 °C annealing.

To further study the performance of a-IGZO TFTs with different S/D electrodes, we used the $G$-function method to analyse the contact characteristics of each device after annealing at 180 °C. The $G$-function method is widely used to analyse the contact characteristics of TFTs [10, 11]. When using this method, we need to assume that the mobility of TFTs does not vary with the source and drain voltage $V_{DS}$ but only with the gate voltage $V_G$. The output conductance $G$ of TFTs can be calculated using the following equation [10, 11]:

$$G = \frac{I_{DS}}{V_{DS}}$$

(1)

In addition, the output conductance $G$ is the reciprocal of the total resistance [10, 11]:
where \( R_{\text{total}} \) is the total resistance of the TFT, \( R_{\text{ch}} \) is the channel resistance, and \( R_{\text{c}} \) is the contact resistance between electrodes and semiconductors. The \( R_{\text{ch}} \) and \( R_{\text{c}} \) can be calculated by the following formula [10, 11]:

\[
R_{\text{ch}} = \frac{1}{\text{intercept}(G, V_{\text{ds}}) + \text{slope}(G, V_{\text{ds}}) \times V_{\text{ds}}}
\]

\[
R_{\text{c}} = \frac{1}{G - \frac{1}{\text{intercept}(G, V_{\text{ds}}) + \text{slope}(G, V_{\text{ds}}) \times V_{\text{ds}}}}
\]

where slope (\( G, V_{\text{DS}} \)) and intercept (\( G, V_{\text{DS}} \)) are the slope and intercept of the \( G-V_{\text{DS}} \) curve. Figure 4a shows the output curve of an a-IGZO TFT with various kinds of S/D electrodes, where the \( V_G \) is 30 V and the \( V_{\text{DS}} \) is from 0 V to 40 V. The output conductance \( G \) of three kinds of a-IGZO TFTs is calculated using equation (1) (shown in figure 4b). We find that the a-IGZO TFT with ITO/Cu/ITO electrodes has the highest output conductance \( G \). As shown in figure 4c, we find that the device using the ITO/Cu/ITO electrode has the lowest contact resistance. The contact resistance of copper and Mo/Cu/Mo electrodes to IGZO is approximately 10^4 \( \Omega \), while that of ITO/Cu/ITO electrodes to IGZO is approximately 10^5 \( \Omega \). Figures 4d-4f compares the \( R_{\text{ch}} \) and \( R_{\text{c}} \) of a-IGZO TFTs with different S/D electrodes. The \( R_{\text{ch}} \) curve and \( R_{\text{c}} \) curve of the ITO/Cu/ITO composite electrode device have no intersection, which indicates that the contact between ITO and IGZO is ohmic [10, 11]. A Schottky barrier is formed between the Cu and IGZO or the Mo and IGZO (figures 5e-5f) [10, 11]. A schematic diagram of the contact between the S/D electrode and IGZO is shown in figures 5a-5d. The work functions of Mo and ITO are 4.37 eV and 4.5 eV, respectively [12]. Because of the differences in film composition and film-forming conditions, the work function (WF) of IGZO ranges from 4.3 eV to 7.6 eV. From our results, it can be inferred that the work function of IGZO is approximately 4.5 eV.

Figure 4. (a) Output curves, (b) Output conductance vs \( V_{\text{DS}} \) and (c) contact resistance vs \( V_{\text{DS}} \) curves of a-IGZO TFTs with various kinds of S/D electrodes; channel resistance and contact resistance curves of (d) copper electrode devices, (e) Mo/Cu/Mo composite electrode devices and (f) ITO/Cu/ITO composite electronics.
4. Conclusion

We compared the thermal stability and contact performance of a-IGZO TFTs with a Cu electrode, a Mo/Cu/Mo electrode and an ITO/Cu/ITO S/D electrode. After samples were annealed at 180 °C or 350 °C, the $I_{DS}$-$V_{G}$ curves and $I_{DS}$-$V_{D}$ curve of the a-IGZO TFTs with the Cu electrode or the Mo/Cu/Mo S/D electrode deteriorated, while those of a-IGZO TFTs with the ITO/Cu/ITO S/D electrode did not. Through characterization with SEM, we inferred that the electrical property deterioration of the devices was due to an interface separation between Mo and Cu during annealing, which led to an increase in contact resistance. We used the G-function method to extract the $R_C$ of a-IGZO TFTs with the various kinds of S/D electrodes. The a-IGZO TFT with an ITO/Cu/ITO electrode had a smallest contact resistance and showed an ohmic contact between the a-IGZO and ITO. From the point of view of thermal stability and contact performance, ITO/Cu/ITO is a better structure than Mo/Cu/Mo.

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