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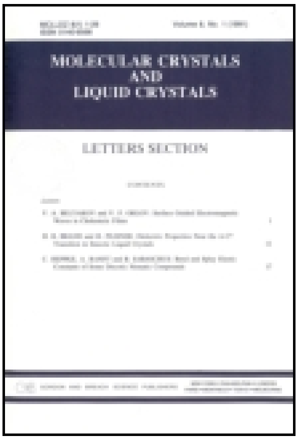

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Screen-Printed Cu Source/Drain Electrodes for a-InGaZnO Thin-Film Transistors

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Screen-Printed Cu Source/Drain Electrodes for a-InGaZnO Thin-Film Transistors

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We report screen-printed copper source/drain electrodes for a-InGaZnO (a-IGZO) thin-film transistors (TFTs). The best electrical characteristics of the a-IGZO TFTs were a field-effect mobility of 2.06 cm^2/Vs, a threshold voltage of 3.40 V, an on/off current ratio of 6.0×10^3 A/A, and a subthreshold swing of 7.02 V/decade. Resulting TFT performances indicate that blocking the inter-diffusion of Cu and impurities is a key factor to fabricate low leakage current and high performance a-IGZO TFTs with printed Cu S/D electrodes.

Keywords a-IGZO; screen printing; copper ink; thin-film transistor; source/drain electrodes; oxide-based TFTs

Introduction

In recent years, printing-based lithography and related electronic devices have attracted much attention because subsequent processes such as photolithography and, wet or dry etching processes are not required. Among the various printing methods, a screen printing method is commonly used for the fine patterning of multilayered interconnection, and integrated circuits [1–2]. The screen printing method has several advantages, such as a reduction of the amounts of materials used and simple process steps that can reduce the manufacturing cost. Therefore, there have been many efforts to apply the screen-printing method to make switching or driving thin-film transistors (TFTs) in the display fields [3]. In particular, to make printed source/drain (S/D) electrodes, most recent studies have focused on printable metal electrodes such as silver and gold electrodes owing to their high electrical conductivity. However, since these materials are relatively expensive compared to conventional vacuum-based S/D electrodes (Mo, Cr), new materials for S/D electrodes are required for printing-based TFTs [4–6]. Among the possible printable electrodes, Cu metal is a good candidate to replace the silver and gold in S/D electrodes, due to its high conductivity and low cost. It has been used to fabricate antenna electrodes for RFID or conductive electrodes of flexible displays by a printing method [7–9]. However, there have been no reports to apply the printed Cu S/D electrodes for fabrication of a-InGaZnO (a-IGZO) TFTs which are considered as next-generation switching and driving devices.

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In this study, we applied the screen printing technique to form the Cu source/drain electrodes of a-IGZO TFTs. We studied electrical characteristics of a-IGZO TFTs with printed Cu source/drain electrodes based on transfer and output characteristics.

Experimental

We fabricated screen-printed copper source/drain electrodes for a-IGZO TFTs with an inverted-staggered bottom-gate structure. Heavily doped n-type silicon was used as a gate electrode and a substrate, at the same time. A 200 nm-thick thermally grown silicon oxide layer (SiO_x) was used as a gate dielectric layer. Then, the a-IGZO active layer was deposited on the SiO_x/Si substrate using a radio-frequency (RF) magnetron sputtering system. Sputtering was carried out on a working pressure of 5 mTorr, a RF power of 400 W and a gas mixing ratio of $Ar/O_2 = 50/5$ sccm. The a-IGZO samples were annealed in a box furnace at 300°C for 1h in an ambient oxygen. Finally, the source/drain electrodes are printed by a screen-printing method. The printing conditions were optimized by controlling the mesh size of the pattern mask, the viscosity of the copper paste, the printing speed, and the distance between the screen and the substrate. After that, the printed electrodes were annealed under ambient nitrogen (200 sccm) at 140°C for 40 min.

Measurements

The microstructure of the screen printed copper electrodes were examined using an optical microscope and confocal microscope. Time-of-flight secondary ion mass spectrometry (TOF-SIMS) measurement were performed to analyze the interface between the Cu electrodes and the active layer. The electrical characteristics of the a-IGZO TFTs were measured using a Keithley 4200-SCS semiconductor parameter analyzer in the dark at room temperature.

Results and Discussion

Figure 1(a) shows microscope image of a mask for the screen printed Cu S/D electrodes. The minimum channel length was determined by varying the mesh size of the mask and the viscosity of the Cu paste. We found that the optimum viscosity and mesh size for S/D patterning were 155,000 cPs and 640 mesh/inch, respectively. Channel lengths (L) ranging from 50 to 100 μm were successfully obtained, as shown in Fig. 1(b). The channel width (W) was 1000 μm. The thickness of the screen-printed Cu electrodes was 25 to 30 μm as measured by a confocal microscope, as shown in Fig. 1(c). It should be noted that the wavy edge patterns are observed in the edge of S/D electrodes as shown in Figs. 1(b) and (c), which is frequently observed in printing-based TFTs [10]. However, because it is known that effective channel length variation of wavy edge patterned TFT is small ($\sim\mu$m) compared to channel length ($\sim$ tens of μm) even for the large peak-to-peak value of wavy patterns, the wavy edge pattern effect can be ignored when the channel length is long.

Figure 2(a) and (b) show representative transfer and output characteristics of an a-IGZO TFT with printed Cu S/D electrodes ($L = 90$ μm). Severe degradations of current levels at low V_{DS} condition both in the transfer and output characteristics ($V_{DS} < 10$V) due to the high gate leakage current. The origin of the gate leakage current can be characterized by the diffusion of metal ink through the S/D printed regions. To confirm inter-diffusion of Cu into underlying layers, a TOF-SIMS analysis was performed, as shown in Fig. 3. The

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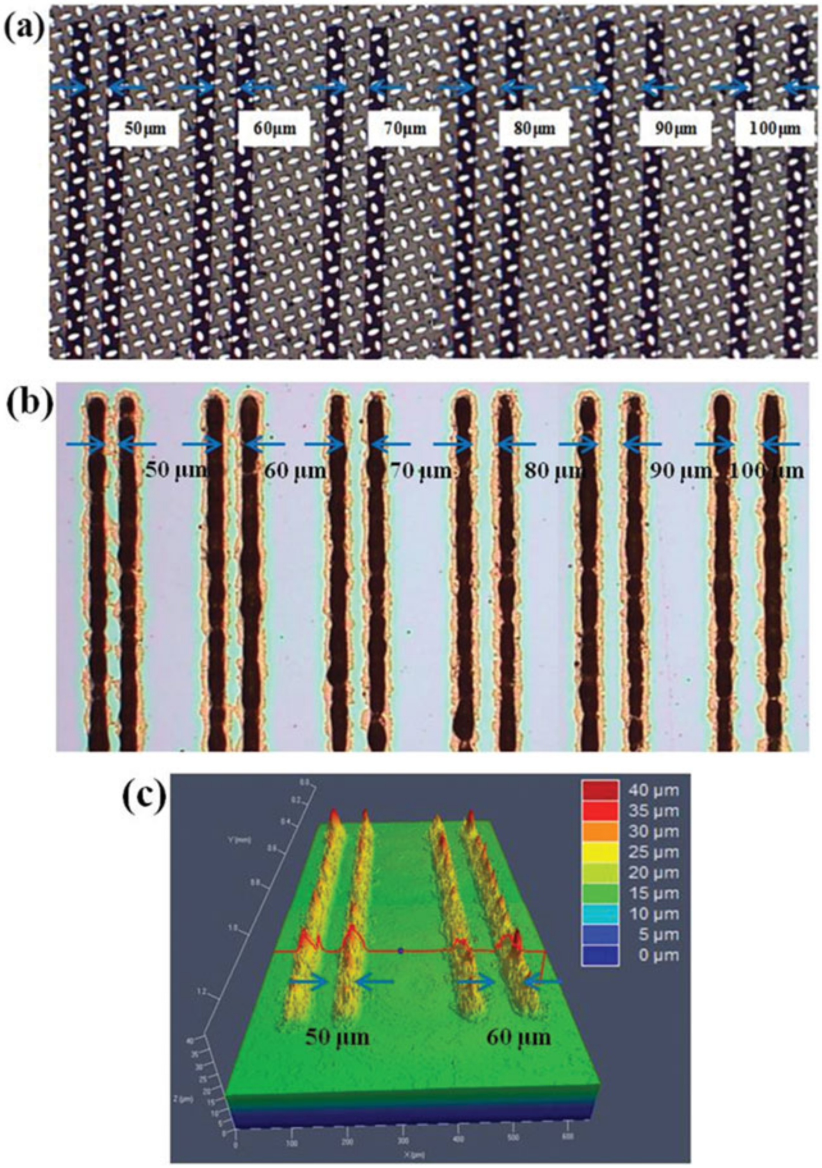

Figure 1. Optical microscope images of (a) mask and (b) printed S/D electrodes on the a-IGZO active layer. (c) Confocal microscope image of printed Cu electrodes.

Cu signal was detected with In, Ga, and Zn signals, indicating that there is Cu diffusion into the channel and the insulating layers. An increase in the gate leakage can be also observed for typical TFTs with printed S/D electrodes, such as those consisting of silver [11]. We speculate that the diffused Cu creates a current path by forming Cu filament through the pinholes of the active and gate insulator layers. Therefore, blocking the Cu diffusion is important to improve the performance of a-IGZO TFTs with printed Cu S/D electrodes.

Further analysis was performed by extracting the field-effect mobility and subthreshold slope values depending on the channel lengths. Typically, drain current can be expressed

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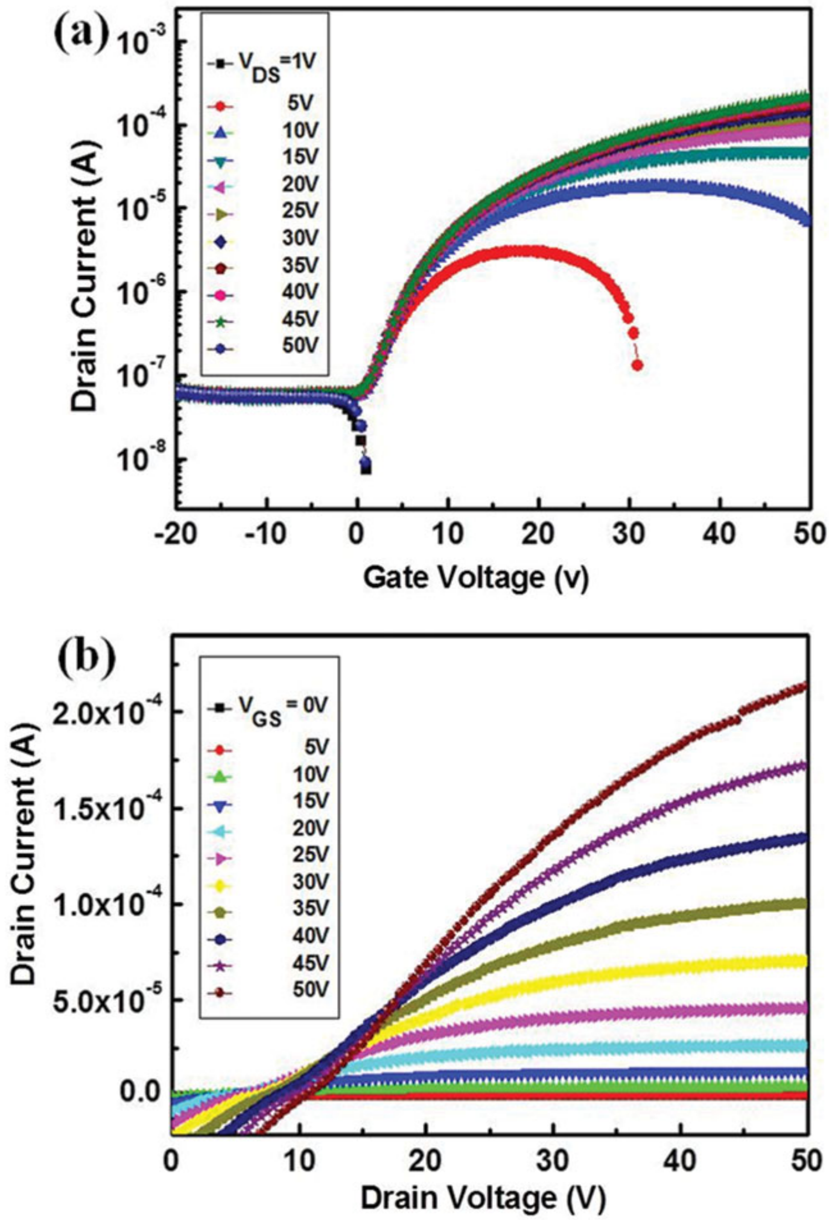

Figure 2. The electrical characteristics of a-IGZO TFT with printed Cu S/D electrodes ((a) output and (b) transfer characteristics).

by the following equation in the saturation region;

$$I_{DS} = \left(\frac{WC_{i\mu FE}}{2L}\right)(V_{GS} - V_{th})^2 \text{ for } V_{DS} > V_{GS} - V_{th} \tag{1}$$

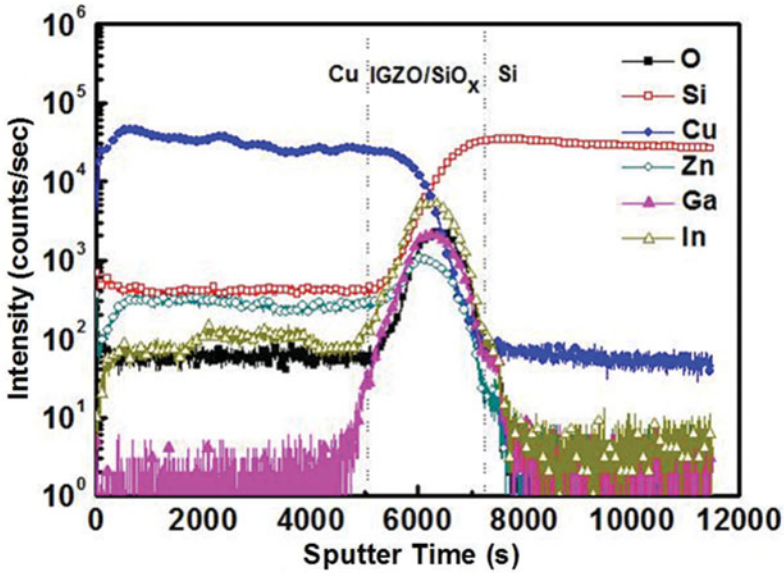

Figure 3. TOF-SIMS depth profile of fabricated a-IGZO TFT with screen printed Cu S/D electrodes.

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Here, I_{DS} is the drain-to-source current, V_{th} is the threshold voltage, W is the channel width, and C_i is the capacitance of SiO_x gate insulator. The field-effect mobility values can be extracted by the equation (1) from the slope of linear fitting of $\sqrt{I_{DS}}$ with respect to $V_{GS.}$

The subthreshold slope (SS) can be extracted using the following equation,

$$SS = \frac{dV_{GS}}{d\,(\log I_{DS})} \tag{2}$$

Figure 4 shows the extracted μ_{FE} and SS values in saturation regions depending on the channel lengths. The μ_{FE} values gradually increased when the channel length was increased due to the decreasing parasitic resistance effect as compared to the channel resistance. On the other hand, constant SS values were obtained, except when $L = 60$ μm, as shown in Fig. 4. The average SS values was about 6.5 V/dec, which is about 10 times larger than that in conventional a-IGZO TFTs with Mo and IZO S/D electrodes [12]. Because the SS values are closely related to the density of states distribution in the sub-bandgap region [13], it can be supposed that the printing process of Cu S/D electrodes is an origin of a decrease of field-effect mobility by increasing the trap density in the channel region, which also influences on contact resistance. Further quantitative calculation can be performed using the relationship between maximum trap densities, and the SS values, which is given as [14],

$$SS = \frac{kT}{q\log(e)}\left[1 + \frac{q}{c_i}\left(\sqrt{\varepsilon_s N_{bs}} + qN_{ss}\right)\right] \tag{3}$$

Here, k is the Boltzmann constant, q is the elementary charge, ε_s is the dielectric constant of the semiconductor layer, N_{BS} is the maximum bulk trap density, and N_{SS} is the maximum interfacial trap density. Since, we used the same active layer/gate insulator structure with our previous report [15], the increase of SS values are responsible for increase of bulk trap density. Therefore we can ignore the effect of interfacial trap density in Eq. (3)

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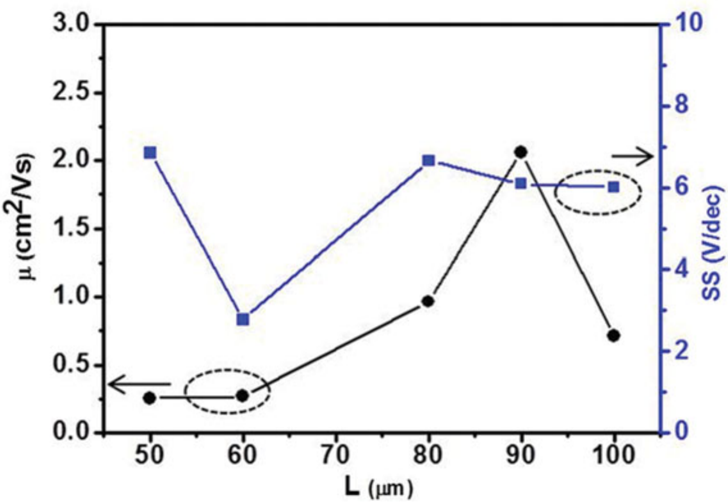

Figure 4. The mobility and subthreshold swing values of a-IGZO TFT as a function of channel length.

and, the N_{BS} can be calculated using a following equation [16],

$$N_{bs} = \frac{1}{q\varepsilon_s}\left[\left(\frac{SS\log(e)}{kT/q} - 1\right)C_i\right]^2 \quad (4)$$

Resulting N_{bs} value was about 1.02×10^{19} cm^{-3} eV^{-1} when $SS = 6.5$ V/dec, which is much larger than that of conventional a-IGZO TFT with vacuum deposited S/D electrodes [17]. Since the Cu atom acts as shallow donor-like states as well as acceptor-like states in oxide-based semiconductor depending on a deposition condition or a process variation [16][18], and other impurities in the ink solvent can generate defect states in sub-bandgap region of the a-IGZO active layer, control of inter-diffusion of Cu and impurities is a key parameter to suppress leakage current and to improve the performance of a-IGZO TFTs with printed Cu S/D electrodes.

Conclusions

In conclusion, we demonstrated a-IGZO TFTs with screen printed Cu S/D electrodes. The inter-diffusion of Cu atoms and impurities significantly influences on the performance of a-IGZO TFTs such as the leakage current, the field-effect mobility, and the subthreshold swing. Therefore, blocking the inter-diffusion of Cu and impurities is the key factor to fabricate low leakage current and high performance a-IGZO TFTs with printed Cu S/D electrodes.

Acknowledgment

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