Reduced contact resistance of a-IGZO thin film transistors with inkjet-printed silver electrodes

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Abstract

In this study, high performance amorphous In–Ga–Zn–O (a-IGZO) TFTs were successfully fabricated with inkjet-printed silver source-drain electrodes. The results showed that increased channel thickness has an improving trend in the properties of TFTs due to the decreased contact resistance. Compared with sputtered silver TFTs, devices with printed silver electrodes were more sensitive to the thickness of active layer. Furthermore, the devices with optimized active layer showed high performances with a maximum saturation mobility of 8.73 cm²·V⁻¹·S⁻¹ and an average saturation mobility of 6.97 cm²·V⁻¹·S⁻¹, Ion/Ioff ratio more than 10⁷ and subthreshold swing of 0.28 V/decade, which were comparable with the analogous devices with sputtered electrodes.

Keywords: inkjet print, a-IGZO, thin film transistors, silver electrode

(Some figures may appear in colour only in the online journal)

1. Introduction

In recent years, amorphous metal oxide (AOS) such as indium gallium zinc oxide (a-IGZO) thin film transistors (TFTs) have been widely studied due to the high field effect mobility, good uniformity and good optical transparency [1–5]. Most studies on a-IGZO TFTs so far have focused on vacuum process [6–8]. The source/drain (S/D) electrodes such as aluminum (Al), copper (Cu) and silver (Ag) have been widely used for fabricating TFTs [9–11], and almost all of them exhibit excellent properties. In contrast, very limited studies have been reported about printed S/D electrodes on a-IGZO based TFTs. Inkjet print technology is a developing and convenient way to fabricate electron devices for its simple process, direct patterning, low-cost and no need for vacuum [12–14]. Besides, lower process temperature could be compatible with flexible devices [15].

Silver ink has been widely used as an alternative approach to low-cost, high conductivity, printable conductors compared with other inks such as ITO, PEDOT and Au ink, etc. Thus far, the key point of applying silver ink in electrodes fabricating is poor electrical contact between active layer and silver electrodes because of deleterious interfacial chemical interactions or organic sandwich. To date, Ethan et al have
reported poor-performance IGZO TFTs with inkjet-printed silver-based ink compared with the graphene electrode [16]. Yoshihiro et al. have analyzed printed silver on a-IGZO and found that the carbon and hydrogen contained in printed Ag electrodes seriously affect the TFTs properties [17]. Very recently, we reported inkjet-printed nanoparticle-based silver ink for fabricating S/D of TFTs under a heated substrate and the devices showed a little but not very outstanding performance [18], which showed that the organic in silver nanoparticle ink could seriously affect the TFTs properties.

In the present study, a kind of precursor silver ink with very few organic was utilized for preparation of S/D of a-IGZO TFTs. Specially, we demonstrate a-IGZO TFTs with inkjet-printed electrodes exhibiting mobilities as high as 8.73 cm²/V·s, which is comparable with the sputtered one, and shows that this substantial mobility reflects very low contact resistance at the electrode-semiconductor interface.

To the best of our knowledge, it is the first time that a-IGZO TFTs with inkjet-printed silver S/D electrodes has come to be so high with no other treatment or modifying.

2. Experimental details

Bottom gate top contact structure (figure 1) was adopted to fabricate a-IGZO TFTs with inkjet-printed S/D electrodes. Silver ink purchased from Ink-Tec (InkTEC-JII-010) was used as the conductive ink materials. First, a 300 nm-thick Al–Nd alloy (3 wt.% of Nd) film was deposited by DC magnetron sputtering on a glass substrate, followed by an anodizing process to fabricate a-IGZO films. Second, sputtering on a glass substrate, followed by an anodizing process (3 wt.% of Nd) film was deposited by DC magnetron sputtering with a magnetic field of 80 W. Then an annealing process of 400°C was utilized for defect reduction. At last, silver ink was ink-jet printed to form S/D electrodes by a Dimatix (DMP-2800) piezo-inkjet printer with 10PL cartridge, the substrate temperature was maintained at 60 °C to facilitate solvent evaporation, and channel W/L was set from 550 µm/60 µm to 550 µm/318 µm. Post deposition annealing was performed at 130 °C on a hot plate for 8 min. Besides, devices with sputtered Ag were fabricated for reference.

The dimensions of the printed electrodes were measured by a Nikon Eclipse E600 POL with a DXM1200F digital camera (Nikon, DeWitt, IA). TFT properties were studied using a semiconductor parameter analyzer (Agilent 4155C, Santa Clara, CA) under ambient condition. The device structure was examined using transmission electron microscopy in which energy dispersive x-ray spectroscopy (EDS, Bruker, Adlershof, Berlin, Germany) was also carried out to analyze the distribution of elements. The roughness of a-IGZO films was detected by x-ray diffractometer System (PANalytical, Empyrean, the Netherlands).

3. Results and discussion

Transfer characteristics of a-IGZO TFTs with printed Ag electrodes (VDS = 10.1 V) with various thicknesses were shown in figure 2(a). Their electrical properties, such as threshold voltage (Vth), the saturation mobility (μsat) and sub-threshold swing (SS) were summarized in table 1. For comparison, the detail representative parameters of referenced devices are listed in table S1 (stacks.iop.org/JPhysD/51/165103/mmedia). It is worth noting the value of Vth of the devices with sputtered electrodes was linearly reduced from 7.99 V to 3.68 V by increasing lactive without any significant change in the μsat, SS and Ion/off ratio, which is in great agreement with previous reports [19, 20]. Besides, the device with inkjet-printed Ag showed non-Ohmic contact because of apparent current crowding from the inset pictures in figure S1(a) [21]. This implied a higher work function of inkjet-printed Ag than sputtered Ag, which was proven to be 4.87 eV and 4.78 eV by the Kelvin Probe, respectively.

It is worth noting that the μsat and Ion/off increased positively as increasing of the thickness of a-IGZO layer from 25 nm to 80 nm. The SS and threshold voltage shifted negatively as increasing of the thickness of a-IGZO. These observed phenomena are not in agreement with the case of sputtered silver electrodes. Table S2 shows the channel length dependence of the mobility for 80 nm a-IGZO TFT with inkjet-printed Ag electrodes. As we can see, with the channel length increases from 60 µm to 318 µm, the devices properties almost maintained at the same level except the Ion/off ratio, which may due to the increasing of channel resistance as the channel lengths increase. TFTs with inkjet-printed silver showed comparable properties with sputtered ones when the active layer was 80 nm.

To elucidate the origin of the present large mobility enhancements, the contact resistances of TFTs with inkjet-printed Ag electrodes was explored with the transfer line method (TLM) [22]. Figure 3(a) shows the total ON resistance (Rsat) as a function of channel thicknesses at gate voltage of 10 V. The TFTs contact resistance could be obtained from the y-axis intercept and Rchannel from the slope. From the slope, we can see that the total ON resistance is substantially larger than the contact resistance in the linear regime. The total contact resistances are 4065.3 Ω·m at 25 nm, 632.5 Ω·m at 40 nm and 81.8 Ω·m at 80 nm, which reveals increasing channel thickness has a positive improvement on reducing
contact resistances. Furthermore, the total ON resistance was plotted as a function of channel length for different gate voltage and the experimental values with linear curves for each $V_{GS}$ were fitted in figure 3(b). For all the devices, the total contact resistance decreases with increasing $V_G$. The values of $R_c$ were in the ranges of several $\Omega \cdot m$ from 18.4 $\Omega \cdot m$ at 30 V to 239 $\Omega \cdot m$ at 5 V, which was almost at the same level with the channel resistance and thus acceptable in terms of device performance.

The roughness of the a-IGZO films with different thicknesses was characterized by x-ray reflective system. With the increase of IGZO thickness, the roughness monotonically increases from 1.057 nm to 1.486 nm. The rough surface could enhance the bonding strength of two layers, so this could explain why the contact resistance decreased with the increased thickness, and thus lead to increased $\mu_{sat}$ and $I_{on}$.

Figure 4(a) displays the high-resolution transmission electron microscopy (HR-TEM) images of the TFTs with inkjet-printed electrodes. Unlike sputtered Ag, silver particles interconnect like network, and there exist numerous distributed pores inside the Ag electrodes and the interface due to the different formation mechanism. The silver precursor decomposed in the liquid-phase and produced individual atoms or clusters, and then thermal sintering step would evaporate the liquid and force the atoms or clusters to become close to each other [23], and the sputtered Ag electrode was formed layer by layer. It seems like the pores caused the insufficient contact between electrodes and active layer. But from the magnified interface picture, we can see it clearly the two layers contact tightly just as the sputtered electrodes as shown in figure 4(b), which offer a valid channel for carriers transporting. In addition, as shown in figure 4(c), the line scan profile obtained from energy-dispersion x-ray spectroscopy (EDS) confirmed that there was no deleterious interfacial chemical interactions or diffusion and the interface was very clear.

Table 1. Electrical properties of a-IGZO with inkjet-printed Ag electrodes TFTs with various channel thicknesses.

| Thickness (nm) | $\mu_{sat}$ (cm$^2$ V$^{-1}$ s$^{-1}$) | $I_{on}/I_{off}$ SS (V/dec) | $V_{in}$ (V) |
|---------------|-------------------------------|-----------------------------|--------------|
| 25            | 2.01                          | $3.99 \times 10^6$          | 1.28         | 10.95        |
| 40            | 3.86                          | $1.77 \times 10^7$          | 1.21         | 7.19         |
| 80            | 6.23                          | $6.85 \times 10^7$          | 0.37         | 0.88         |

Figure 2. Transfer curves for the a-IGZO TFT with (a) ink-jet printed (b) sputtered silver electrodes as a function of the active layer thickness.

Figure 3. Total $R_{on}$ resistance versus channel length of (a) various channel thicknesses (b) various gate voltage when the channel is 80 nm. Data measured at $V_{ds} = 1$ V, colored lines show linear fits to data.
4. Conclusions

In summary, the fabrication of a-IGZO TFTs was carried out using inkjet-printed silver electrodes. The contact resistance decreased significantly with the increased active thickness, which may due to the increased roughness. The optimized devices showed high performances with a maximum saturation mobility of 8.73 cm²·V⁻¹·S⁻¹ and an average saturation mobility of 6.97 cm²·V⁻¹·S⁻¹, $I_{on}/I_{off}$ ratio more than 10⁷ and SS of 0.28 V/decade, which were comparable with the analogous devices with sputtered silver. These results envision that inkjet-printed silver is a promising candidate for S/D of a-IGZO TFTs.

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