Corrigendum

P-1.22: Influence of Electrode Materials on Electrical Properties of IGZO TFTs

In [1], changes have been made to the following:

- The full version of the article has been added to this version after publication.

Reference

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Influence of Electrode Materials on Electrical Properties of IGZO TFTs

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Abstract

To investigate the effects of electrode materials on the electrical performances of the IGZO TFTs, the IGZO TFTs with three different electrodes (Au, Cu, or Al) were prepared using glass as substrate, IGZO as channel layer, Al_2O_3 as gate insulating layer, respectively. The results show that all the three metals can be used as the electrodes of IGZO TFTs. The experimental electrical properties of the three IGZO TFTs can be ranked as follows: (i) μ_{FE} and I_{ON}/I_{OFF}: Au > Cu > Al; (ii) V_{TH}: Cu > Au > Al; (iii) SS: Cu > Al > Au. The Au-electrode IGZO TFTs have the best overall electrical performance, exhibiting the highest I_{DS} (41.9 μA, $V_{GS} = V_{DS}$ = 20 V), I_{ON}/I_{OFF} (4.36×10^7), μ_{FE} (18.11 cm^2 /Vs), and the lowest SS (0.32 V/dec). The impact of electrode materials on the electronic performance of IGZO TFT was the result of multiple factors working together: the conductivity of the electrode material; the contact potential; the change of carrier concentration in the channel layer causing by the oxidation of diffusion of electrode material. The overall electrical performance of Cu and Al electrode IGZO TFTs are slightly inferior to that of the Au one, but both Cu and Al are low-cost and high-performance IGZO TFT electrode materials, which are more conducive to mass production and large-scale applications in FPDs.

Keywords: ***Indium gallium zinc oxide; Thin-film transistor; Electrode material; Electrical properties; Subthreshold swing; Contact barrier***

1. Introduction

The thin-film transistors (TFTs) based on indium gallium zinc oxide (IGZO) have been gradually replacing hydrogenated amorphous silicon (a-Si: H) in the new generation of flat-panel display (FPD) devices due to their high mobility (> 10 cm^2 /Vs), good large-size uniformity, and low preparation temperature. In IGZO TFT devices, the electrodes contain gate, source(S), and drain(D) electrodes, which are often metals, or their alloys or conductive semiconductors. The "on" or "off" states of a TFT is realized by applying different voltages on the three above electrodes [1]. The electrodes materials in TFTs should meet the following requirements in general: excellent conductivity and good patterning; in terms of the S/D electrodes, they should form a good Ohmic contact with the channel layer material [1,2].

Copper (Cu) and aluminum (Al) are good conductors, so usually employed as electrodes materials in electronics devices. Michael -son et al. compared the conductivity of some common metals [3], and indicated that only silver (Ag) has a slightly higher conductivity than Cu. But Ag is very easy to be contaminated and difficult to realize patterning by etching, so Ag is not widely used in TFT devices. The conductivity of golden (Au) is slightly lower than that of Cu, but Au is not easy to be oxidized in the air, its physicochemical properties are stable. Au may be good electrodes materials for TFT devices.

Herein, the bottom-gate-top-contact (BGTC) IGZO TFTs with three different electrodes were prepared with glass as the substrate; Au, Cu and Al as the electrodes; Al_2O_3 as the gate insulating (GI) layer, and IGZO as the channel layer, respectively. The effects of the three electrode materials on the electrical performance of the IGZO TFTs were comparatively analyzed.

2. Experimental section

The schematic diagram of our designed bottom-gate top-contact (BGTC) IGZO TFT is given in Fig.1, in which Al_2O_3 is used as GI layer, IGZO as channel, and Au,Cu, or Al as electrodes of GI and S/D, and the channel width (W), length (L) are 1000 μm and 400 μm, respectively. The detail fabrication process can be refered to our previous paper [13]. The main preparation procedure is as follows: the glass substrate was ultrasonically cleaned in acetone, anhydrous ethanol and deionized (DI) water for 10 minute in sequence and dried in a vacuum oven at 60 ℃ for 1 h. The dried glass substrate was put into a plasma cleaner and processed for 5 min in an oxygen plasma atmosphere, and then 100 nm thick Au, Cu or Al GI electrodes were deposited by DC magnetron sputtering at 100 W. Then the 300 nm thick of Al_2O_3 GI layer was obtained by reactive magnetron sputtering an Al target at 75 W. The 100nm thick IGZO (In_2O_3: Ga_2O_3: ZnO =1:1:1mol%) channel layer was then prepared by radio-frequency (RF) magnetron sputtering at 75 W. Finally, the S/D electrodes (100 nm) were patterned by laser-cut Mo shadow mask. The physical image of the obtained IGZO TFT with Au electrode is exhibited in Fig.1d.

3. Results and discussion

3.1 Electrical performance of IGZO TFTs with different electrodes

The output characteristic curves of IGZO TFTs with three electrodes at V_{DS} in the range of 0~20V and V_{GS}=20V are displayed in Fig. 2a. It shows that the output currents (I_{DS}) of the three IGZO TFTs are sorted as Au > Cu > Al，the TFT with the Au electrode having the largest I_{DS}. In particular, as displayed in Fig.2b, the saturated I_{DS} (V_{DS}=V_{GS} = 20 V) of IGZO TFTs with Au, Cu, and Al electrodes are 41.9, 32.2, and 26.3 μA, respectively, which indicates that Au has the optimal output characteristics and driving ability, Cu is the second best and Al is the worst.

From the linear region of the output characteristic curve, the total resistance (R_{on}) of the TFT device can be obtained by the transmission linearity theory (TLM), which is calculated as [4]:

$$R_{on} = \partial V_{DS} / \partial I_{DS} = R_{ch} + R_p \qquad (1)$$

where R_{ch} is the channel resistance and R_p is the contact resistance. With a certain channel width and length, R_{ch} can be approximated as a fixed value. When $V_{GS} = V_{DS} = 20$ V, the R_{on} of the IGZO TFTs with Au, Cu, and Al electrode are 0.48, 0.62, and 0.76 MΩ, respectively (Fig.2b). The Al electrode has the largest contact resistance, followed by Cu, and Au has the lowest, which also indicates that the Au electrode IGZO TFT has the the best output characteristics and driving capability.

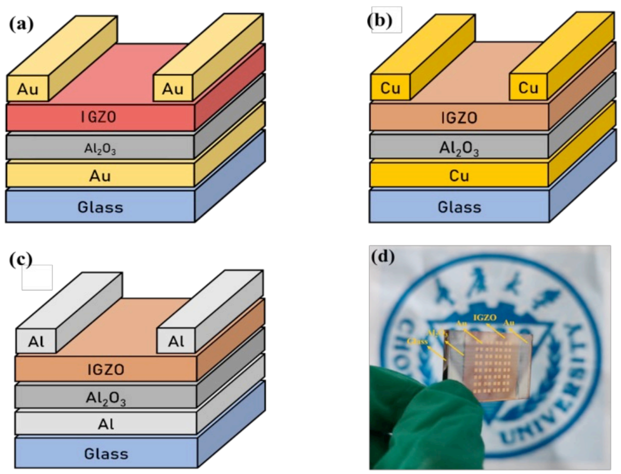

Fig.1. Schematic cross-section of BGTC type IGZO TFTs with: (a) Au electrode, (b) Cu electrode, (c) Al electrode, (d) Physical view of IGZO TFT with Au electrode.

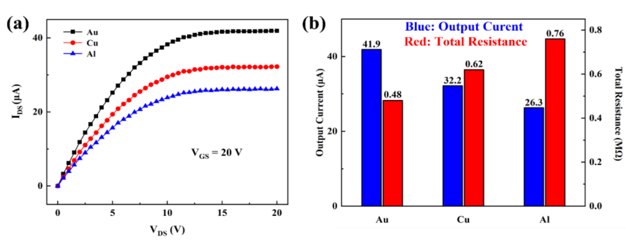

Fig.2. Comparison plots of (a) output characteristic curve (V_{GS} = 20 V) and (b) output current and total resistance (V_{GS} = V_{DS} = 20 V) for Au, Cu, and Al electrode IGZO TFTs.

The transfer curves of IGZO TFTs with different electrode at V_D=10V and the V_{GS}-$I_{DS}^{1/2}$ relationships are demonstrated in Fig.3a and Fig.3b, respectively. The switching characteristics of the TFTs are all evident in these curves in Fig.3a. The electrical properties of these IGZO TFTs are summarized in Table 1 and shown in Figs.3c-d. It can be seen that the electrical properties of the three IGZO TFTs are superior, indicating the potential of the IGZO TFTs with Au, Cu or Al electrodes to be applied in the FPD field.

In comparison, the Au-IGZO TFT has the best overall electrical performance with the highest field-effect mobility (μ_{FE}=18.11 cm^2 / Vs), the lowest subthreshold swing (SS=0.32 V/dec), and the highest current-switching ratio (I_{ON}/I_{OFF} = 4.36×10^7).All the four electrical properties (μ_{FE}, V_{TH}, SS and I_{ON}/I_{OFF}) of the IGZO TFT with Cu electrodes are larger than those of the Al one. Since the higher of μ_{FE} and I_{ON}/I_{OFF} and the lower V_{TH} and SS are desirable, thus the overall electrical performance of the Cu-IGZO TFT is not better than that of the Al one.

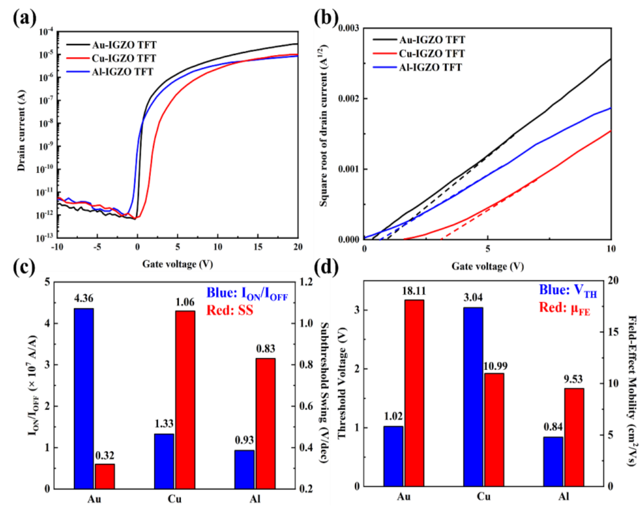

Fig.3. (a) Transfer characteristic curves, (b) V_{GS} - $I_{DS}^{1/2}$ relationship curves, (c) I_{ON}/I_{OFF} and SS ;(d) V_{TH} and μ_{FE} of IGZO TFTs with Au、Cu、Al electrode.

Table 1. Summary of electrical properties of IGZO TFTs with different electrodes

Electrode material	μ_{FE} (cm^2/Vs)	V_{TH} (V)	SS (V/dec)	I_{ON}/I_{OFF} (10^7)
Au	18.11	1.02	0.32	4.36
Cu	10.99	3.04	1.06	1.33
Al	9.53	0.84	0.83	0.927

In summary, when all other conditions are same, the electrical performances of the three IGZO TFTs has the following order: (i) μ_{FE} and I_{ON}/I_{OFF}: Au > Cu > Al (corresponding to the total resistance R_{on} at $V_{GS} = V_{DS}$ = 20 V, Al > Cu > Au); (ii) V_{TH}: Cu > Au > Al; (iii) SS: Cu > Al > Au.

3.2 Analysis of the reasons to cause the differences in the electrical performance of TFTs with different electrode materials

The S/D electrodes are in direct contact with the channel layer to form a current path of TFT. In addition to the channel layer, there are three factors related to electrodes to affect the current: the conductivity of the electrode material; the contact potential between the electrodes and the channel layer, the change of carrier concentration in the channel layer causing by the electrode.

For a more in-depth discussion, the work function, conductivity, and lattice constant of the three electrode materials, their possible oxides and IGZO are summarized in Table 2.

Table 2. Comparison of physical properties of three electrode materials, their possible oxides and IGZO [3,5,6]

Materials	Conductivity(S/m)	Work function Φ(eV)	Lattice constant (Å)
Au	4.89×10^{6}	5.1	4.065
Cu	59.6×10^{6}	4.65	3.597
Al	37.5×10^{6}	4.28	4.046
Cu_2O	$10^{-6}\sim10^{-1}$	5.0	4.207
CuO	0.1 ~ 1	5.3	3.423
Al_2O_3	$10^{-11} \sim 10^{-4}$	4.7	4.785
IGZO	1.72×10^{2}	4.5	3.295

(1) Conductivity of the electrode materials

From Table 2, it shows that if only the conductivity of the electrode is considered, at the same V_{GS} and V_{DS}, the magnitude order of I_{DS} is Cu > Au > Al, which is different from the ordering of the I_{DS} experimental results, Au > Cu > Al. Therefore, the electrode conductivity should not be the only influencing factor.

(2) Contact potential

Theoretically, the S/D electrodes should form an Ohmic contact with the channel layer, and the contact potential between electrodes and the semiconductor material of the channel layer should be as low as possible [7]. Due to the unlike work function of different metal materials, the contact potentials vary even in contact with the same semiconductor, which affects the V_{TH} and, I_{ON}/I_{OFF}, etc. The higher the contact potential, the smaller the I_{DS} at the same V_{DS}, in other words, the higher the contact potential, the larger the threshold voltage is need to get a same I_{DS}.

From Table 2, it shows that the work functions(Φ) for Au, Cu, Al, and IGZO are 5.10, 4.65, 4.28, and 4.50 eV, respectively [3], and the electron affinity energy χ is 4.16 eV for IGZO [8]. If the fermi energy of the metal and semiconductor are respectively donated as E_{FM} or E_{FS}, then the difference of work functions ($qV_D = E_{FM}-E_{FS}$) of the Au, Cu, and Al S/D electrodes with the IGZO channel layer are 0.60 and 0.19 eV and -0.22eV, respectively, while the barrier heights ($\Phi_{ns}= E_{FM}-\chi_S$) are 0.94 and 0.39 eV and -0.12eV, respectively.

The energy band diagrams of electrodes and IGZO before and after contacting with each other are given in Fig.4. When the three metals are in contact with the IGZO channel layer, owing to the difference of Fermi energy between metals and semiconductor, a built-in electric field may come into being. Typically, due to the larger Φ of Au and Cu, but lower Φ of Al than that of IGZO, the surface energy bands of the IGZO channel layer will cause an upward curvature [9] for Au and Cu but a downward bending [10] for Al electrode. The corresponding energy bands are exhibited in Fig. 4b~d, respectively.

With respect to the barrier heights at the contact surfaces of the Au, Cu, and Al S/D electrodes with the IGZO channel layer, Al has the smallest contact barrier, followed by Cu, and the highest one is Au, so theoretically, Al/IGZO and Cu/IGZO should have better contact performance than Au/IGZO. Thus, at the same V_{DS}, the magnitude order of I_{DS} theoretically is Al > Cu > Au, and that of V_{TH} is Au > Cu > Al, but the experimental results of I_{DS} are ordered as Au > Cu > Al, and that of V_{TH} is ordered as Cu > Au > Al, indicating the theoretical and experimental results are inconsistent with each other means, besides the effect of the contact potential, there should be another reasons resulting in this difference.

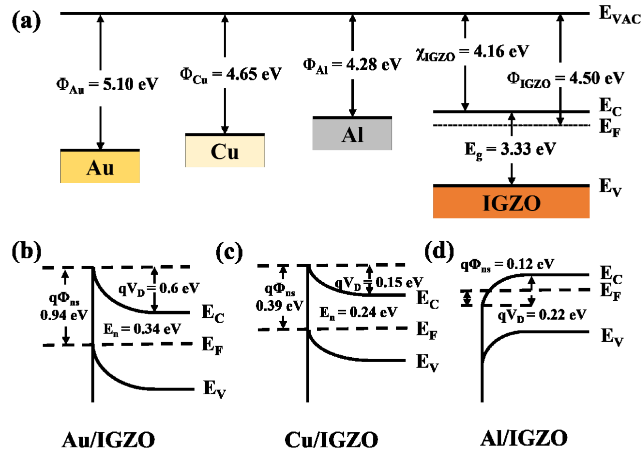

Fig.4. Schematic energy band diagrams of IGZO: (a) before contact, (b, c, d) contact with Au, Cu, and Al, respectively.

(3) Oxidation and Diffusion of S/D metals and interfacial defects

If the oxidation of Al, Cu and Au is considered, it can be found that: the conductivity of the oxide Al_2O_3 is 10^{-11} ~ 10^{-4} $S.m^{-1}$, is much smaller than that of Cu_2O (10^{-6} ~ 10^{-1} $S.m^{-1}$) and CuO (0.1 ~ 1 $S.m^{-1}$), and Au is not easy to be oxidized, so once the Al and Cu electrodes are oxidized, the I_{DS} of the TFT will drastically reduce. Meanwhile, if the oxygen that forms the oxide comes from the diffusion of O in IGZO, the oxygen content in the channel layer decreases and the concentration of the oxygen vacancies and carriers increases [11], resulting in a smaller V_{TH}.

Since the S/D electrodes directly contacts with the semiconductors, the metal ion may diffuse into the channel layer and causing the change of the carrier concentration in the channel layer or some interface defects. Intrinsically, IGZO is a n-type semiconductor, the oxygen vacancies are its main carrier, so the factors to decrease the oxygen vacancies will result in a worse conductivity of IGZO, leading to a larger V_{TH}, a smaller I_{OFF} and SS; but a smaller V_{TH}, larger I_{OFF} and SS would be got if the carrier concentration in the channel layer increases.

From Table 1, it is found that among the three IGZO TFTs with different electrode, the Al-TFT has the smallest V_{TH}, while the Cu one has the largest V_{TH}, which may be due to the easy diffusion of Al metal: if the trivalent Al element diffuses into IGZO and replace the divalent Ga or Zn, one more electron will be obtained for each atom substitution (Al becomes a donor impurity for IGZO), which will lead to an increase of carrier concentration, and a smaller V_{TH}. Cu and Au are not easy to diffuse into IGZO, and even the Cu or Au intrudes into IGZO, they are divalent elements along with Ga and Zn, so their introduction will not result in a significant change of carrier concentration, so the order of V_{TH} is related to another factors.

From Table 1, it can be seen that the SS of the Au electrode IGZO TFTs (0.32 V/dec) is the lowest, followed by Al (0.83 V/dec), and the highest (1.06 V/dec) for Cu. All of them are at a small level, which indicates that the density of the interfacial defective states of the TFTs with the three electrodes are low [12], and this may be attributed to the good contact properties between IGZO channel layer and Al_2O_3 GI layer, since they have a similar thermal expansion coefficient (4.31×10^{-6} K^{-1} / 4.5×10^{-6} K^{-1}) and work function (4.5 eV / 4.7 eV) for IGZO and Al_2O_3, respectively. The contact will cause less interfacial traps under the thermal stresses between them and the electrical conductivity of the front channel is relatively less affected by them. However, from the microscopic point of view, the value of SS is ordered as Au < Al < Cu, which is related to the oxidation and diffusion of Al and Cu leading to the change of carrier concentration in the IGZO channel layer, resulting in the corresponding larger SS.

4. Conclusion

In summary, three BGTC-type of IGZO TFTs with Au, Cu and Al as the electrodes were prepared and the impact of electrode materials on the electronic performance of IGZO TFT was compared and analyzed from three aspects: the conductivity of the electrode material; the contact potential; the change of carrier concentration in the channel layer causing by the oxidation of diffusion of electrode material. It is found that:

(1) All the three metals (Au, Cu or Al) can be used as the electrodes of IGZO TFTs. The three IGZO TFTs possess excellent electrical performances, can meet the performance requirements of TFT, having the potential to be applied in the FPD field.

(2) The experimental electrical properties of the three IGZO TFTs can be sequenced as follows: (i) μ_{FE} and I_{ON}/I_{OFF}: Au > Cu > Al; (ii) V_{TH}: Cu > Au > Al; (iii) SS: Cu > Al > Au.

(3) The Au-electrode IGZO TFTs have the best overall electrical performance, exhibiting the highest I_{DS} (41.9 μA, $V_{GS} = V_{DS} = 20$ V), I_{ON}/I_{OFF} (4.36×10^7), μ_{FE} (18.11 cm^2 /Vs), and the lowest SS (0.32 V/dec).

(4) If the electronic performance of IGZO TFT with different electrode material was analyzed just based on the electrode conductivity, the order of theoretical I_{DS} is Cu > Au > Al , but experimental $I_{DS:}$ Au > Cu > Al; and just based on the contact potential, theoretically I_{DS} is Al > Cu > Au, V_{TH} is Au > Cu > Al, but the experimental I_{DS} : Au > Cu > Al, V_{TH} : Cu > Au > Al, implying that the theoretical and experimental results are not in agreement with each other, indicating that the conductivity of the electrode material and the contact potential between the S/D electrodes and the channel layer can not completely account for the difference electronic properties of IGZO TFTs caused by electrode material.

(5) Overall, the impact of electrodes on TFT performance involves multiple aspects, some of which may be contradictory, making it very complex to accurately grasp and deeply understand their changing patterns. Although the general electrical performance of Cu and Al electrode IGZO TFTs is slightly deficient in comparison with that of the Au electrode devices, both Cu and Al are low-cost and high-performance IGZO TFT electrode materials, which are more favorable for mass production and large-scale applications in the FPD field.

5. Acknowledgements

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