Performance of Organic Thin-Film Transistors Controlled by Electrode and Device Structures

Chien-Hsien Yu, Tan-Fu Lei, Jin-Long Liao, Jing-Yi Yan, and Jia-Chong Ho

***Abstract*—We have fabricated organic thin-film transistors (OTFTs) of top contact (TC) structures using silver electrode based on triethylsilylethynyl anthradithiophene (TES-ADT) with mobility above 0.41 $cm^2s^{-1}V^{-1}$, current modulation higher than 5×10^7 and sub-threshold swing below 0.65 V/dec.. The electrical characteristics of OTFTs are not only corresponding to the work function of source and drain electrodes materials but also to the surface tension and deposition energy of them. The effects of work function and surface tension dominate the electrical characteristics in bottom contact (BC) device. On the other hand, TC device is affected by deposition energy dominantly.**

***Index Terms*—Contact resistance, organic compounds, thin-film transistors (TFTs).**

I. Introduction

THE organic thin-film transistors (OTFTs) have been under extensive studying and research in order to reach low cost, lightweight, and flexible applications in such items as active-matrix display [1], sensors, smart cards and electronic identification tags. Organic semiconductors with soluble conjugated molecular in particular, have received special attention [2], [3] due to their low-temperature processing, low-cost manufacturing, large area coverage, structure flexibility and promising electrical characteristics comparable to hydrogenated amorphous silicon. However, the active layer forming on dielectrics and electrodes is affected by the surface characteristics of dielectrics and electrodes [4]–[6] resulting in electrical barrier in the interface and the crystallinity of organic semiconductor that determine the performance of OTFT. Devices with large contact resistance can greatly limit the performance of OTFT, such as higher power consumption, bias stress instability [7] and resistor–capacitance (RC) time delay. Contact resistance can be directly correlated with the structure and the morphological difference across the channel/electrode interface in OTFT. We can improve the interface characteristics, by selecting source and drain electrodes with proper work function electrodes [6], metallic organic electrodes [8]–[10] or surface oxidation treatment [11]. Although extensive studies on the electrode–organic semiconductor and the effects in pentacene OTFTs have been reported [12]–[14], few investigations have been done regarding the solution processable active layer of OTFT. In this paper, we compare the different work function metal electrodes and find out the surface tension compatibility of metal electrodes to solvent and the deposition rate of electrode which may affect OTFT performance as well as the contact resistance of semiconductor–metal electrode.

II. Materials and Devices

A. Materials

The gate electrode, indium–tin–oxides (ITO) is deposited on glass substrate by RF magnetron sputtering. The insulator is made of silicon dioxide by chemical vapor deposition. The active layer on insulator is TES-ADT which is synthesized according to known procedures [15]. ITO, Ag, Au, Ti, Co, Ni, and Cr are selected as electrodes of source and drain and deposited separately with sputtering, thermal evaporation and e-beam deposition in thickness from 100 to 150 nm.

B. Fabrication of Devices

Both of the bottom contact (BC) and the top contact (TC) device structures shown as Fig. 1 are fabricated on glass substrate with thickness of 300 nm silicon dioxide dielectrics. In BC devices, ITO, Ag, Au, Ti, Co, Ni, and Cr are used as source and drain electrodes. After deposition and patterning processes of the gate electrode and the dielectrics, the source and drain electrodes are made by the thermal evaporation or electron-beam deposition. Then the semiconducting active layer is fabricated with TES-ADT by spin-coating under the air atmosphere, and then processed with 2-min thermal annealing at 90 °C in N_2 glove box. To improve the crystallinity of active layer, solvent vapor annealing is required after film forming [16]–[18]. On the other hand, the source and drain of TC device is made of Ag for comparison.

III. Results and Discussion

We get the performance of OTFTs with mobility higher than 0.41 $cm^2 \cdot V^{-1} \cdot s^{-1}$, current modulation higher than 5.0×10^7, sub-threshold swing below 0.65 V/dec. and threshold voltage below 16.0 V in TC device with Ag as source and drain electrodes, as shown in Fig. 2. Moreover, in BC device, we get mobility higher than 0.07 $cm^2 \cdot V^{-1} \cdot s^{-1}$, current modulation higher than 2.0×10^6, sub-threshold swing below 1.2 V/dec.

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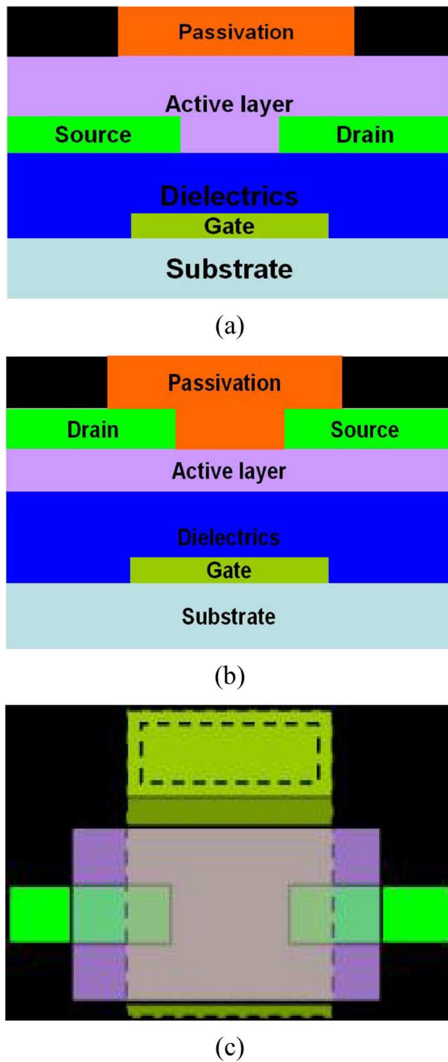

Fig. 1. Schematic of device structures. (a) Bottom contact (BC). (b) Top contact (TC). (c) Top view of device.

and threshold voltage below 10.2 V with Au as source and drain electrodes, as shown in Fig. 3. For comparison, the electrical characteristics of the values obtained with ITO, Au, and Ag electrodes are shown in Table I and Fig. 4.

The BC devices show much better electrical characteristics of Au and ITO than of Ag. From the point of view of work function difference, the bigger difference between the work function of metal and the highest occupied molecular orbital (HOMO) of semiconductor (around 5 eV), i.e. the higher energy barrier for carrier transport in semiconductor/metal interface, results in higher contact resistance. We evaluated the work function of source and drain electrodes in BC devices with photoelectron spectrum by using the AC-2 to test the surface in the air. The work functions for Ag, ITO and Au are 4.8, 5.0, and 5.1 eV, respectively. Therefore, work function compatibility might be a reason for much better electrical characteristics of Au and ITO than of Ag in BC devices.

However, BC devices with Ni, Ti, Co, and Cr as source and drain electrodes show smaller mobility, below $0.001\mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$, or even without transistor characteristics with repeated experiments.

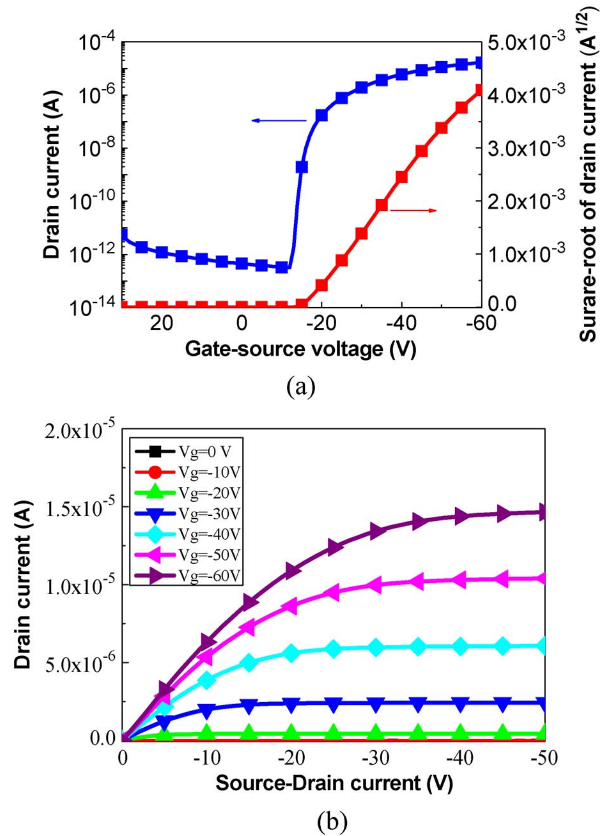

Fig. 2. (a) Drain—current versus gate—source voltage. (b) Drain–current versus source–drain voltage for a TES-ADT OTFT with a channel length of 100 μm, and channel width of 500 μm. The device had a mobility of $0.41\mathrm{cm}^2 \cdot \mathrm{V}^{-1} \cdot \mathrm{s}^{-1}$, current modulation of 5×10^7 and sub-threshold swing 0.65 V/dec.

The surface tensions of Au, Ag, Ni, Ti, Co, and Cr are 1140, 1205, 1940, 1938, 2424, and 2090 mJ/m^2 [19], respectively. Obviously, the surface tension of Au and Ag are much smaller than the others. For this reason, the BC devices with higher surface tension metals as source and drain electrode have depressed the OTFTs performance. To verify this point, we measured the surface morphology by polarized optical microscopy (OM) and scanning-electron microscopy (SEM). Different crystalline boundary is found in polarized OM (as shown in Fig. 5 which shows "macroscopic" wetting of the semiconducting organics and continuous film forming during spin coating process. On the other hand, SEM result (as show in Fig. 6 shows that "microscopic" discontinuing of the semiconducting organics in the electrode to semiconducting organics boundary which arises the discontinuous gap for electron transport. Therefore, the lack of transistor performance might be due to the surface tension mismatch between organics and high surface tension electrodes.

This result suggests that electrical characteristics of OTFTs are not only correlated to the work function of the source and drain electrodes but also affected by the intrinsic surface properties of metal electrode. Considering the active layer forming on electrodes, the organic semiconductor is crystallized from liquid-to-solid interface rather than gas to solid interface compared to vacuum processes. Therefore, the crystallization behavior can be correlated directly with the surface tension com-

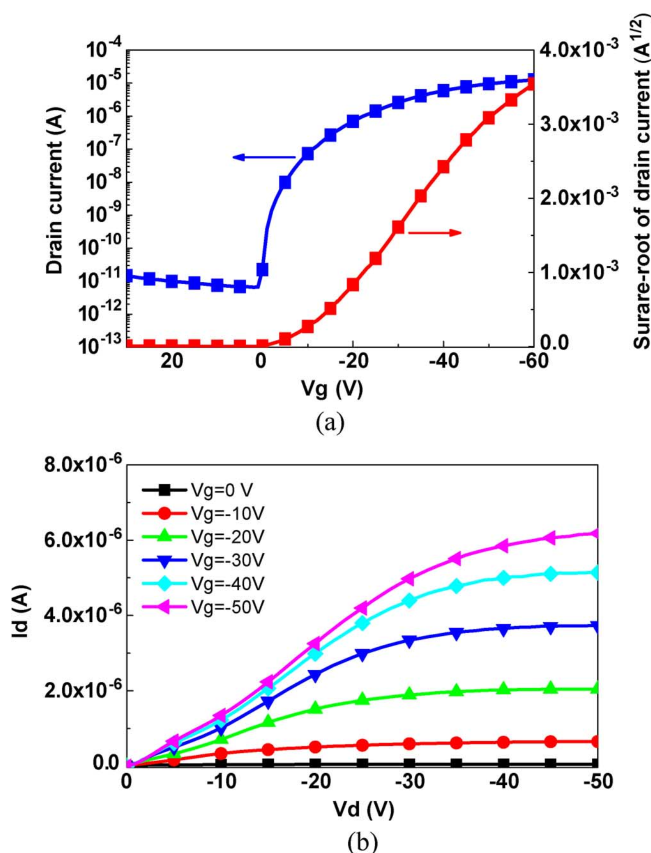

Fig. 3. (a) Drain–current versus gate to source voltage. (b) Drain–current versus source–drain voltage for a TES-ADT OTFT with a channel length of 30 μm, and channel width of 500 μm. The device had a mobility of $0.07 \mathrm{cm}^2\mathrm{V}^{-1}\mathrm{s}^{-1}$, current modulation of 2×10^6 and sub-threshold swing 1.2 V/dec.

TABLE I
ELECTRICAL CHARACTERISTICS OF TC AND BC TES-ADT OTFTS WITH Au, Ag, AND ITO ELECTRODES

	bottom contact			top contact		
	mobility	on/off	SS	mobility	on/off	SS
Au	0.07	$1.8\text{x}10^6$	1.12	0.04	$9\text{x}10^6$	0.53
Ag	0.004	$8.3\text{x}10^4$	1.28	0.41	$5\text{x}10^7$	0.65
ITO	0.089	$2.8\text{x}10^6$	0.69	-	-	-

patibility of the electrodes and the solvent as well as sensitive to solvent drying rate during film forming.

Conversely, TC devices show much better electrical characteristics of Ag than of Au. There should have other effect except the work function (contact resistance) since the contact area in TC device is much larger than in BC device and the contact resistance difference in TC device is not a dominant effect for electrical characteristics. We believe the deposition energy of electrode may be a dominant effect in this case. The reason is higher melting point and much higher boiling point of Au than of Ag. The partial vapor pressure of Au is smaller than of Ag. Consequently, higher heating power is required during Au deposition for keeping constant deposition rate (1 Å/s in this work). The

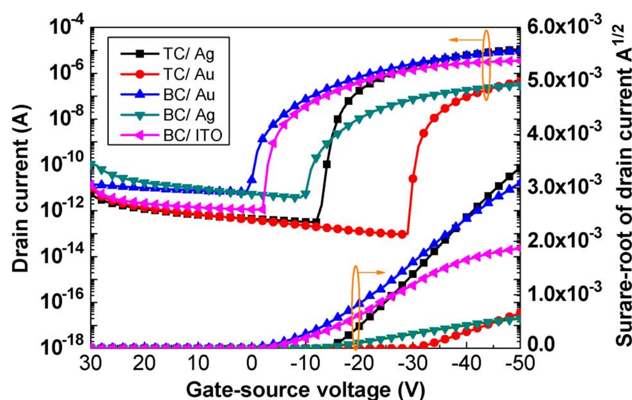

Fig. 4. Drain–current versus gate–source voltage for TC and BC TES-ADT OTFTs with Au, Ag, and ITO electrodes. Channel length of TC/Ag is 100 μm, TC/Au 109 μm, BC/Au 30 um, BC/Ag 50 μm, and BC/ITO 80 μm.

Fig. 5. Polarized optical microscopy of BC TES-ADT OTFT with Ni electrode (Mag. X200).

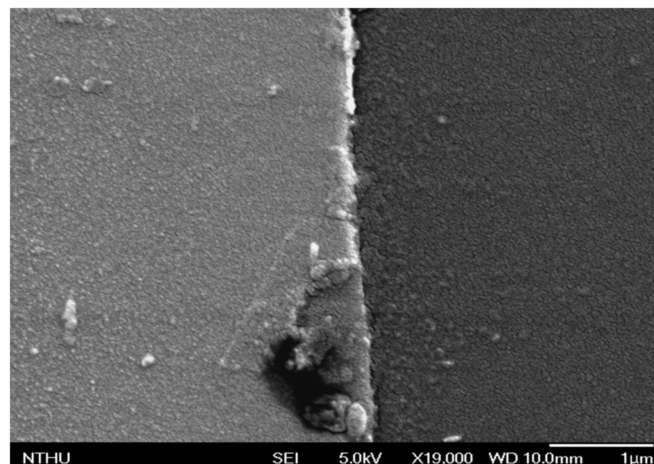

Fig. 6. Scanning electron microscopy of BC TES-ADT OTFT with Ni electrode (Mag. X19000).

Au atom with higher kinetic energy may damage the organic semiconductor and affect the electrical characteristics. Therefore, TC devices show much better electrical characteristics of Ag than of Au, although Au has more compatible work function than Ag.

IV. Conclusion

The electrical performance of solution processable OTFT is affected by electrode due to the different work function, surface tension and deposition energy. The effects of work function and surface tension dominate the electrical characteristics in BC device. On the other hand, TC device is affected by deposition energy dominantly. In addition to the electrical performance, the cost and stability trade-off should be evaluated for the optimum solution.

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