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Metal Oxide Buffer Layer Thickness Influence on the Performance of Pentacene Thin Film Transistors

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Authors' contributions

This work was carried out in collaboration between all authors. Authors WH and ZS designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors WP and YC managed the analyses of the study. Author WP managed the literature searches. All authors read and approved the final manuscript.

Research Article

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ABSTRACT

High performance top contact organic thin-film transistors (TC OTFTs) with bilayer electrodes (MoO_3/Au) are fabricated. The interface properties of metal electrodes with organic active layer have an important effect on the OTFTs performance. We demonstrate the MoO_3 layer is working as a buffer layer which can lower the charge injection barrier and reduce the contact resistance, and study the devices characteristics changing with the buffer layer thickness. Comparing with conventional TC OTFTs, the organic transistor with 10nm buffer layer shows the highest performance with field-effect mobility increasing from 0.17 to 0.69 $cm^2/V{\cdot}s$, threshold voltage downshifts from –13 to –5.3 V, and the on/off current ratio is about 50 times higher.

Keywords: Organic thin-film transistor; pentacene; OTFT; MoO_3; buffer layer.

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1. INTRODUCTION

Over the last decade, organic thin film transistors (OTFTs) based on small molecules or conjugated polymers have been the attractive candidates for a variety of low cost, large area, commercial electronics including smart cards, sensor, radio frequency identification tags (RFID), and flat panel displays [1–5]. Among all the active materials, pentacene film provides OTFTs with the highest known mobility (1 $cm^2/V \cdot s$) and high on/off current ratio [6,7]. However, in most of OTFTs work, researchers usually focus on the organic semiconductor materials and ignore the influence of the contact resistance (R_c) on the OTFTs' performance between metal electrode and organic material. Owning to the fact that the majority carriers forming the conductive channel in OTFTs are generally injected from the metal electrode into the organic semiconductor, the devices' performance largely depend on the interface properties between the metal electrode and organic active layer.

Recently, several groups start to carry out the research works about the interfacial properties between the metal electrode and organic semiconductor layer. In another field of organic semiconductors being widely studied that is organic light-emitting diodes (OLEDs), researchers found that OLEDs' luminescent efficiency depend on the metal/organic interface morphology, energetic and carrier transport. Many efforts have been done to modify the electrodes and interfaces properties in order to increase the brightness/efficiency of the devices, as well, the interface properties research works have become a hot spot in the organic devices field. Based on the TC structural OTFTs devices, results show that the devices' characteristics are really relevant to organic semiconductor materials, device structure, active layer thickness and the environment temperature, etc [8-10]. In previous work, we have demonstrated that introducing a buffer layer between metal electrode and organic layer is an effective way [11], which can obviously improve the OTFTs' and OLEDs' performance [12,13].

In this paper, we choose the top contact (TC) type device structure and pentacene as the active layer. The metal gold which has relatively high work function (5.1eV) made by vacuum thermal evaporation as the source-drain (S-D) electrodes. In order to lower the charge carrier injection barrier and reduce the contact resistance between the gold electrode and organic semiconductor, we insert a metal oxide MoO_3 as a buffer layer between them, this MoO_3/Au bilayer electrode can effectively lower the hole injection barrier from gold into the pentacene layer, which means the carrier injection ability has been enhancing and the R_c has been reduced as well. The devices' performance with the metal oxide buffer layer have been improved, and by optimizing the buffer layer thickness, we get high performance and low working voltage OTFTs.

2. MATERIALS AND METHODS

The molecular structure of pentacene and bilayer electrodes TC-OTFTs device structure are shown in Fig. 1. Pentacene (98% purity) is purchased from Tokyo Kasei Kogyo Co. Ltd. (Japan) and used without any further purification. The substrate is n-type heavily doped silicon (resistivity of 0.01～0.025Ω•cm), coved with 130 nm gate dielectric silicon nitride (Si_3N_4) which is grown by plasma enhanced chemical vapor deposition (PECVD) method. We use reactive ion etching (RIE) to etch the Si_3N_4 out and form the transistor gate electrode. Prior to organic film processing, the wafers are cleaned with a standard wet-cleaning procedure. The organic semiconductor pentacene layer is formed by thermal deposition in an organic deposition chamber under a base pressure of $3x10^{-4}$ Pa, the

deposition rate is about 3nm/min and the pentacene thickness is about 50nm. Then, the bilayer S-D electrodes are deposited onto the pentacene layer and formed in a metal deposition chamber after the organic layer deposition, the metal oxide buffer layer thickness is changing from 0, 2, 5, 10 to 20nm, and all the devices have the same Au thickness about 100nm. During the S-D electrodes deposition, the transistor channel is formed by using a mask, which defining the channel length and width are 140um and 1040um respectively. All devices are characterized in atmosphere using two Keithley 2400 source-measure units at room temperature.

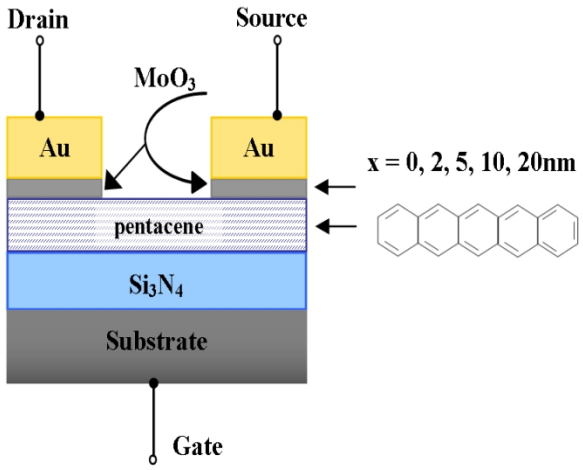

Fig. 1. Schematic cross section of the TC OTFTs with bilayer D-S electrode and molecular structures of pentacene

3. RESULTS AND DISCUSSION

Pentacene is a well known p-type organic semiconductor and the pentacene OTFTs are operated in accumulation mode. The field-effect mobility and the threshold voltage of conventional pentacne reference OTFTs with Au electrodes are 0.17 $cm^2/V{\cdot}s$ and -13 V respectively[11] based on our fabrication process. In order to show the interface effect on the OTFTs performance and study the performance changing with the buffer layer thickness, we measure the I-V curve of this bilayer electrodes OTFTs. Fig. 2(a)–(d) show the source-drain current (I_{DS}) versus source-drain voltage (V_{DS}) of the pentacene OTFTs with MoO_3/Au bilayer S-D electrodes when the gate (V_G) is scanned from 0 to -30V.

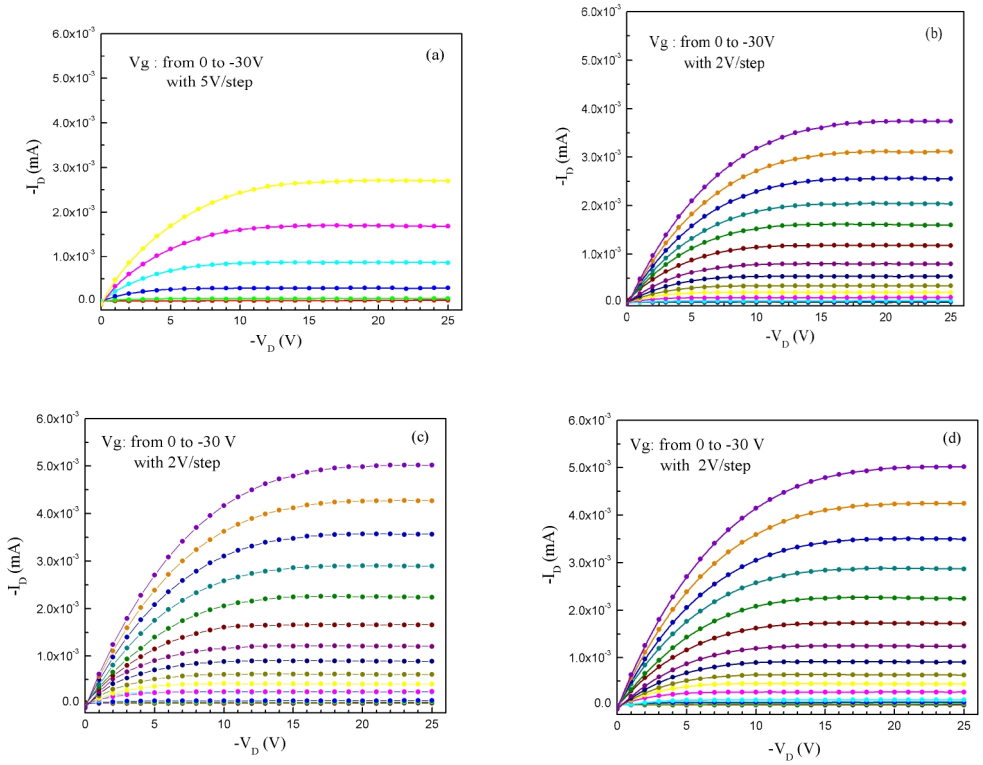

Fig. 2. Source-drain current voltage characteristics of the MoO_3/Au bilayer electrodes OTFTs with different buffer layer thickness (a=2nm, b=5nm, c=10nm, d=20nm)

The results show typical *P*-channel transistor characteristics. The output curves display very good and the saturation currents changing quadratically as the function of V_G. As the buffer layer thickness changing from 2nm to 10nm, the saturation currents are increasing gradually, the highest field-effect mobility is 0.69 $cm^2/V{\cdot}s$ and the threshold voltage is -5.3 V respectively when the buffer layer thickness is 10 nm. And then the saturation current of the channel is slightly dropping when the buffer layer thickness increases to 20nm. The corresponding plots of $-I_{DS}$ and $(-I_{DS})^{1/2}$ versus V_G (V_d is 20V) are shown in Fig. 3 with 10nm buffer layer. The field-effect mobility (μ) is calculated at the saturation regions from the following equation: [14]

$$I_{DS} = \frac{\mu W C_i}{2L}(V_G - V_T)^2$$

Where L is the channel length, W is the channel width, C_i is the capacitance per unit area of the insulator, V_T is the threshold voltage and μ is the field-effect mobility.

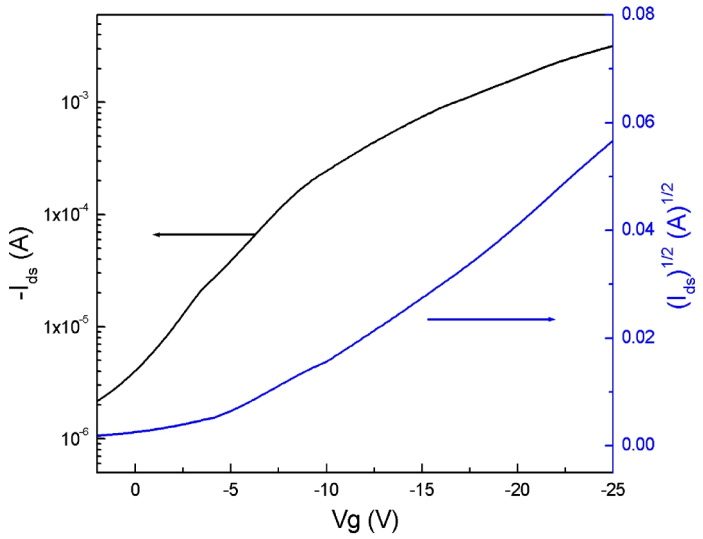

Fig. 3. Transfer characteristics of OTFTs with 10nm MoO_3 buffer layer

The calculated mobility value, threshold voltage and on/off current ratios for the reference and bilayer electrodes OTFTs (with different buffer layer thickness) in this study are summarized in Table 1.

Table 1. Electrical parameters of the OTFTs

Electrodes structure	Field-effect mobility （$cm^2/V·s$）	Threshold voltage (V)	On/Off current ratio
Au	0.17	-13	$1×10^3$
MoO_3/Au（2nm）	0.42	-9.1	$2.4×10^4$
MoO_3/Au（5nm）	0.5	-6.5	$2.0×10^4$
MoO_3/Au（10nm）	0.69	-5.3	$5.0×10^4$
MoO_3/Au（20nm）	0.68	-5.5	$5.0×10^4$

These results demonstrate that the introduction of the metal oxide buffer layer MoO_3 play an important role in the TC OTFT devices. In order to understand the MoO_3/Au bilayer OTFTs' performance improvement, we show the energy level diagrams for the pentacene, MoO_3 and Au in Fig. 4. The highest occupied molecular orbital (HOMO) of pentacene lies at 5.0 eV and is aligned with the valence band of MoO_3. Comparing with the contact properties of inorganic semiconductor/metal, the organic semiconductor/metal interface properties are more complicated. Since the metal electrodes are deposited by evaporation on the organic semiconductor layer, the interface between them has a profound impact on the electrical properties. The interface dipoles and interface states have been found and strongly affect the metal and organic semiconductor energy level alignment. According to research results [15-17], the metal atoms, especially the heavy metal atoms, can diffuse into the organic semiconductor and form an metallic film when metal is evaporated onto the organic layer. It's been proved that these diffusion metal atoms will lower the work function of gold film on pentacene layer to 4.7 eV, this value is relatively small comparing with the Au bulk work function 5.1 eV, that means the carrier injection barrier become higher and also the Rc will

increase due to this metallic film [15]. MoO_3 is a wide gap semiconductor and its valance band position at around 5.2 eV. That means there are no injection barrier for the hole transfer from bilayer electrode into the pentacene layer. X-ray photoelectron spectroscopy (XPS) analysis has been performed to understand the chemical composition of the buffer layer. The result shows that it's MoO_3 layer by the thermal deposition under vacuum condition. This buffer layer can avoid the metallic film and achieve a perfect interface without hole injection barrier, which enhances charge injection and reduce the R_c. With 10 nm thickness buffer layer, it shows the highest performance, and when it increases to 20 nm, the hole injection ability is restrained by the carrier traps in the MoO_3 buffer layer, the devices show lower saturation current and lower field-effect mobility.

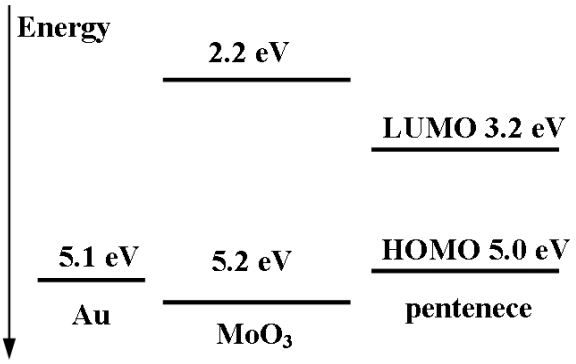

Fig. 4. Energy level diagrams of pentacene, MoO_3 and Au

4. CONCLUSION

In this manuscript, we have studied and fabricated high performance top contact pentacene OTFTs with optimizing MoO_3 buffer layer thickness.. This metal oxide buffer layer between the gold and organic semiconductor layer can lower the hole injection barrier and reduce the contact resistance, the OTFTs' gain the highest performance, such as saturation current, field-effect mobility and working voltage, etc., when the buffer layer thickness is 10nm. And also this bilayer electrodes TC OTFTs have the potential application due its high field-effect mobility and low working voltage properties.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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