Novel electrode architecture for transparent organic thin-film transistors

Fang-Chung Chen[1]*, Tung-Hsien Chen[1], and Yung-Sheng Lin[2]
[1]Dept. of Photonic and Display Institute, National Chiao Tung University, Hsinchu, Taiwan
[2]Dept. of Photonics and Institute of Electro-optical Engineering, National Chiao Tung University, Hsinchu, Taiwan
Phone:886-3-5131484, E-mail:fcchen@mail.nctu.edu.tw

Abstract

One novel electrode-architecture has been adapted to fabricate transparent OTFTs. The device has more than 70% transmittance, yet reminds high performance. Furthermore, we also use transfer line method to prove that the device performance enhancement indeed contributes from the reduction of the contact resistances. It is anticipated that the transparent OTFTs would be very suitable to be the driving circuits for liquid crystal displays (LCDs).

1. Introduction

Organic thin-film transistors (OTFTs) have been attracting much attention for their potential applications, such as low-end smart cards, and low-cost radio frequency identifications, and especially, driving flat panel displays. The high mobility of OTFTs, which is comparable with that of amorphous silicon (a-Si), has been achieved. Low process temperature and great flexibility also makes OTFTs promising candidate for next generation electronics.

On the other hand, it is also of great interest to develop transparent OTFTs, since the backlight can transport through the as-made driving circuits in liquid crystal displays (LCDs). Although transparent OTFTs haven been reported previously. The transmittance is still not quite satisfied.[1,2] The major problem of the low transmittance comes from the opaque electrodes of common OTFTs. Recently, transition metal oxides have been demonstrated as good hole injection materials for p-type organic semiconductors.[3] In this work, a novel electrode-architecture, consisting of transparent electrodes and the metal oxides as the buffer layer, has been demonstrated successfully to fabricate transparent OTFTs. The device has more than 70% transmittance, yet reminds high performance.

2. Results

To verify the new electrode architecture, we firstly made the device on Si substrates. The devices consists of highly doped Si regions as the gate electrodes, and 200 nm thermal SiO_2 as the dielectric layer. The device structure is shown as Figure 1a. The SiO_2 surface was further modified by poly(α-methylstyrene) to improve the device performance. Then, 60 nm of pentacene was thermally evaporated to be the semiconducting layer. Before sputtering indium-tin-oxide (ITO) or thermally evaporation of Al or Au as the source and drain electrodes through a shadow mask, metal oxides were evaporated to be as a buffer layer. Electrical measurements were performed under the atmosphere using a Keithley 4200 semiconductor parameter analyzer at the room temperature.

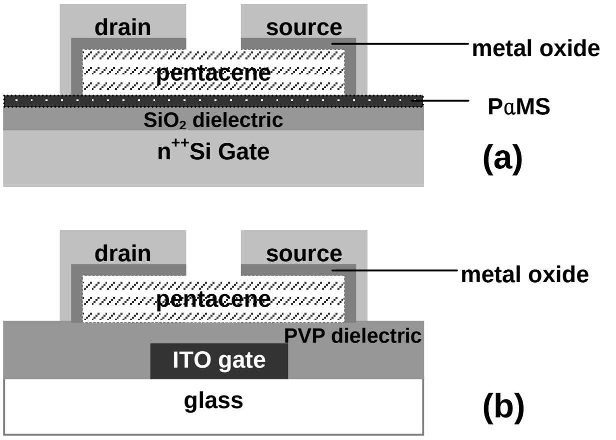

Figure 1. The device structure of TFTs on (a) a Si substrate; and (b) a glass substrate.

Figure 2 shows the device output characteristics with and without the deposition of the metal oxide buffer layer with the ITO electrodes. It can be seen that the device with the modified electrodes has more than fifty times output current comparing with that without the buffer layer. In addition, the current-voltage relationship follows Ohmic law in the linear region, suggesting good contacts was formed. Figure 3 illustrates the transfer characteristics of the OTFTs with electrodes made of ITO and ITO/ metal oxides. Similarly, it is apparent that the device performance is enhanced dramatically by incorporated the buffer layer. For the device with metal oxide I, the threshold voltage and on-off ratio are -16.3V and 3x10^6. The mobility extracted from the saturation region, following the conventional thin-film transistor model, is 0.32 cm^2/Vsec.

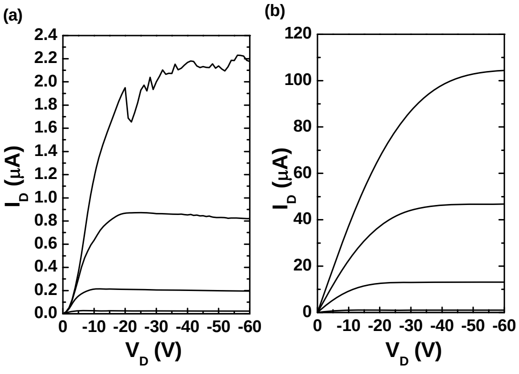

Figure 2. The current-voltage characteristics of S/D electrodes made of (a) ITO and (b) metal oxide + ITO; the gate voltage are 0 V, -15 V, -30 V, -45 V and -60 V. The channel length and width are 100 μm and 2000 μm, respectively.

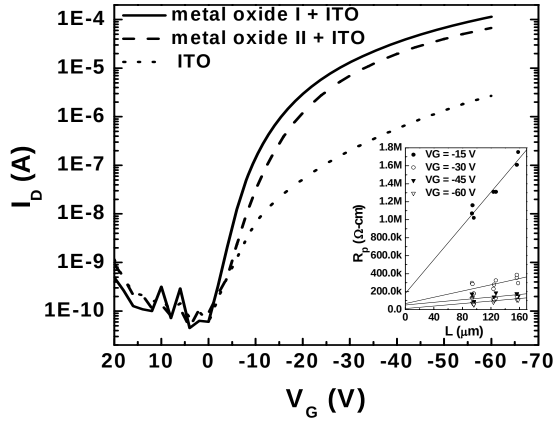

Figure 3. The transfer characteristics of the OTFTs with electrodes made of ITO and ITO/ metal oxides. Inset: the total resistance as a function of channel length at different gate biases.

Different metals, such as Al and Au, are also used as the source and drain electrodes for OTFTs. The results show similar improvement of device performance after adding one buffer layer of metal oxides. The device characteristics of all the devices are summarized in Table 1.

In order to clarify the role played by the metal oxide, transfer line method (TLM)[4-5] was adapted to estimate the contact resistance. The device resistance of one OTFT consists two parts, namely, the channel resistance (R_{CH}), which is contributed from the bulk of the semiconductor, and the parasitic resistance (R_P), according to the following equation,

$$R_T = \left.\frac{\partial V_D}{\partial I_D}\right|_{V_D \to 0}^{V_G} = R_{CH} + R_P \qquad (1)$$

The parasitic resistance R_p can be extracted from the linear regime of the transistor characteristics by plotting the width(W)-normalized (R_TW) as a function of channel length (L) for different gate voltages. The inset of Figure 3 shows the resistance as a function of channel length at gate biased from -15V to -60V for the device with metal oxide I. The extracted contact resistance is 2.7x10^3 Ω-cm, which is much smaller by several orders than that of the device without the buffer layer (3.8x10^6 Ω -cm). Consequently, we infer that the device performance enhancement indeed contributes from the reduction of the contact resistances.

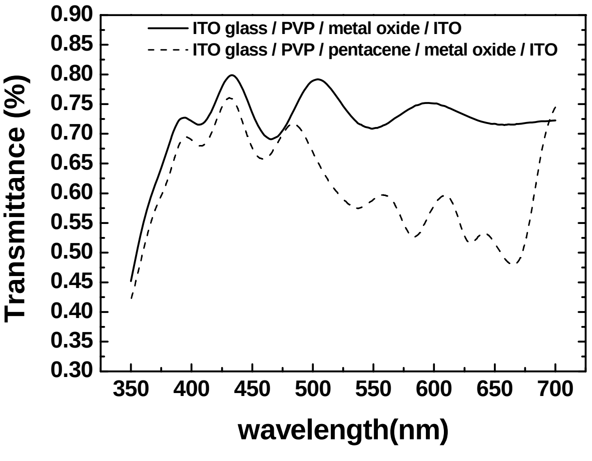

Figure. 4. The transmittance spectra of the device with and without pentacene (600 nm).

The device structure with high light-transmittance is illustrated in Figure 1b. The ITO on the glass substrates was used as the gate electrode. The cross-linked poly(4-vinylphenol) was spin-coated as the dielectric layer. The pentacene and electrodes were made by the procedure described above. From Figure 4, it can be seen that the average transmittance through the substrate, the gate insulator and the electrode in the visible range (400 – 700 nm) is as high as 73.6%. Even after the incorporation of the pentacene layer, the average transmittance reminds 61.5%, which is the highest value reported so far for TFTs made of organic semiconductors.

Figure 5 exhibits the transfer characteristics of the OTFTs with electrodes made of ITO and ITO/ metal oxides. The transparent device with metal oxide has supreme performance. The mobility and on-off ratio of the device are 0.1 cm^2/Vsec and 3.3x10^4, respectively. The threshold voltage is 5.0V and the subthreshold swing is 8.6 V/dec.

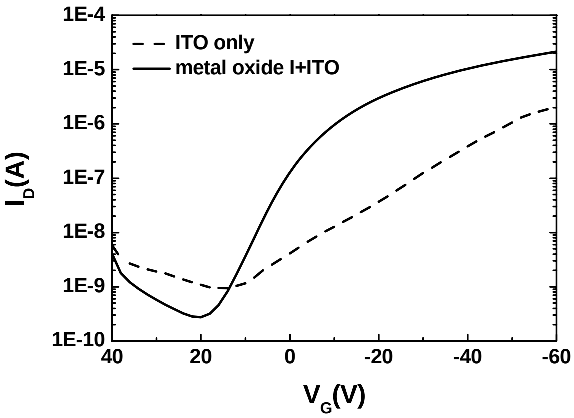

Figure 5. The transfer characteristics of the transparent OTFTs with and without the metal oxide I.

From Fig. 4, it can be found that that major absorption of light comes from the pentacene molecules. Consequently, to have an even higher value of transmittance of the device, we further reduce the thickness of the device. Fig. 6 shows the device characteristics of the devices with different thicknesses. For the device with 20 nm pentacene, the mobility in the saturation region reminded the same, and the on-off ratio decreased slightly to 1.7x10^4. The threshold voltage decreased to 0.8V and the subthreshold swing is improved to 8.0 V/dec. Apparently, the device performance did not change dramatically. The results indicate that similar device performance could be obtained even with a very thin layer of the organic semconducting layer.

Figure 7 shows the transmittance of the device with 20 nm of pentacene. With reduced absorption from pentacene, the average transmittance is as high as 72.2%. The inset of Fig. 7 shows the picture of the OTFT on the color letters and emblem of our institute underneath. The features of these patterns can be seen very clearly.

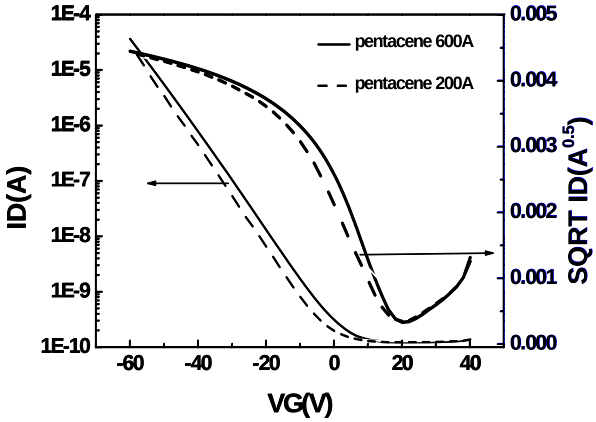

Figure 6. The device characteristics of the transparent OTFTs with different thickness of pentacene.

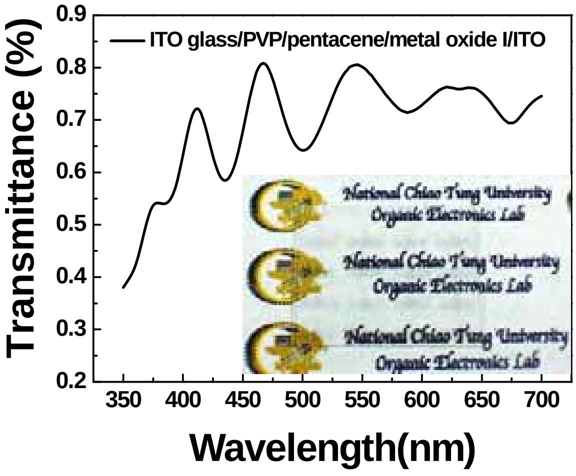

Figure. 7. The transmittance spectra of the device with thinner pentacene layer(200 nm). The inset shows the picture of the OTFT with 20 nm pentacene.

3. Conclusion

The present work has demonstrated one method to fabricate transparent OTFTs. By inserting one layer of metal oxides between the electrode and the semiconductor, the device performance was enhanced dramatically. The transmittance, which is more than 70% in the visible region, is obtained. It is the highest value ever reported so far for TFTs made of organic semiconductors. Furthermore, transfer line method was also applied to prove that the device performance enhancement indeed contributed from the reduction of the contact resistances.

4. Acknowledgements

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Table 1. The parameters of OTFTs with different electrodes on Si substrates.

electrode	Mobility (cm^2/Vs)	Threshold Voltage (V)	On-off ratio	Contact resistance (Ω-cm) @V_G = -60V
Au	0.29	-20.2	$1.9\text{x}10^6$	$9.0\text{x}10^3$
Au/MO I	0.31	-16.6	$3.0\text{x}10^6$	$3.6\text{x}10^3$
ITO	0.017	-20.7	$5.2\text{x}10^4$	$3.8\text{x}10^6$
ITO/ MO I	0.32	-16.3	$2.7\text{x}10^6$	$2.7\text{x}10^3$
ITO/ MO II	0.17	-15.7	$8.9\text{x}10^5$	$5.0\text{x}10^4$
Al	$1.8\text{x}10^{-4}$	-27.9	$1.0\text{x}10^2$	$3.6\text{x}10^8$
Al/ MO I	0.32	-16.9	$4.3\text{x}10^6$	$1.1\text{x}10^4$
Al/ MO II	0.24	-16.2	$1.6\text{x}10^6$	$2.5\text{x}10^4$