Enhanced performance of C60 organic field effect transistors using a tris(8-hydroxyquinoline) aluminum buffer layer*

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Abstract: We have investigated the properties of C60-based organic field effect transistors (OFETs) with a tris(8-hydroxyquinoline) aluminum (Alq3) buffer layer inserted between the source/drain electrodes and the active material. The electrical characteristics of OFETs are improved with the insertion of Alq3 film. The peak field effect mobility is increased to 1.28×10^{-2} cm^2/(V·s) and the threshold voltage is decreased to 10 V when the thickness of the Alq3 is 10 nm. The reason for the improved performance of the devices is probably due to the prevention of metal atoms diffusing into the C60 active layer and the reduction of the channel resistance in Alq3 films.

Key words: organic field effect transistors; buffer layer; C60; Alq3; channel resistance

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1. Introduction

Organic field effect transistors (OFETs) received much attention due to their unique properties, such as low-temperature and low-cost fabrication processes, light weight and mechanical flexibility, and their potential application in active matrix displays, electronic paper and radio-frequency tags[1, 2]. So far, much of the work has focused on researching p-type OFETs, but only a few n-type OFETs have been reported. One of the most probable reasons for the fewer n-type reports is poor electron injection from the electrode into the active layer[3]. Moreover, using low-work-function metals as contact electrodes may seem beneficial for electron injection, but in fact they can easily oxidize and readily form reactive complexes with the organic semiconductors[4]. In addition, the diffusion of metal atoms at the interface can form organo-metallic complexes, which will increase the energy barrier[5]. However, the development of n-type OFETs is very important for practical applications such as organic complementary circuits. So it is crucial to develop methods to reduce the energy barrier and to improve the carrier injection efficiency of n-type OFETs.

Recently, much effort has focused on the optimization of devices in order to obtain high carrier-injection efficiency for n-type OFETs. Jeongsoo *et al.*[6] have reported performance enhancement with a bathophenanthroline (Bphen): Cs electron injection layer between the C60 and an Al electrode. Heeger *et al.*[7] enhanced the performance of OFETs by introducing a titanium sub-oxide (TiO_x) injection layer. In addition, research on using the organic materials as a modified layer has received much attention[8]. All approaches show an effective carrier injection for the higher performance of n-type OFETs.

In this paper, we fabricated top-contacted C60-based OFETs. Tris (8-hydroxyquinoline) aluminum (Alq3), which has been used extensively as modified layers[9, 10], was used as the buffer layer at the electrode/active layer contacts. Compared with a bare modified device, the Alq3 modified devices exhibit higher performance. The field-effect mobility is improved and the threshold voltage is decreased with increasing Alq3 film thickness. Furthermore, we have analyzed the reasons for the improved performance of the devices. The insertion of Alq3 film leads to the reduction of the channel resistance and the prevention of metal atoms diffusing into the C60.

2. Experiment

Figure 1(a) shows the schematic diagram of C60 based OFETs, and Figures 1(b) and 1(c) gives the molecular structures of C60 and Alq3, respectively. The devices were prepared on heavily doped n-type Si wafers as the gate electrode, a 350 nm thermally grown SiO_2 layer ($C_i \approx 7.6$ nF/cm^2) was the gate dielectric. The wafers were cleaned with acetone, methanol and deionized water in turn. 100 nm approx polymethyl methacrylate (PMMA) ($C_i \approx 3.0$ nF/cm^2) films, used as the thin insulators, were fabricated by spin-coating in order to avoid electrons becoming trapped by the hydroxyl (OH) group in the inorganic insulating layer and the C60 interface. Then a 30 nm C60 thin film was thermally evaporated at a deposition rate of 0.6 Å/s under 2×10^{-4} Pa, and an Alq3 interlayer (0, 5, 10 and 15 nm) was deposited with another deposition source successively. Finally, the 150 nm Al source and drain electrodes were thermally evaporated through a shadow mask. The channel length (L) is 80 μm and the width (W) is 12 mm. The electrical characteristics were measured using two Keithley 2400 source meters and a Keithley 485 picoammeter at room temperature under Ar atmosphere conditions.

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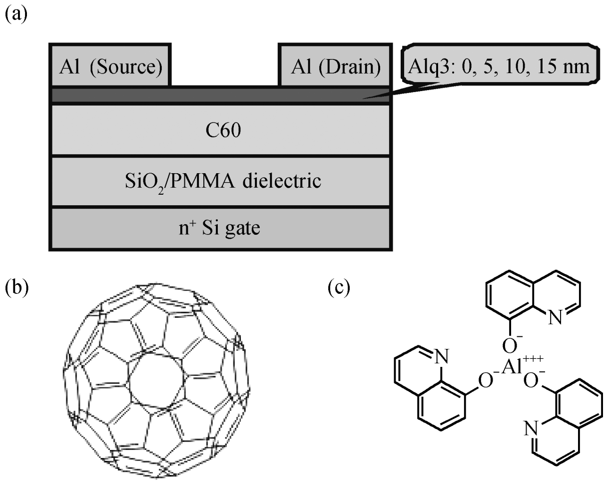

Fig. 1. (a) Schematic diagram of top-contact/bottom gate C60 OFETs with an Alq3 interlayer. (b) Molecular structure of C60. (c) Molecular structure of Alq3.

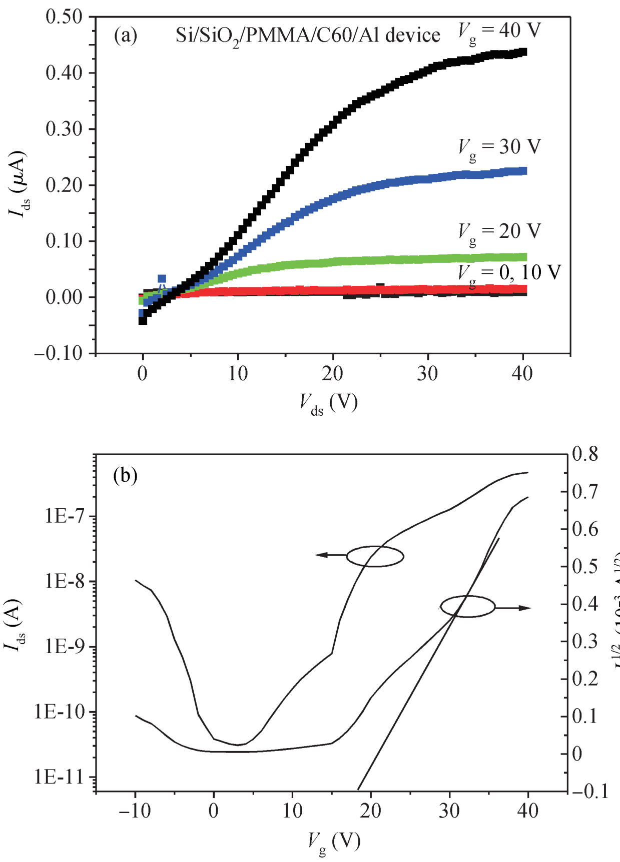

Fig. 2. (a) Output and (b) transfer characteristics, respectively, of C60 OFETs using an Al electrode.

3. Results and discussion

Figure 2 shows the output and the transfer characteristics of C60 OFETs without an Alq3 buffer layer. The linear and saturation regions are observed with the increase of drain voltage (V_{ds}). The output current (I_{ds}) is 4.37 × 10^{-7} A at 40 V gate voltage (V_g). Figure 3 shows the electrical characteristics

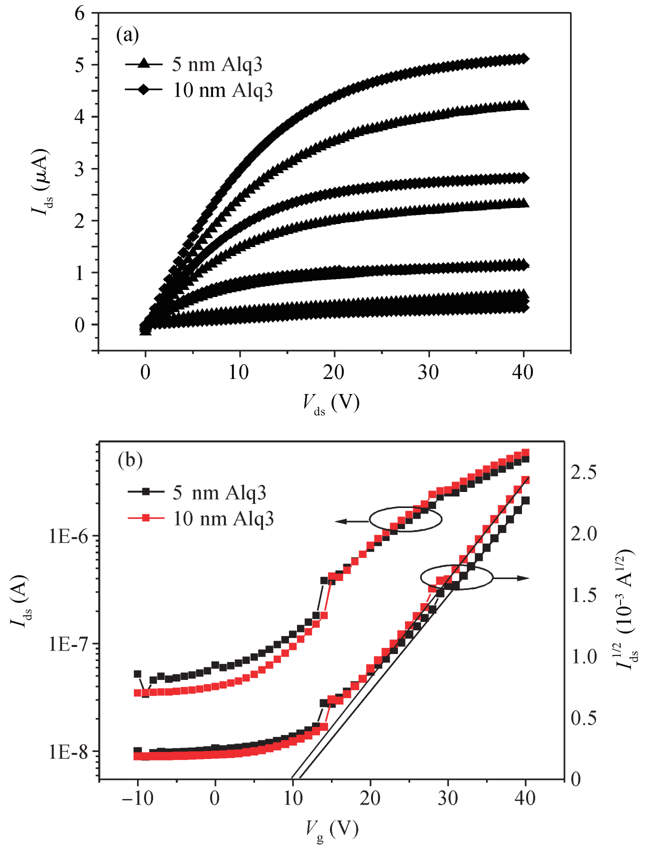

Fig. 3. (a) Output and (b) transfer characteristics, respectively, of C60 OFETs with Alq3 film thicknesses of 5 nm and 10 nm.

Table 1. Summary of the electrical performance parameters for OFETs with different thickness Alq3 buffer layers.

Alq3 (nm)	Mobility ($cm^2/(V{\cdot}s)$)	V_{th} (V)	I_{on}/I_{off}	$C_i(SiO_2/PMMA)$ (nF/cm^2)
0	1.71×10^{-3}	18	10^4	5.9
5	1.12×10^{-2}	11	10^2	5.9
10	1.28×10^{-2}	10	10^2	5.9
15	1.88×10^{-3}	21	10^2	5.9

of the devices with 5 nm and 10 nm thick Alq3 interlayers. All the devices exhibit typical n-channel operational characteristics. Compared with the bare modified devices, the devices with the Alq3 interlayer show a higher output current and a lower threshold voltage. When the thickness of Alq3 is 10 nm, the saturation current of the device is up to 5.12 μA, and this is the maximum of the draw current.

The field effect mobility and threshold voltage of these devices are calculated using the saturated drain current versus gate voltage relation in the following equation:

$$I_{ds} = \frac{WC_i\mu}{2L}(V_g - V_{th})^2, \quad (1)$$

where W and L are the channel width and length, C_i is the gate dielectric capacitance per unit area, V_g is the gate voltage, I_{ds} is the saturated drain current and μ is the field effect mobility. Table 1 shows the summary of the electrical performance parameters for OFETs with different thicknesses of Alq3 buffer

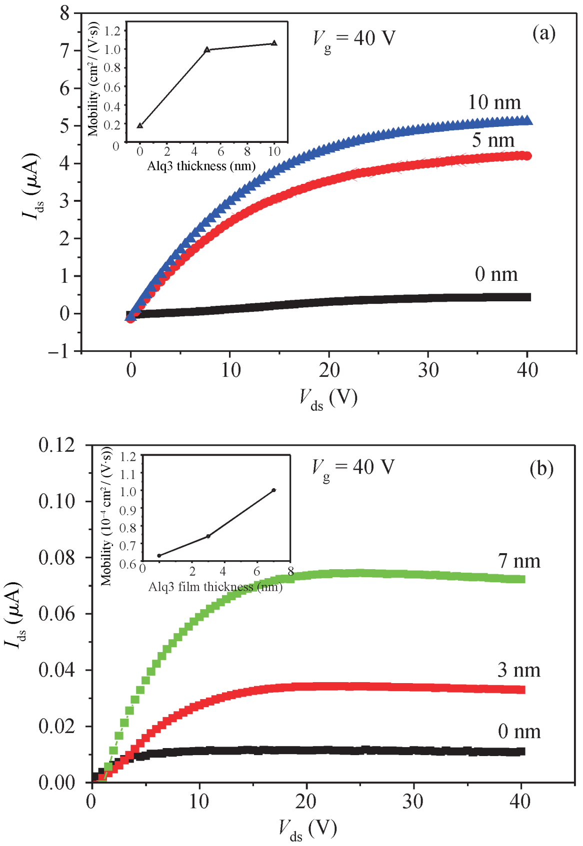

Fig. 4. Output characteristics of C60 OFETs with an Alq3 interlayer in an (a) Ar and (b) air environment measured at $V_g = 40$ V. The inset shows the μ respectively.

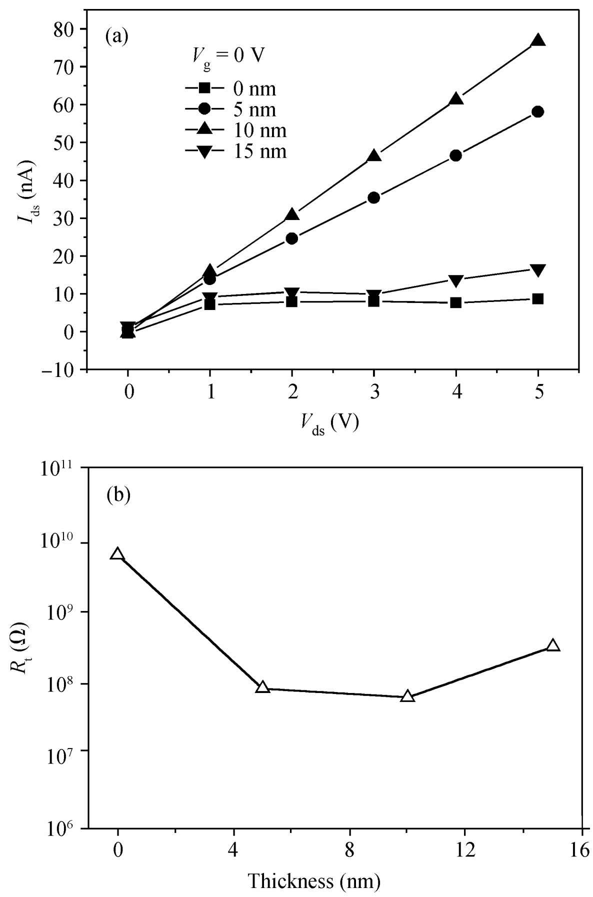

Fig. 5. (a) Output characteristics and (b) channel resistance of C60 OFETs with Alq3 film thickness of 0, 5 and 10 nm for $V_g = 0$ V and at low V_{ds}.

layers. It can be seen that the field effect mobility (μ) of the devices increase and the threshold voltage (V_{th}) decrease apparently with the increase of film thickness. The peak field-effect mobility is up to 1.28×10^{-2} cm^2/(V·s) and the V_{th} decreased to 10 V. The on-off ratio (I_{on}/I_{off}) of the devices decreased slightly with 10 nm thick Alq3. When the thickness of the Alq3 interlayer is over 10 nm, the performance of the device begins to decline.

Generally, an Alq3 ultrathin film can prevent oxygen and/or water from permeating into an active layer and increase the performance of devices since Alq3 is one of the most heat and air stable materials[9]. To verify the reason for the higher performances measured in our experiment, we fabricated devices with another two (3 nm, 7 nm) buffer layers and tested them in air for comparison. The result shows that the performance of the devices is lower than that measured in an Ar environment. As shown in Fig. 4, the output characteristics of those devices with more modified layers are still higher than that without them. So, this supposition can be excluded.

In order to understand how electron injection and transport is improved by the insertion of an Alq3 buffer layer, the diffusion of Al atoms should be considered. Generally, it seems that Al metal is an ideal electrode material for n-type OFETs because of its proper work function. However, when an Al electrode deposits directly onto a active layer, a large injection barrier and poor contact will be caused by the penetration of Al atoms[11]. Song *et al.*[9] reported that Alq3 effectively blocks electrode atoms diffusing into the active layer in an organic photovoltaic (OPV) device. According to this explanation, the performance of the devices can be analyzed in our experiment. As shown in Fig. 2(a), the output curves of the device without an Alq3 buffer layer displays an S-shape, which represents a typical non-ohmic contact. However, in Fig. 3(a), the plus Alq3 buffer layer displays linear behavior, which suggests an ideal ohmic Al/C60 contact[12]. With the increasing Alq3 film thickness, more Al atoms will be obstructed and/or unfavorable chemical reactions at the electrode/organic interfaces will not occur. Although an energy barrier is also produced between Alq3 and C60, the results show that the ultrathin Alq3 buffer layer has hardly any effect on the electron injection to the C60 active layer. In contrast, the role of blocking the penetration of atoms seems more obvious. However, when the thickness of the Alq3 thin film is greater than 10 nm, the performance of the device tends to decrease, which indicates that the injection of carriers from Al to the C60 active layer has worsened. This result demonstrates that the performance of the device can be improved by blocking the diffusion of metal atoms into the active layer with the insertion of Alq3 film.

Additionally, the total resistance between the Al/C60 interfaces may also affect the performance of OFETs. The transistor total resistance (R_t) can be expressed as[13]:

$$R_t = R_{ch} + R_c, \qquad (2)$$

where R_{ch} is channel resistance, and R_c is the source and drain contact resistance. Figure 5 shows the output characteristics and the total channel resistance (R_t) of C60 OFETs with Alq3 film thicknesses of 0, 5, 10 and 15 nm for $V_g = 0$ V and low V_{ds}. It is clear that the charge carrier density increases with an increasing Alq3 interlayer thickness, leading to the decrease of the total OFET channel resistance (R_t), which enhances the values of μ[13]. However, when the Alq3 interlayer thickness is over 10 nm, the R_t increases again and the performance of the device decreases. Moreover, Torsi *et al.*[14] have presented an analytical model of the two-dimensional potential distribution in OFETs. Their result indicated that the alteration of R_t will influence the V_{th}, the higher the R_t, the larger the V_{th}. Hence the reduction of R_t caused by the Alq3 modified layer will reduce the V_{th} and increase the off-state current (I_{off}), which is not beneficial for the I_{on}/I_{off}, as shown in Table 1. Therefore, it can be indicated that the introduction of Alq3 may not be the best modified material, even though the electrical characteristics of the devices are improved. This research on the use of organic materials as buffer layer is still significant.

4. Conclusion

We have described the effect of an Alq3 interlayer between the metal Al electrode and the C60 active layer in OFETs. The device performance can be improved by modifying the electrode/active layer with different Alq3 thicknesses. With increasing Alq3 thickness, the I_{ds} and μ is enhanced, the V_{th} and I_{on}/I_{off} are changed apparently. The reason for this is that the buffer layer can effectively prevent metal atoms diffusing into active layer. Moreover, the charge carrier density increases with the insertion of Alq3 film, leading to the decrease of the channel resistance, which enhances field effect mobility. This result indicates that using organic materials as a modified layer is an effective and simple method to prepare high-performance n-channel OFETs.

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