Thickness dependence of mobility of pentacene planar bottom-contact organic thin-film transistors

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Abstract

We have fabricated planar bottom-contact organic thin-film transistors as a function of the thickness of the pentacene active layer. The highest mobility of the planar bottom-contact transistors is 0.47 cm²/Vs with only a 7 nm pentacene active layer. Our planar bottom-contact transistors show much higher mobility than conventional bottom-contact counterparts and even higher than the reported mobility values of top-contact counterparts for each thickness in the range from 2.5 to 10 nm. We find that spike at the edges of source and drain electrodes seriously deteriorates device performance.

Keywords: Planar bottom-contact architecture; Organic thin film transistor; Field effect mobility; Pentacene; Thickness

1. Introduction

Organic thin film transistors (OTFTs) [1] are emerging as an inexpensive alternative to amorphous silicon devices due to their attractive features such as a simple fabrication process, low cost and mechanical flexibility. Recently, the performance of OTFTs has been significantly improved by modifying dielectric surface and/or source and drain (S/D) electrodes, or using novel dielectric materials. However, the achievement of high performance OTFTs was mostly in top-contact (TC) configuration rather than in bottom-contact (BC) configuration [1]. Very recently, to improve the performance of BC-OTFTs, we have reported a simple but effective device architecture, a planar bottom-contact (pBC) configuration (see inset in Fig. 1(a)) for high-performance OTFTs [2]. By embedding and planarizing the source/drain electrodes in a gate dielectric layer, our pentacene pBC transistors show superior performance to conventional BC (cBC) devices (see inset in Fig. 1(b)) [2] and the mobility is comparable to the best reported value of TC devices with similar materials to date. The improvement is believed to originate from a reduced contact resistance in planar bottom-contact configuration. In this work, we report the thickness dependent mobility of pentacene pBC transistors. For each thickness, we find the pBC device shows higher mobility than those of our control cBC counterparts and even TC transistors reported to date.

2. Experiments

We built transistors on SiO2/Si without surface/interface treatment. We fabricated pBC and cBC transistors with a various thickness of the pentacene active layer from 2.5 nm to 10 nm. The source and drain electrodes (31 nm Pt along with 2 nm Cr as adhesive layer) were patterned by conventional photolithography, etching and lift-off techniques, and deposited by DC-sputtering. The channel length and width of our transistors is 22.9 μm and 5000 μm, respectively. The planar bottom-contact architecture and of the experiments have been reported in detail elsewhere [2].

3. Results and discussion

Fig. 1(a) and (b) show the output characteristics of the pBC and cBC devices with a 7 nm pentacene film, respectively. The mobilities in saturation regime (at $V_{ds} = -80$ V) of the pBC and cBC devices are 0.47 cm²/Vs and 0.1 cm²/Vs, respectively. We observed linear behavior of the $I_{ds}$-$V_{ds}$ characteristics in the...
small bias range in the pBC configuration, in contrast to a nonlinear behavior in the cBC configuration. This indicates that the contact resistance, which is mostly due to the carrier injection barrier, was reduced in the pBC configuration and thus the performance of the device was improved [2].

Fig. 2 shows the thickness dependence of the mobility measured in the linear regime (at $V_{ds} = -20$ V) and in the saturation regime (at $V_{ds} = -80$ V) of the pBC and cBC devices as a function of the thickness of the pentacene active layer. At least four devices were measured for each thickness, and the data points represent the maximum mobility obtained. Previously, Kiguchi et al. [3] and Ruiz et al. [4] have discussed depletion and accumulation layer thicknesses in BC and TC

Fig. 1. Output characteristics of the transistors with a 7 nm thickness of pentacene active layer (a) pBC-OTFT (with inset showing the pBC architecture with SiO$_2$ as insulator) and (b) cBC-OTFT (with inset showing the cBC architecture).

Fig. 2. Field-effect mobility as a function of the thickness of the pentacene film in pBC and cBC architectures.

Fig. 3. Tapping-mode atomic force microscopy. (a) A source or drain electrode embedded in gate dielectric layer showing a spiky edge, with an inset of surface profile along the line in the image. (b) 10 nm pentacene in a pBC configuration showing a spiky edge. (c) 10 nm pentacene in a pBC configuration showing a less spiky edge.
pentacene transistors on SiO$_2$/Si system with Au as source/drain electrodes, respectively. Here we do not discuss such an issue. However, the mobility of our pBC device with a 7 nm pentacene active layer (0.47 cm$^2$/Vs) approached to that of the device with a thickness of the pentacene active layer more than 50 nm (0.48 cm$^2$/Vs) [2], indicating that the saturation thickness may be around 7 nm for pentacene pBC transistor. As seen in Fig. 2, the mobility measured in linear regime is lower than that in saturation regime for both pBC and cBC devices. This trend is in agreement with the result for TC device [4]. Furthermore, for each thickness, the pBC device shows much higher mobility than the cBC counterparts, and the linear mobility of the pBC devices is higher than the saturation one of the cBC counterparts. In the case of the saturation mobility of the pBC transistors, the mobility increase rapidly with film thickness from 0.074 cm$^2$/Vs at a thickness of 2.5 nm to 0.47 cm$^2$/Vs at each thickness, the pBC device shows much higher mobility in agreement with the result for TC device [4]. Furthermore, for each thickness, the pBC device shows much higher mobility than the cBC counterparts, and the linear mobility of the pBC devices is higher than the saturation one of the cBC counterparts. In the case of the saturation mobility of the pBC transistors, the mobility increase rapidly with film thickness from 0.074 cm$^2$/Vs at a thickness of 2.5 nm to 0.47 cm$^2$/Vs at a thickness of 7 nm.

Compared with the thickness dependent mobility of the pentacene cBC transistors to date [3], we find that our pBC transistors show much higher mobility than the reported value of the cBC devices, while our control cBC devices show poorer performance than those. This comparison further confirms our pBC configuration is superior to the cBC configuration. Furthermore, compared with the thickness dependent mobility of the pentacene TC-OTFTs [4], we find, for each thickness, our pBC devices exhibit higher mobility. Besides possible influence on carrier injection by using Au as the source/drain electrodes in the TC-OTFTs [4], the reason for higher mobility of our pBC transistor may be due to presence of metal atom diffusing into organic active layer in TC configuration during fabrication of the top S/D electrode [5]. We have found that the diffusion of Au into pentacene active layer reduced the (channel) mobility near the S/D electrodes [6]. This comparison suggests that pBC architecture exhibits striking advantage over TC architecture, in particular to very thin organic active layer, and means that the organic active layer can be thinner than 10 nm in planar bottom-contact configuration without trade-off in device performance. Thinner organic active layer certainly could greatly lower production costs due to reducing material consumption and short manufactory time, in particular for vacuum deposition method.

Our effort developing the planar BC-OTFTs is on controlling contact between S/D and organic active layer, which could reach the mobility ceiling of the devices. However, we and others find device-to-device variation in device performance even with the same materials. Fig. 3(a) is an atomic force microscopy (AFM) image of the edge of the S/D electrode without organic active layer. We can see that the edge is spiky and the height of spikes reaches 130 nm (see inset surface profile along the line). Fig. 3(b) and (c) show AFM images of the electrode edges in the pBC devices with a 10 nm pentacene active layer. The corresponding mobilities in saturation regime of the devices in Fig. 3(b) and (c) are 0.0045 cm$^2$/Vs and 0.41 cm$^2$/Vs, respectively. Obviously, the inferior performance of the device, whose edge shape of the electrode is shown in Fig. 3(b), is mainly due to the spike-induced effect since we did not observe obvious morphological difference in the channel region. Spikes at the edge of electrode could induce defects and in turn traps at the electrode/organic interface, impeding charge injection. The appearance of spikes is common in BC configuration, stemming from photolithography and life-off processes. The composition of the spike may be photo-resist, metal material, or mixture of them. The results suggest the importance to eliminate spike and control shape of electrodes in bottom-contact configuration.

4. Conclusion

In conclusion, we have measured the dependence of the field-effect mobility of OTFTs on the thickness of the pentacene films using our recent proposed planar bottom-contact architecture. Compared to the mobility of our control cBC counterparts and the reported mobility of the conventional BC devices and TC devices, we find that the pBC device shows much higher mobility than those for each thickness. It is essential to eliminate spikes and control shape of electrodes in bottom-contact configuration for high-performance OTFTs.

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References