Vol 18 No 8, August 2009
1674-1056/2009/18(08)/3530-05

Chinese Physics B

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Study of top and bottom contact resistance in one organic field-effect transistor*

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(Received 30 December 2008; revised manuscript received 11 February 2009)

This paper reports that the organic field-effect transistors with hybrid contact geometry were fabricated, in which the top electrodes and the bottom electrodes were combined in parallel resistances within one transistor. With the facility of the novel structure, the difference of contact resistance between the top contact geometry and the bottom contact geometry was studied. The hybrid contact devices showed similar characteristics with the top contact configuration devices, which provide helpful evidence on the lower contact resistance of the top contact configuration device. The origin of the different contact resistance between the top contact device and the bottom contact device was discussed.

Keywords: organic field-effect transistor, top contact geometry, bottom contact geometry, hybrid contact geometry

PACC: 7280L, 7340C, 7340T, 7360F

1. Introduction

In recent years, organic field-effect transistors (OFETs) has attracted intense interest because of their potential applications in the fields of organic thin-film transistor memory, flexible pressure sensors, photovoltaic cells, integrated circuits and RFID tags.[1−5] And the performance of the OFETs has made great improvements; a highest mobility of 43 $cm^2 \cdot v^{-1} \cdot s^{-1}$ was reported for single crystal rubrene, and the subthreshold swing and on/off ratio even approached 100 mV/dec and 10^8, respectively. These values are comparable to hydrogenated amorphous silicon TFTs.[6,7] However, with increasing performance, parasitic contact effects more and more become a limiting factor for potential applications.[8] The charge injection process and contact resistance for different transistor designs have been widely investigated,[9−11] but the intrinsic mechanism was still unclear and some of the results were even controversial from different sources of literature.

Usually, the OFETs were fabricated either in top contact (TC) or bottom contact (BC) configuration. It was generally considered that the TC OFETs had less contact resistance and higher performance than that of the BC ones due to the advantages of a larger contact area between the organic layer and the electrodes, a uniform film and less influence from the image charges and an additional work function difference.[12,13] While for the BC geometry, it was considered that it could alleviate the influence of the anisotropic mobility, donor-like bulk traps and charge effect between the electrodes and the dielectric surface, as well as keep the metal contamination or reaction away from the organic materials.[14−16] Whereas, it was necessary to point out that all the transistors referred to above were either independent top contact structures or bottom contact structures. To our knowledge, no one had directly compared the different geometry resistance under the same ambience, which helped to come to a direct and substantial conclusion.

In this paper，we fabricated OFETs with a new hybrid contact (HC) geometry, in which the top electrodes and the bottom electrodes were combined in parallel resistances between the source and drain in one transistor. The main advantage of the HC geometry was the fact that it provided identical fabrication process and test ambience for the two contact styles, which enabled us to directly contrast the contact re-

*Project supported by National Basic Research Program of China (973 Program) (Grant No 2006CB806204) and National Natural Science Foundation of China (Grant Nos 60676001, 60676008 and 60825403).

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sistance between the top contact and bottom contact configurations in one single device.

2. Experimental

The schematic diagrams of HC OFET were shown in Fig.1(a), and the corresponding scanning electron microscopy (SEM) image was shown in Fig.1(b). HC OFETs were fabricated on a highly doped n^+-Si wafer with a 300 nm thermally grown oxide layer. The substrate was ultrasonically cleaned in acetone, alcohol and then deionized water. Then, two groups of 30 nm thick gold interleaved lines were patterned and deposited by conventional photolithography. The gold lines were 4 μm wide and 60 μm long with a varied interval from 8 μm to 16 μm in different transistors, and the minimum gap at the interleaved region was 2 μm. Prior to the deposition of the active layer, the substrate surface was treated with octadecyltrichlorosilane (OTS). Subsequently, copper phthalocyanine (CuPc) was thermally evaporated under the vacuum of 3×10^{-4} Pa with a thickness of 50 nm. Finally, a 50 nm thick gold source and drain electrodes were formed on the CuPc film by e-beam evaporation through a metal shadow mask, which was manipulated under microscopic observation. The channel width of the top electrodes was fixed to 500 μm and the length ranged from 60 μm to 100 μm. During the top electrodes depositing, owing to the rather rough surface of the gold lines, the sparse CuPc film, and even a high active energy by the e-beam deposition means, the tiny gold particle penetrated through the active layer[17] and formed vast thin conductible filaments. Consequently, the top electrodes and the bottom gold lines were connected spontaneously. Then the HC OFETs were fabricated, in which the bottom metal arrays served as comb-shaped bottom electrodes. The I–V tests showed that the top electrodes and the relevant bottom electrodes were in short circuit, namely, interconnected. The schematic test points were shown in the right inset of Fig.1(b). As long as one probe contacted the point P, the other probe contacted either of the source or drain electrodes, the acquired resistances were both about several hundreds Ohm, which was far less than the resistance of the organic semiconductor in the channel. It implied that the top electrodes and the relevant bottom electrodes had a good interconnection. For comparison, ordinary top contact and comb-shaped bottom contact OFETs were also fabricated with the same process.

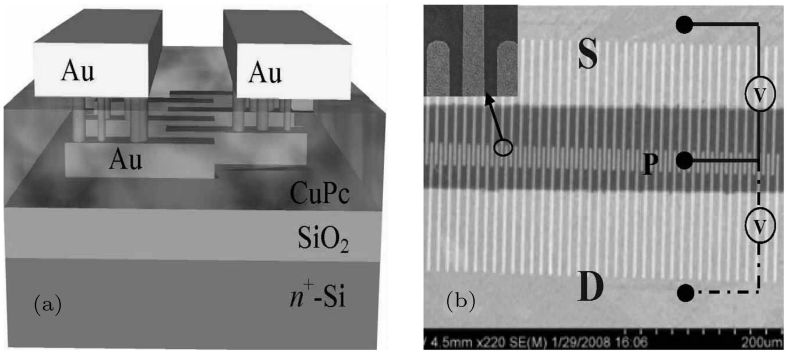


Fig.1. (a) Schematic diagrams of HC OFET; (b) the SEM images of an HC OFET, the left inset is the zoomed SEM image in the channel and the right inset is the schematic probe positions during the I–V test.

3. Results and discussion

Figure 2 showed typical drain output characteristics of the HC OFETs [Fig.2(a)], TC OFETs [Fig. 2(c)] and the comb-shaped BC OFETs [Fig. 2(d)]. Figure 2(b) showed the transfer characteristics of the HC OFETs. All the transistors exhibited an obvious field effect with operation in a p-type accumulation mode. The linear behavior of the drain current in Figs.2(a), 2(c) at low drain voltage values indicated that good Ohmic contact was realized between source/drain electrodes and the organic semiconductor.[18] While for the BC OFETs [Fig.2(d)], the nonlinear behavior and the S-shaped curve at low drain voltage and unsaturated drain current at high drain voltage implied that they had a high contact resistance[19] and were evidently influenced by the

short-channel effect.[20] More than this, the drain current of the BC OFETs was 1 ∼ 2 orders of magnitude less than the TC/HC OFETs. It indicated that there was a large device resistance in the BC geometry. While for the HC OFETs [see in Fig.2(a)], the good linear behavior at low drain voltage and saturated characteristics at high voltage showed that they suffered little contact effect or short-channel effect. Also it was obvious that the TC and HC OFETs had a similar curve profile in the drain output characteristics. As a result, we considered that the top electrodes played a predominant role in the HC OFETs. When the source and drain were biased, most of the induced carriers spontaneously chose a lower resistance channel to transport through the transistor. And the resulting channel was related to the top electrodes. If not, the carriers would transport the channel mainly through the bottom electrodes, therefore, the drain output characteristic of the HC OFETs would be nonlinear in low source drain voltage and unsaturated in high source drain voltage due to the short channel of the bottom electrodes.[19,20] But it did not occur, and little short channel effect was found in the HC OFETs [see in Fig.2(a)].

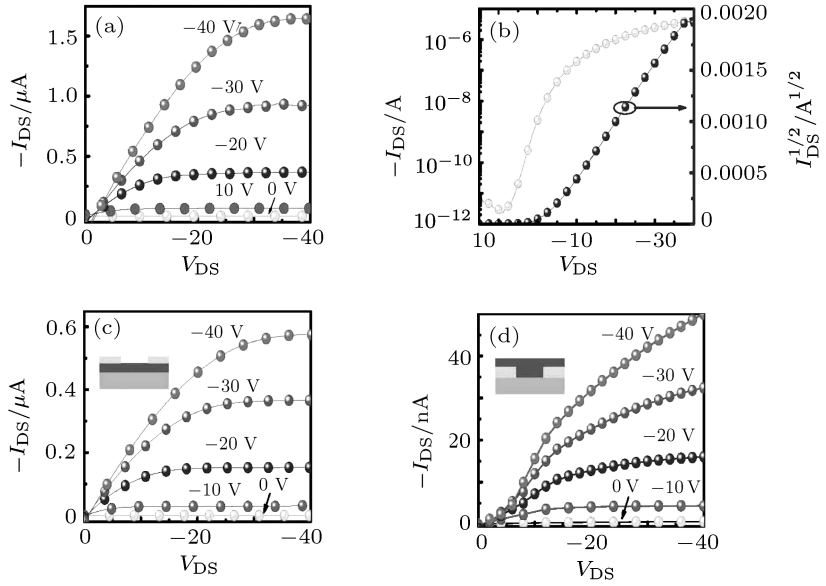


Fig.2. (a), (b) show drain output and transfer characteristics of the HC OFET, respectively; and (c), (d) for the conventional TC OFETs and BC OFETs, respectively.

In fact, the conclusion could be verified by changing the device channel length with the same source-gate bias (–40 V). If the channel length of the bottom electrodes was varied from 2 μm to 6 μm, it hardly decreased the saturated drain output current. At the same bias, changing the channel length of the top electrodes from 60 μm to 100 μm, the relevant current obviously decreased about 50%. The channel modulation did not work for the bottom electrodes. Considering that a lower total device resistance (consisted of contact resistance and channel resistance) is yet a higher channel resistance than that of the bottom electrodes, we find that the top electrodes have lower contact resistance. Figure 3(a) showed a schematic diagram of resistance in the HC geometry. Although much of the literature showed quite low contact resistance under the BC geometry for the OFETs,[21] Joshua N. Haddock *et al* revealed that the fork-like bottom electrodes with short channel still had big contact resistance.[20] Similarly, despite low channel resistance, the bottom electrodes still suffer much larger resistance than the top electrodes in the HC OFETs. The large contact resistance persistently impeded the current flowing out/in the bottom electrodes, subsequently, the drain current which flowed through the bottom electrodes was quite small and the main current flowed through the top electrodes, as shown in Fig.3(b).

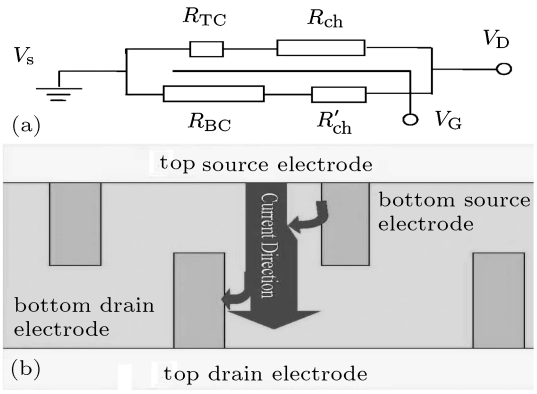


Fig.3. (a) The top electrodes and bottom electrodes were combined in parallel resistances. The resistances R_{TC}, R_{ch}, were the contact resistance and channel resistance for the top electrode, respectively; The resistances R_{BC}, R'_{ch} were the contact resistance and channel resistance for the bottom electrode, respectively; (b) schematic diagram of the current direction in the hybrid OFETs.

For the HC OFETs, the bottom and top electrodes were fabricated with the same process and operated under the same electrical parameters, while the contact resistance or total resistance were remarkably different from each other. It is necessary to find out the origin of the great different resistance between the TC and BC configurations.

Up to now, the study of device resistance，especially on contact resistance, has still been an interesting and challenging topic. It was well known that the charge carrier injection intensively depended on the energetic barrier between the work function of the electrode and the highest occupied molecular orbital (HOMO) or the lowest unoccupied molecular orbital (LUMO) energies of the organic semiconductor, as well as the effective injection area. In the case of HC OFETs, the top and bottom electrodes were fabricated in the same process at the same time and keep the same potential at any time as they connected in integration. Therefore the factors which related to the work function difference or resulted in a variety of Fermi energy were able to be ignored. Considering the just adverse deposition procedure between the electrodes and the organic material, we concluded that the different growing style between the metal electrodes depositing on the organic semiconductors and the organic materials growing on the prepatterned bottom electrodes could be responsible for the obviously different contact resistance. The influence was illuminated in the following aspects.

Firstly, it resulted in a bigger contact area for the top electrodes than the bottom electrodes. The big effective contact area implied small contact resistance.[22] During the process of depositing top electrodes, parts of the tiny gold particles would fill in the interspaces of the organic semiconductor and grow along the CuPc grains, and finally enwrap the organic surface with the increasing gold thickness. Simultaneously, parts of the particles penetrated into the active layer, as shown in Fig.4(a). Due to the extraordinary roughness of the organic-electrode interface, the real contact area between the top electrodes and the organic layer was bigger than the planar size of the top electrodes, which had been quite a bit larger than the side contact area of the bottom electrodes. For the BC geometry, the organic materials could only cover the whole planar surface of the bottom electrodes at the most, while the side surface area of the bottom electrodes is quite small because of very thin thickness. Although it is difficult to observe the CuPc morphology on the side bottom electrodes, we thought it would be similar as the morphology on the upper side of the bottom electrodes [see in Fig.4(b)]. The small side area implied that the effective injection area between the CuPc and bottom electrodes was much smaller than that of the TC configuration devices, and resulted in a bigger contact resistance in the BC configuration devices.[22] The conclusion made according to our experiments was in accordance with the results reported in the literature,[19] however, they did not give a detailed explanation.

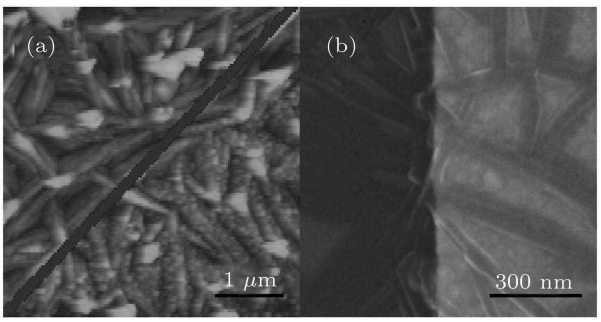


Fig.4. (a) AFM (Atomic force microscopic) image of the gold top electrode (right) on CuPc (left); (b) SEM image of CuPc on the edge of the gold bottom electrode (the left is the channel and the right is the gold bottom electrode).

Secondly, the anisotropic mobility of the organic semiconductors would also add an additional resistance to the bottom electrodes. The anisotropic mobility adding an additional resistance to the TC geometry has been reported previously,[14] but little literature has reported that the anisotropic mobility would increase device resistance for the BC geometry. As a

general rule, it was difficult for the carriers to transport from a molecule to the adjacent one which had a different arranged order, especially because the stake angle of the latter is vertical to the former. Prior to the organic layer deposition, the bottom electrodes had been fabricated on the dielectric surface, whose sides were obviously vertical to the substrate. Some literature has found that the organic molecule would stand on the surface of the poly gold and silicon dioxide in the course of deposition.[23] Therefore, for the bottom electrodes, the initial several molecule layers on the electrode sides and the nearby dielectric surface were out of order [see Fig.4(b)]. That was equivalent to insert a thin film between the electrodes and the active layer, and subsequently increased the resistance of the bottom electrodes. The morphological discontinuity around the bottom electrodes was also reported extensively.[24]

Indeed, some other factors, for example the shape of the organic-metal interface, would result in different injection efficiency between the TC and BC geometry. Yet the above two aspects, we think, were the main reasons which made the BC geometry have a bigger contact resistance than TC.

4. Conclusions

The OFETs with an unusual HC structure were fabricated, in which the top electrode and the bottom electrode were combined in parallel resistances. With the facility of the HC OFETs, we made a direct contrast of the device resistance between the top contact geometry and the bottom contact geometry. We considered that the different deposition sequence would be the main reason why there was an obviously different resistance between the BC geometry and the TC geometry. It illustrated the following main aspects: a) the bottom electrodes had a smaller contact area; b) the anisotropic mobility added an additional resistance to the bottom electrodes. So the OFETs with BC geometry made a larger resistance than that of the TC geometry.

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