Effect of electrode design on crosstalk between neighboring organic field-effect transistors based on one single crystal

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The design of high-integration organic circuits must be such that the interference between neighboring devices is eliminated. Here, rubrene crystals were used to study the effect of the electrode design on crosstalk between neighboring organic field-effect transistors (OFETs). Results show that a decreased source/drain interval and gate electrode width can decrease the diffraction distance of the current, and therefore can weaken the crosstalk. In addition, the inherent low carrier concentration in organic semiconductors can create a high-resistance barrier at the space between gate electrodes of neighboring devices, limiting or even eliminating the crosstalk as a result of the gate electrode width being smaller than the source/drain electrode width. © 2018 The Japan Society of Applied Physics

Organic circuits have promised to revolutionize our daily life by enabling the fabrication of low-temperature cost-effective electronic devices, for their potential applications in flexible and conformable electronics. It has been demonstrated that crosstalk, i.e., interference between neighboring operated devices, extensively exists in organic circuits. This crosstalk causes the measured mobility to be overestimated and device functionalization to be unreliable, resulting in difficult circuit design and failed circuit operation. One available method of minimizing crosstalk is to pattern the semiconductor active layer of organic field-effect transistors (OFETs). For example, Zhu et al. suppressed crosstalk by patterning rubrene crystalline thin film, which was fabricated using the electron-beam lithographic Au patterns, combined with the coverage of a 1,2-dipalmitoyl-sn-glycero-3-phosphocholine (DPPC) monolayer and a postdeposition annealing process. Minari et al. minimized crosstalk by patterning the nucleation and growth of dioctylbenzothienobenzothiophene (C8-BTBT) film on the wettable pattern regions under vacuum ultraviolet light. Briseno et al. reduced crosstalk by applying an octadecyltriethoxysilane (OTS)-modified pattern surface to provide a controllable nucleation for the vapor growth of an organic single crystal on desired regions. Although organic semiconductor patterning can effectively eliminate crosstalk, the patterning of organic thin film is limited in its low precision, low integration, low efficiency, and high cost. Because of the inherent fragility of organic materials, their patterning is not compatible with the conventional photolithography technology that has been extensively used in Si-based electronics. At the same time, the patterning of organic crystals introduces a difficulty in crystal difference, resulting in device difference and therefore the challenging problem in circuit design. The miniaturization of organic circuits requires high integration of OFET devices with high precision and low cost. Therefore, it may be more desirable to fabricate organic circuits based on a whole organic semiconductor layer, where the device pattern is directly determined by the electrode pattern. Therefore, it is essential to study the effect of electrode design on crosstalk. Clarification of this problem is favorable for exploring the possible methods of reducing and even eliminating crosstalk on the basis of electrode design, which is extremely important for the minimization and integration of organic circuits. Until now, however, only a few groups have experimentally shown crosstalk between OFETs, or have studied such crosstalk.

Here, we applied rubrene single crystals to experimentally study the effect of electrode design on the crosstalk phenomenon between neighboring organic devices. Compared with organic thin film, an organic single crystal possesses essentially perfect molecular ordering and is free of grain boundaries, making it show nearly ideal transistor behavior and is therefore ideal for fundamental studies. The rubrene single crystal, which has been extensively used for fundamental studies in organic electronics, was selected as the semiconductor layer. Only one organic crystal was applied to fabricate multiple operated devices for studies of parameters such as device space, source/drain electrode interval, and gate electrode width. It was found that the diffraction distance of the current decreases with source/drain electrode interval and gate electrode width, and crosstalk can be effectively limited and even eliminated when the gate electrode width is smaller than the source/drain electrode width.

To study the crosstalk phenomenon between devices, we fabricated four bottom-gate top-contact OFETs based on one rubrene single-crystal microbelt by a simple mechanical manipulation method described in the previous report. The fabrication process of the device array is as follows. First, poly(methyl methacrylate) (PMMA) in anisole was spin-coated onto a Si substrate as the dielectric. The thickness of the PMMA insulation layer was ~300 nm. Dielectric capacitance was generally ~10 nF cm⁻². Then the rubrene single-crystal microbelt was put onto the PMMA dielectric using the tip of the mechanical probe. Finally, the preprepared gold films were mechanically transferred onto the rubrene microbelt as the source/drain electrodes. The rubrene single-crystal microbelts were grown by a physical vapor transport process in a horizontal tube furnace. Microbelts with lengths exceeding hundreds of micrometers were selected to provide us a chance to fabricate multiple devices based on one single crystal. All electrical measurements were carried out in air. A schematic image and optical micrograph of the multiple devices based on one rubrene single-crystal microbelt are...
Experimental observation of crosstalk phenomenon between rubrene FETs based on one single crystal microbelt. (a) Schematic image and (b) optical micrograph of the multiple devices based on one single crystal. Scale bar: 50 µm. Device No. 1 had channel length $L = 191.5$ µm and width $W = 34.5$ µm. (c) Measured transfer curves of device No. 1 when only device No. 1 was operated. (d) Transfer curves of device No. 1 with interference from devices No. 2, No. 3, and No. 4. The arrow shows increasing device space. $V_{SD} = -20$ V.

Fig. 1. Uniform crosstalk between rubrene devices, which is prerequisite to evaluating the influence of crosstalk. The space between the pair of electrodes enables some of the accumulated carriers to move at the shortest distance between source and drain electrodes, but not along the fringing electric field as diiffraction carriers. In the semiconductor, the distribution of the fringing electric field between source and drain electrodes is nonuniform, as shown in the upper schematic image of Fig. 2(d). When $W_S > W_E$, the accumulated carriers could be transported not only along the shortest distance between source and drain electrodes, but also along the fringing electric field (as diffraction carriers).

In order to further verify the formation mechanism of crosstalk, we designed the following experiment. Firstly, an OFET with a wide semiconductor layer was fabricated. Subsequently, the width of the semiconductor ($W_S$) was gradually decreased by scratching the semiconductor layer in the direction of the channel width using a mechanical probe. (b) Transfer curves of the device at different $W_S - W_E$. (c) Ratio of on-state current $I_{on}$ versus $W_S - W_E$ characteristic at different $W_S - W_E$, $L$, initial on-state current of the device prior to scratching the semiconductor; $I$: on-state current of device after scratching the semiconductor. $V_G = -20$ V. When the device space is small, the carrier transport of different devices will be affected by each other owing to the presence of the public carrier channel between electrode pairs. We refer to the carrier that move along the fringing electric field as diffraction carriers.

Fig. 2. Dependence of source/drain current on $W_S - W_E$, where $W_S$ and $W_E$ are the width of the semiconductor and width of source/drain electrode, respectively. (a) Schematic diagram showing the gradual decrease of the semiconductor width ($W_E$) by scratching the semiconductor layer in the direction of the channel width using a mechanical probe. (b) Transfer curves of the device at different $W_S - W_E$. (c) Ratio of on-state current $I_{on}$ versus $W_S - W_E$ characteristic at different $W_S - W_E$, $L$, initial on-state current of the device prior to scratching the semiconductor; $I$: on-state current of device after scratching the semiconductor. $V_G = -20$ V. The insets in (c) are typical optical micrographs of the devices with $W_S - W_E = 118.6$, 51.7, and 3.1 µm, channel length $L = 30.8$ µm, the width $W = 31.6$ µm. Scale bar: 50µm. (d) Schematic images showing the carrier transport along the nonuniform fringing electric field in the semiconductor. The fringing electric field-induced transport channel of carriers is partly blocked by scratching the semiconductor.
By scratching the semiconductor layer, some diffraction carriers are blocked [middle schematic image in Fig. 2(d)], resulting in the decreased current with decreasing \( W_S - W_E \). The fringing electric field in the region far from the source/drain electrode, where the diffraction carriers are scarce, is weak. In this case, the change in the on-state current with semiconductor width is small, resulting in the slowly decreasing \( I/I_0 \) with decreasing \( W_S - W_E \). At the region near the electrode, the fringing electric field is dramatically enhanced, where the change in \( W_S - W_E \) will seriously affect the change in the number of diffraction carriers. As a result, \( I/I_0 \) decreases sharply with decreasing \( W_S - W_E \). When \( W_S - W_E = 0 \), i.e., the semiconductor width is equal to the electrode width, the carrier channel via the fringing electric field is completely blocked [bottom schematic image in Fig. 2(d)]. Therefore, as mentioned in previous papers,\(^\text{8–13}\) patterning the semiconductor active layer to block the transport channel of the diffraction carriers is an effective method of avoiding crosstalk.

To find a possible way of minimizing crosstalk on a large-area semiconductor layer, we investigated the possible impact factors on crosstalk. As shown in Fig. 2(c), the current is almost unchanged in the region far from the source/drain electrode, where the fringing electric field is negligible. Here, to show the fringing-electric-field-induced effect on carrier transport, we define the diffraction distance as the \( W_S - W_E \) value where the current presents a 2% change in \( I/I_0 \) versus \( W_S - W_E \) characteristic curves. This value is equal to the interval between the electrode and the edge of the fringing electric field, as schematically shown in Fig. 3(a). The measurements were carried out using one rubrene single-crystal microbelt with various electrode interval/channel lengths. Figure 3(b) shows the optical micrograph of the devices. The electrode interval/channel lengths of the five devices were 14.6, 71.4, 96.6, 106.7, and 166.6 µm. First, the devices with different electrode interval/channel lengths were measured. The measured transfer curves and the corresponding mobility are shown in Figs. 3(c) and 3(d), respectively. The mobility increases with increasing channel length, which is in good agreement with previous reports.\(^\text{26–28}\) Subsequently, for each device with fixed electrode interval/channel length, the electrical properties were measured in the same way as shown in Fig. 2(a). Figures 3(e) and 3(f) show the effect of the interval between source and drain electrodes, i.e., the channel length, on the diffraction distance. The ratio of the on-state current \( I/I_0 \) versus \( W_S - W_E \) is given in Fig. 3(e). The dotted line in Fig. 3(e) corresponds to a 2% current change compared with the initial current value. The diffraction distance is extracted from the \( W_S - W_E \) value at the intersection point of the dotted line and \( I/I_0 \) versus \( W_S - W_E \) curves, as presented in Fig. 3(f). The diffraction distance is \( \sim 70 \mu m \) for the device with the electrode interval/channel length of \( L_S = 166.6 \mu m \), but only \( \sim 10 \mu m \) for the device with \( L_1 = 14.6 \mu m \). The diffraction distance decreases with decreasing electrode interval/channel length, which can be explained by the presence of the fringing electric field between the source and drain electrodes. In a large-area organic semiconductor crystal layer, the decreased electrode interval/channel length introduces a weakened fringing electric field, as schematically shown in the insets of Fig. 3(f), resulting in the decreased diffraction distance.

Considering the fringing electric field to be distributed in the direction of the channel width, the effect of gate electrode width on the diffraction distance was investigated by fabricating multiple devices with different widths of the gate electrode on one rubrene crystal. Figures 4(a) and 4(b) show the schematic image and optical micrograph of the devices. Five field effect transistors with different gate widths from 20 to 60 µm were fabricated on one rubrene crystal. The gold gate electrode was prepared on polyethylene terephthalate (PET) by photolithography. The source/drain electrode width was fixed at \( \sim 40 \mu m \). Figures 4(c) and 4(d) show the initial transfer curves and the corresponding mobility at different gate electrode widths. It can be observed that the open voltage is almost unchanged at \( W_G > W_E \), shows a weak change at \( W_G = W_E \), and shifts obviously in the positive direction with further decrease of \( W_G \). These results show that a smaller gate electrode width will weaken the effect of the gate electrode, so that a high gate voltage is required to deplete the carriers of the organic semiconductor, resulting in a higher open voltage. The relationship between gate width and diffraction distance was studied by the same method as presented in Fig. 2(a). Figure 4(e) shows the ratio of the on-state current \( I/I_0 \) versus \( W_S - W_E \) at different gate electrode widths, and Fig. 4(f) shows the corresponding dependence of the diffraction distance on gate electrode width. It is clear that the diffraction distance of the device changes with gate electrode width. With decreasing gate electrode width, the distribution region of the induced carriers between the semiconductor and insulator becomes limited, resulting in the weakened carrier transport channel and decreased diffraction distance. When the gate electrode width is smaller than the source/drain electrode width, as shown in the inset of Fig. 4(e), the current first remains unchanged by the gradual scratching of the
semiconductor in the direction of channel width, but then dramatically decreases once the scratch crosses the channel between the source and drain electrodes, i.e., $W_S < W_D < 0$. These results show that a gate electrode width smaller than the source/drain electrode width effectively limits crosstalk because the induced carrier distribution is mainly localized at the gate electrode. Different from inorganic semiconductors, the conductive channel of organic semiconductors strongly depends on the applied gate voltage owing to the extremely low carrier concentration in organic semiconductors. At those regions of the semiconductor/dielectric interface without a gate electrode, the absence of the induced carriers produces a high-resistance barrier that can effectively prevent carrier transport. As a result, crosstalk can be dramatically weakened and even eliminated. On the other hand, it should be mentioned that a gate electrode width smaller than the width of the source/drain electrode ($W_G < W_D$) will result in decreased performance, for example, $\mu = 1.78 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ at $W_G = 30 \mu\text{m}$ and $W_D = 40 \mu\text{m}$, whereas $\mu = 2.93 \text{ cm}^2 \text{V}^{-1} \text{s}^{-1}$ at $W_G = W_D = 40 \mu\text{m}$. However, as presented in the inset of Fig. 4(f), the transistor still shows typical field-effect characteristics when the gate electrode width is slightly smaller than the width of the source/drain electrode. In this case, the diffraction distance can be well limited.

In conclusion, we applied rubrene crystals to study the effect of electrode design on crosstalk among OFETs. The device space, source/drain electrode interval, and gate electrode width were demonstrated to be related to crosstalk. Crosstalk can be weakened by a weakened fringing electric field due to a decreased source/drain electrode interval and a limited carrier channel due to a decreased gate electrode width.

Different from its inorganic counterparts, crosstalk between organic transistors can be effectively limited and even eliminated when the gate electrode width is smaller than the source/drain electrode width, because of the presence of a high-resistance barrier created by the interval between gate electrodes. These results may enable future device and circuit design on large-area unpatterned organic thin films or single crystals.

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