Air-stable Ambipolar Organic Heterostructure Transistors with Various Sexithiophene Alkyl-substituted Derivatives

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1. Introduction
The development of organic thin-film transistors (OTFTs) with a performance comparable or superior to that of a-Si:H TFTs is an important goal for organic electronics. In most silicon-based microelectronics, the use of complementary logic elements requires n- and p-channel (ambipolar) semiconductors. This complementary technology has enabled the construction of digital circuits, which operate with low power dissipation and a good noise performance. Organic CMOS logic circuits based on discrete n- and p-type transistors have also been reported. [1] On the other hand, the use of organic ambipolar transistors, which work as both p- and n-channel transistors, can simplify the design of organic CMOS integrated circuits. CMOS inverter circuits were fabricated with organic ambipolar transistors based on heterogeneous blends of p- and n-semiconductors or a single semiconductor with a narrow band gap.[2-4] Furthermore, ambipolar devices were also demonstrated by using heterostructures of p- and n-type semiconductors.[5-9] High device performance can be achieved in continuous and flat films through the heterojunction effect.[10]

In this work, we further investigated the effect of mobilities of p-type semiconductors on ambipolar transistor performance by fabricating ambipolar organic heterojunction transistors with n-type F 16CuPc and various p-type sexithiophene alkyl-substituted derivatives as active layers.

2. Experimental
The molecular structures of sexithiophene alkyl-substituted derivatives (α6T, DE-α6T and DH-α6T) used in this study are shown in Fig. 1, along with the OTFT device schematic structure. A heavily n-doped Si substrate acts as the gate electrode with a 300 nm thermally grown SiO2 layer (C~10 nF/cm2) as the gate dielectric. F16CuPc thin films approximately 5 nm and α6T, DE-α6T and DH-α6T thin films of approximately 20 nm were continuously vacuum-deposited from two deposition sources. During deposition, the substrate temperatures were set at 120 °C for F16CuPc films and RT for α6T, DE-α6T and DH-α6T films under a base pressure of less than 1 × 10^{-3} Pa. Film thicknesses and growth rates were monitored by a thickness and rate monitor (CRTM-6000, ULVAC). Then the films were annealed at the temperature of 160 °C for 6h in the dark. Finally, Au source and drain electrodes of approximately 100 nm were vacuum-deposited through a shadow mask with a channel width of 5 mm and a length of 70 μm. The electrical characteristics of these heterostructure OTFTs were measured using a two-channel voltage current source/monitor system (R6245, ADVANTEST) under ambient laboratory air conditions.

3. Results and Discussion
Figure 2 displays the typical drain current-voltage (I_D - V_D) characteristics obtained for an F16CuPc/DH-α6T TFT operating in the hole-entancement and electron-enhancement modes, respectively. The p-channel operational characteristics of the ambipolar TFT are different from those of TFTs with only a DH-α6T layer. At negative gate voltages |V_G|<30, unusual characteristics were observed: |I_D| does not saturate and rapidly increases for |V_D|-|V_G|>10V, which can be explained by the contribution of drain-induced electrons. Similarly, at positive gate voltages |V_G|>20, n-channel operational characteristics of the ambipolar TFT identical to those of TFTs with only an F16CuPc layer are observed. For |V_G|<30 V and |V_D|-|V_G|>30V, an increase in nonsaturated I_D could also be observed, which originates from drain-induced holes. The electric parameters of the ambipolar TFT were estimated using the standard analytic theory of metal oxide.
semiconductor field-effect transistors (MOSFETs). From the plots of $|I_D|^{1/2}$ vs $V_G$ shown in Fig. 3, field-effect hole and electron mobilities of $1.77 \times 10^{-3}$ cm$^2$/Vs and $8.18 \times 10^{-3}$ cm$^2$/Vs for the ambipolar TFT, respectively, were derived in the saturation region.

![Figure 2](image1)  
**Figure 2** Drain current-voltage ($I_D - V_D$) characteristics of an F$_{16}$CuPc/DH-a6T TFT working in hole-enhancement and electron-enhancement modes.

![Figure 3](image2)  
**Figure 3** $I_D^{1/2}$ vs $V_G$ at fixed $|V_D|$ of 60 V for the heterostructure TFT.

Table 1  Summary of mobilities for ambipolar TFTs with various p-type sexithiophene alkyl-substituted derivatives

<table>
<thead>
<tr>
<th>Mobility (cm$^2$/Vs)</th>
<th>Single layer device (p type)</th>
<th>Ambipolar device</th>
</tr>
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<tbody>
<tr>
<td>a6T</td>
<td>8.0E-3</td>
<td>p 1.50E-3</td>
</tr>
<tr>
<td>DE-a6T</td>
<td>0.2</td>
<td>n 2.00E-3</td>
</tr>
<tr>
<td>DH-a6T</td>
<td>0.04</td>
<td></td>
</tr>
</tbody>
</table>

In such F$_{16}$CuPc/a6T device, good ambipolar behavior was observed. However, for F$_{16}$CuPc/DE-a6T device, only weak p-channel behavior was observable. These ambipolar field-effect mobilities were derived and shown in Table 1.

The ambipolar mobilities for F$_{16}$CuPc/a6T and F$_{16}$CuPc/DH-a6T devices have the same order of magnitude, and are comparable to the unipolar mobilities of single-layer thin-film transistors, while the p-type mobility of DE-a6T/F$_{16}$CuPc device was only observed and very lower. F$_{16}$CuPc is one of air-stable n-type organic semiconductors with high electron field-effect mobility of ca. 0.03 cm$^2$/Vs. As shown in Table 1, the much difference of their device performance was attributed to the ratio of $\mu_p/\mu_e$.

The ratios of a6T and DH-a6T are about 1 ~ 2, lead to equivalently electron- or hole-injunction, and obtain a high device performance for ambipolar organic heterojunction transistors.

4. Conclusions

In conclusion, ambipolar transport was realized in organic heterojunction transistors with n-type F$_{16}$CuPc and various p-type sexithiophene alkyl-substituted derivatives as active layers. The electron and hole mobilities of organic heterojunction transistors with F$_{16}$CuPc/a6T and F$_{16}$CuPc/DH-a6T have the same order of magnitude, and are comparable to the unipolar mobilities of single-layer thin-film transistors, while the p-type mobility of DE-a6T/F$_{16}$CuPc device was only observed and very lower. The much difference of their device performance was attributed to the ratio of $\mu_p/\mu_e$. The ratios are about 1~2, lead to equivalently electron or hole injunction, and obtain a high device performance for ambipolar organic heterojunction transistors.

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References


