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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 $F_{16}CuPc$ 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 SiO_2 layer (C_i ~10 nF/cm^2) as the gate dielectric. $F_{16}CuPc$ thin films approximately 5 nm and α6T, DE-α6T and DH-α6T thin films of approximately 20 nm were continually vacuum-deposited from two deposition sources. During deposition, the substrate temperatures were set at 120 ^{o}C for $F_{16}CuPc$ 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 ^{o}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.

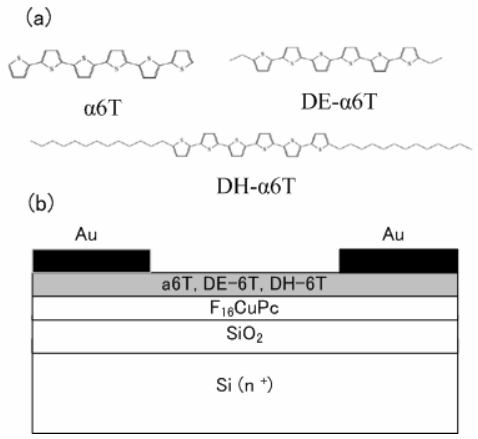

Figure 1 (a) α6T, DE-α6T and DH-α6T molecular structures, (b) schematic structure of OTFT based on $F_{16}CuPc$/α6T, DE-α6T or DH-α6T layers. The dimensions are not scaled.

3. Results and Discussion

Figure 2 displays the typical drain current-voltage (I_D - V_D) characteristics obtained for an $F_{16}CuPc$/DH-α6T TFT operating in the hole-enhancement 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 $|V_D|-|V_G|>10$V, 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 $F_{16}CuPc$ layer are observed. For $|V_G|<30$ V and $|V_D|-|V_G|>30$V, 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 x 10^{-3} cm^2/Vs and 8.18 x 10^{-3} cm^2/Vs for the ambipolar TFT, respectively, were derived in the saturation region.

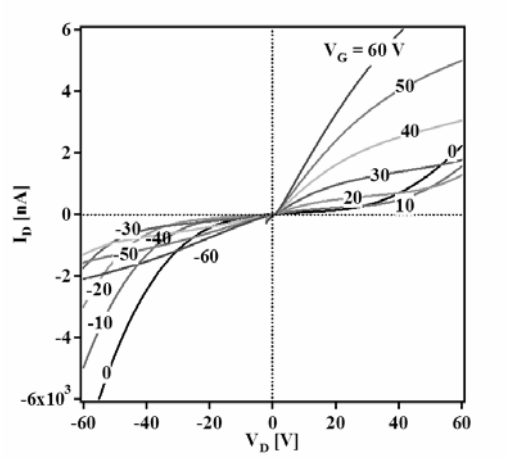

Figure 2 Drain current-voltage (I_D - V_D) characteristics of an F_{16}CuPc/DH-α6T TFT working in hole-enhancement and electron-enhancement modes.

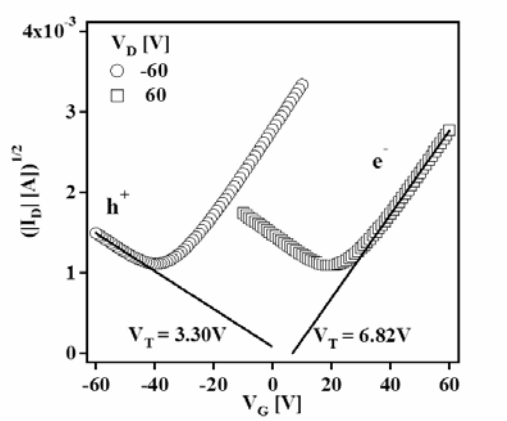

Figure 3 $I_D^{\ 1/2}$ vs V_G at fixed $|V_D|$ of 60 V for the heterostructure TFT.

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

Mobility (cm^2/Vs)	Single layer device (p type)	Ambipolar device	
		p	n
α6T	8.0E-3	1.50E-3	2.00E-3
DE-α6T	0.2	3.00E-5	-
DH-α6T	0.04	1.77E-3	8.18E-3

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 I.

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 μ_p / μ_n. 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 μ_p / μ_n. 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

[1] B. Crone, A. Dodabalapur, Y.-Y. Lin, R. W. Filas, Z. Bao, A. LaDuca, R. Sarpreshkar, H. E. Katz and W. Li: Nature **403** (2000) 521.

[2] A. Bael, J. D. Wind and A. Jenekhe: Adv. Funct. Mater. **14** (2004)891.

[3] Y. Kunugi, K. Takimiya, N. Negishi, T. Otsuo and Y. Aso: J. Mater. Chem. **14** (2004)2840.

[4] E. J. Meijer, D. M. Deleeuw, S. Setayesh, E. Vanveenendaal, B. –H. Huisman, P. W. M. Blom, J. C. Hummelen, U. Scherf and T. M. Klapwijk: Nature Mater. **2** (2004)678.

[5] A. Dodabalapur, H. E. Katz, L. Torsi and R. C. Haddon: Science **269** (1995) 1560.

[6] A. Dodabalapur, H. E. Katz, L. Torsi and R. C. Haddon: Appl. Phys. Lett. **68** (1996)1108.

[7] C. Rost, D. J. Gundlach, S. Karg and W. Rieβ: J. Appl. Phys. **95** (2004)5782.

[8] R. Ye, M. Baba, K. Suzuki, Y. Oishi and K. Mori, Appl. Phys. Lett., **86**, 253505 (2005).

[9] R. Ye, M. Baba and K. Mori, Jpn. J. Appl. Phys, **44**, L581-583 (2005).

[10] R. Ye, M. Baba, K. Suzuki, Y. Oishi and K. Mori, Appl.Surf. Sci., (in press)