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Crystal structures and transistor properties of phenyl-substituted tetrathiafulvalene derivatives

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Received 12 March 2007, in final form 7 August 2007
Published 13 September 2007
Online at stacks.iop.org/Nano/18/424009

Abstract
The crystal structures, thin-film properties, and field-effect transistor (FET) characteristics of tetrathiafulvalene (TTF) derivatives with two phenyl groups are systematically investigated. The highest mobility, 0.11 cm² V⁻¹ s⁻¹, is observed in biphenyl-substituted TTF (1). The correlation between the crystal structures and the FET properties demonstrates that good transistor properties are associated with two-dimensional intermolecular interaction, which is achieved when the molecules are standing nearly perpendicular to the substrate. Since these TTF derivatives are strong electron donors, the use of a metallic charge-transfer salt (TTF)(TCNQ) as the source and drain electrodes has resulted in a considerable reduction of the off current (TCNQ: tetracyanoquinodimethane).

1. Introduction
Organic field-effect transistors (OFETs) are of great current interest from the viewpoint of low-cost easy processing over large areas and on flexible substrates [1]. Over the past two decades, significant progress has been made in improving the performance of OFETs, using such materials as oligoacenes [2], oligothiophenes [3], polythiophenes [4], and metallophthalocyanines [5]. Tetrathiafulvalene (TTF) derivatives have been well known as organic donor molecules constructing organic metals [6], but have recently been noticed as components of OFETs [7]. Mas-Torrent et al have reported high mobilities of 1.4 cm² V⁻¹ s⁻¹ and 1.0 cm² V⁻¹ s⁻¹, respectively, using thiophene-fused TTF (DT-TTF) and dibenzof-TTF (DB-TTF) in single-crystal OFETs processed from solutions, as well as 0.11 cm² V⁻¹ s⁻¹ in tetra(octadecylthio)-TTF films prepared from solution by zone casting [8]. Naraso et al have also achieved a mobility of 0.42 cm² V⁻¹ s⁻¹ in an evaporated-film FET using naphthalene-fused TTF [9]. All these materials have the herringbone structure, and this seems to be a very good structure for realizing high-performance OFETs. However, relatively little effort has been made to explore the correlation between the transistor performance and the crystal structure.

Since phenyl-substituted oligothiophenes have made good OFETs and the analogs have been extensively studied [3b, 10], we have investigated phenyl-substituted TTF molecules (scheme 1). In particular we have found a comparatively high mobility, 0.11 cm² V⁻¹ s⁻¹, in a biphenyl-substituted TTF, 1 [11]. The other TTF derivatives have not exhibited higher performance, but we have systematically investigated the crystal structures, and found many variations of the herringbone structure. Here we report the preparation and crystal structures of TTF derivatives with phenyl groups (scheme 1), together with the thin-film properties and the transistor performance of the evaporated thin-film OFETs. We analyze the intermolecular interactions of these compounds, including those of well-known DB-TTF (2), on the basis of the calculation of intermolecular overlap integrals, and discuss the requirements for high-performance FET materials.

TTF analogs are also used as source and drain electrodes in the form of the charge-transfer complex. Takahashi et al have achieved the control of work functions of source and drain electrodes by using organic metals like (TTF)(TCNQ),...
and realized stable n-type and ambipolar transistors [12]. Although they have reported this method only for single-crystal transistors, we have adopted this method for thin-film transistors. A considerable reduction of the off current is observed when the active layers are TTF derivatives.

2. Results and discussion

2.1. Syntheses and electrochemistry of phenyl-substituted TTF derivatives

Compounds 1–3, and 6–9 have been described in previous papers [13]. Compounds 4, 5, 10, and 11 are newly synthesized according to scheme 2 [14]. The oxidation potentials of TTF derivatives were measured by cyclic voltammetry. The oxidation potentials of 3–7 with two phenyl groups are larger than those of the unsubstituted TTF (table 1), indicating that the phenyl group works as a weakly electron-withdrawing group. This is more obvious in the 9- and 10-substitutions for all compounds reported herein. Though the synthetic route in scheme 2 may afford a mixture of cis and trans isomers with respect to the two phenyl groups, the crystal structure analyses have revealed only trans-substitutions for all compounds reported in the present paper. The reason is not clear, but possible reasons are: (1) only the thermodynamically stable trans-form is generated in the synthesis, (2) cis–trans isomers transform easily in the process of purification (sublimation), or (3) only the trans-form is obtained during the purification (sublimation).

2.2. Thin-film transistors

The FET devices were fabricated with bottom-contact geometry. Source and drain electrodes were prepared by vacuum deposition of gold/chromium or (TTF)(TCNQ) complex [12, 16] on thermally grown SiO₂ substrates with film thicknesses of 50–100 nm. Subsequently, 50–100 nm organic thin-films of TTF derivatives were thermally evaporated. The devices made from 1–5 and 7 show p-type FET characteristics, but the devices made from other compounds show no FET characteristics. The estimated field-effect mobility and the on/off ratio are summarized in table 2.

For 1, a high mobility of 0.11 cm² V⁻¹ s⁻¹ is observed. Transistors made from 2 (DB-TTF) show a mobility of 0.01 cm² V⁻¹ s⁻¹ without a self-assembled monolayer (SAM), which is of the same order as the reported value 0.06 cm² V⁻¹ s⁻¹ [9]. Recently an improved value,
previously [19], we discuss the estimation of the overlap orbital calculation (figure 2) [20]. The molecular arrangements integrals of the HOMO calculated on the basis of the molecular angle of 155° electrodes are compared in figure 1. The large off current of the Au transistor is improved in the (TTF)(TCNQ) transistor. From the structural point of view. further drops by two orders. This difference will be discussed by the same method, and the resulting bandwidth is 0.1–0.2 eV [21]. This is, however, comparable to 0.2 eV of pentacene and 0.43 eV of sexithiophene [22]. This structure, however, constructs a two-dimensional network in the bc plane, and achieves relatively high mobility [8c]. Two-dimensional conduction is required probably because the thin film is composed of multidomains.

3 and 4: Single crystals of 3 and 4 were grown by the sublimation method. The crystallographic data are listed in table 3. For alkyl chains n = 1 and 2, the crystal structures are essentially isostructural. Although the lattice constants of these compounds closely resemble those of the previously reported n = 4 compound (6) [15c], this is a different structure. Compounds 3 and 4 belong to space group P21, and we could not analyze these crystal structures assuming the space group P21/c like 6.

Compounds 3 and 4 have one crystallographically independent molecule in a unit cell. The crystal structure of 3 is depicted in figure 3. The phenyl groups are tilted from the TTF plane by 14° and 15° for 3, and 12° and 7° for 4. The molecular long axis is nearly parallel to the a-axis. The molecules make a zig-zag chain along the b-axis (figure 3(a)), in which the molecules are alternately tilted in different orientations with dihedral angles of 159° for 3 and 147° for 4. Since these molecules are related to each other by a two-fold screw axis, the intermolecular interaction p is uniform. Intermolecular short S–S contacts of 3.79 Å (3) and 3.87 Å (4) are observed for this interaction. As shown in figure 3, each unit cell contains one chain, but the neighboring chains located at the a and a + c positions are slipped by about a half molecular unit along the molecular long axis, so there is no contact between the TTF parts. Consequently each chain is highly isolated. This is schematically depicted in figure 4. In contrast to the ideal two-dimensional network of 2 (figure 4(a)), 3 and 4 have only one-dimensional interactions (figure 4(b)). The largely slipped arrangement is probably related to the bent structure of the present molecules, in which the directions of the phenyl rings are tilted from the central axis of the TTF part. The calculated overlap integral for p. 2.2 × 10⁻³, is as large as the interactions in 2, but other interchain interactions a and q are by more than one order smaller than the interaction p due to the long interchain distances (figure 3). Since the HOMOs of these molecules are located only on the TTF part, the half-unit displacement largely diminishes the interaction, and the calculated interchain interactions are less than one tenth of the major interaction. The one tenth interaction is not fatally small, if we recall that the interchain interactions of the well-known organic superconductor (TMTSF)₂X (tetramethyltetraselenafulvalene) are about one tenth of the intrachain interaction [23].

This is, however, expected to reduce the transistor performance in comparison with the two-dimensional structure.

6: The crystal structure of 6 has been reported previously [15c], but we briefly describe the molecular packing in comparison with 3 and 4 (figure 5). Although figure 5(b) look like a herringbone structure with the intermolecular dihedral angle of 132°, the center molecule in figure 5(b) is slipped by a half molecular unit along the molecular long axis with respect to the molecules at the lattice points (figure 4(c)). Consequently, the S–S contact is very long (6.04 Å) and the calculated intermolecular overlap p is small (0.18 × 10⁻³). In the previous two compounds, the contacts between the TTF parts remain in one direction, and the interchain
Figure 2. Crystal structure of 2, (a) viewed along the molecular long axis, and (b) viewed along the b-axis. The intermolecular overlap integrals are b: $-2.9$, p: $1.2$, q: $-0.83$, and r: $0.002 \times 10^{-3}$.

Table 3. Crystallographic data of phenyl-substituted TTF derivatives.

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$R = \Sigma||F_o|| - |F_c||/\Sigma |F_o||$, $R_w = [\Sigma w(||F_o|| - |F_c||)^2]/\Sigma w F_o^2]^{1/2}$; $w = 1/\sigma^2$.

Figure 3. Crystal structure of 3, (a) viewed along the molecular long axis, and (b) viewed along the c-axis. The intermolecular overlap integrals are p: $2.2$, a: $-0.16$, and q: $0.18 \times 10^{-3}$ for 3 and p: $6.3$, a: $0.05$, and q: $0.11 \times 10^{-3}$ for 4. In (b), phenyl groups are omitted for clarity.

interactions are lost by the long-axis slipping. In the present compound, however, the contacts between the TTF parts are two-dimensionally destroyed, and each TTF part is highly isolated.

The device made from 6 does not work, in agreement with the small intermolecular interactions in the crystal (figure 5). In general, for these 3–6 compounds, long alkyl chains decrease the transistor performance, probably because the long alkyl chains tend to increase the slip distance along the molecular long axis, and to destroy the intermolecular interactions.

7: Single crystals were grown by the sublimation method. The half units of two molecules A and B are crystallographically independent (figure 6). The molecule is located on an inversion center. The molecular planes of the A and B molecules are oriented in different directions, and the dihedral angle between the TTF skeletons is 155°. The molecules are almost planar, and the phenyl groups are tilted by 5° and 9° from the TTF plane, respectively, for A and B. These molecules are arranged alternately along the a-axis (figure 6(b)), but this is not a real stacking structure because the molecule B is almost parallel to the stacking direction (the a-axis), though the molecule A is nearly perpendicular to this direction. An intermolecular short S–S contact of 3.78 Å is observed between A and B. The adjacent chains
are located at the $b$ and $b + c$ positions, and are slipped by nearly a half molecular unit along the molecular long axis (figure 6(a)). Accordingly, there are no short S–S contacts between these chains, and this compound is regarded as a highly one-dimensional material composed of isolated chains. This zig-zag chain structure has a close resemblance to 3 and 4 (figure 4(b)), although the crystal symmetries are different. Only the uniformly arranged intermolecular overlap $p$ has a meaningful value of $-2.1 \times 10^{-3}$, and no interchain interactions are observed. Together with the existence of two unequivalent molecules, this is the reason for the poorer transistor properties of this compound.

8: Single crystals of the tetraphenyl compound 8 were grown by slow evaporation of the toluene solution. There is one crystallographically independent molecule in a unit cell (figure 7). The four phenyl groups are largely tilted from the TTF plane by $79^\circ$, $21^\circ$, $45^\circ$, and $47^\circ$. The TTF molecule is largely bent at the sulfur atoms, and forms a strongly dimerized structure (figure 7(a)). The intradimer overlap is the so-called ring-over-bond type. The intradimer ($p_1$) and interdimer ($p_2$) interplanar distances are 3.76 Å and 7.11 Å, respectively. The dimerization is also significant, as demonstrated from the calculation of the intermolecular overlap integrals (figure 7). The absence of the FET characteristics is obviously related to the strong dimerization.

10: Single crystals were grown by slow evaporation of the toluene solution. The molecule is located on an inversion center, and a half molecular unit is crystallographically independent like 6. The phenyl group is tilted by $30^\circ$ from the TTF plane. Owing to the thermal rotation of the CF$_3$ unit, the temperature factors of the F atoms are relatively large. The molecules form a layer structure perpendicular to the $a$-axis (figure 8(a)). The dihedral angle between the TTF planes of adjacent molecules is $143^\circ$. The molecular arrangement resembles the herringbone structure, but each molecule is slipped by about one quarter unit along the molecular long axis. Since the long-axis slipping is not large, there is a short intermolecular S–S contact of (3.58 Å) for the interaction $p$. 

---

**Figure 4.** Modifications of herringbone structures. The light gray molecules are slipped by a half molecular unit with respect to the dark molecules perpendicular to the sheet. (a) Usual herringbone structure, 2 and 10, (b) 3, 4, and (c) 6.

**Figure 5.** Crystal structure of 6, (a) viewed along the $b$-axis and (b) viewed along the molecular long axis. In (a) and (b), the butyl groups are omitted for clarity.

**Figure 6.** Crystal structure of 7, (a) viewed along the $a$-axis and (b) viewed along the molecular long axis.
and the calculated overlap is reasonably large (\(-4.0 \times 10^{-3}\)). This interaction constructs a uniform two-dimensional network in the \(bc\) plane (figure 8(b)).

### 2.4. Thin-film morphology

Thin films of these TTF derivatives, vacuum deposited on thermally grown \(\text{SiO}_2\) substrates, were investigated by atomic force microscopy (AFM) and x-ray diffraction (XRD). The AFM images are shown in figure 9. The thin film of 1 shows many small grains owing to rigid and large biphenyl substituents (figure 9(a)), while 2 shows larger grains (figure 9(b)). In general, relatively small molecules like 2, 7, and 8 show large and tight grains, reflecting the good crystallinity, whereas the extension of the alkyl chain from 3 to 5 as well as the introduction of large substituents like 1 tends to reduce the grain size. The thin film of 3 (figure 9(c)) has larger round grains than 4 (figure 9(d)), probably due to the two ethyl groups standing almost perpendicular to the TTF plane. The fluorine compounds 10 and 11 show rough surfaces (figures 9(j) and (k)).

The XRD profiles are shown in figure 10. The tilt angles between the molecular long axis and the layer stacking direction are estimated by using the \(d\)-spacings of these XRD profiles and the lengths of the molecular long axis extracted from the geometry-optimized MOPAC calculations (table 4). For 1 and 2, sharp and clear peaks corresponding to the \(d\)-spacings 24.9 and 13.4 Å are observed (figures 10(a) and (b)). Since the \(d\)-spacings are nearly the same as the calculated molecular lengths, the tilt angles are very small (\(0^\circ - 10^\circ\)). The \(d\)-spacing of the latter compound is larger than the interlayer lattice constant (\(a = 12.082\) Å) [19]. Since the molecules are considerably tilted in the crystal with respective to the crystallographic \(c\)-axis, the layer normal of the thin film does not correspond to the crystallographic \(c\)-axis. This means that, in DB-TTF 2, the structure of the thin film is different from the structure of the crystal. The same happens in 3; owing to the large round grains, the thin film has sharp and clear peaks corresponding to the \(d\)-spacing of 18.3 Å (figure 10(c)). This is larger than the crystal lattice \(a = 11.887\) Å (table 1). The tilt angle is estimated to be \(5^\circ\), and this indicates that the molecule 3 stands almost perpendicular to the substrate. For 4 and 5, reflecting the small grains and the roughness, the thin films have only one peak corresponding to the \(d\)-spacings of 19.5 Å and 21.8 Å, respectively (figures 10(d) and (e)).

The tilt angles are \(22^\circ\) and \(18^\circ\), and the molecules are considerably tilted in the molecular layer. Compound 6 gives two \(d\)-spacings: 19.7 and 24.0 Å (figure 10(f)), which may be accounted for from the existence of two crystal orientations in the film. The tilt angle is \(22^\circ\) for 24.0 Å. Although the crystal structure of 5 has not been analyzed, the observed single \(d\)-spacing indicates that the crystal packing is similar to 4 rather than 6. For 7, no clear peaks are observed. For 8, sharp and clear peaks corresponding to the \(d\)-spacing 13.4 Å are obtained (figure 10(g)), and the tilt angle is \(22^\circ\). For 9, the observed weak peaks give 9.2 Å (figure 10(h)). Since this is much shorter than the molecular length, the molecular long axes are not perpendicular to the substrate. For 10, the profile exhibits sharp peaks corresponding to a \(d\)-spacing of 9.3 Å (figure 10(i)). This is the same as the crystallographic \(b\)-axis (table 3). If the \(b\)-axis is perpendicular to the substrate, the molecular plane is nearly parallel to the substrate (figure 7(b)), and the most conductive direction is perpendicular to the substrate. For 11, the profile shows two \(d\)-spacings, 13.4 and 20.4 Å, indicating the existence of two crystal orientations in the film similarly to the thin film of 6 (figure 10(j)). The estimations of the tilt angles from these values are much longer and shorter than molecular length, indicating that molecular long axes are again parallel to the substrate.

The high mobility of 1 is associated with the small tilt angle; judging from the crystal structures of other compounds, this means a small molecular displacement, and suggests a simple layered structure, although we cannot analyze the crystal structure of this compound. Similarly, the relatively high mobility of 2 is attributed to the small tilt angle. The absence of the device performance of 9 is associated with the disordered morphology suggested from the weak peaks of the XRD profile. Although the crystal structure of 10 is close

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Figure 8. Crystal structure of 10, (a) viewed along the $b$-axis, (b) viewed along the molecular short axis. The intermolecular overlaps are $c: 0.08$ and $p: -4.0 \times 10^{-3}$. In (b), the phenyl groups are omitted for clarity.

Figure 9. AFM images of thin films of (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 7, (h) 8, (i) 9, (j) 10, and (k) 11, deposited on SiO$_2$ substrates. (This figure is in colour only in the electronic version)

to the usual herringbone structure, the absence of transistor characteristics is interpreted from the $d$-spacing, which is almost the same as the crystallographic $b$-axis, indicating the flat molecular orientation parallel to the substrate. Compound
11 gives two d-spacings similarly to 5, destroying the transistor function on account of the boundaries between the two different crystal orientations.

3. Conclusion

In this paper, we have investigated various modifications of the herringbone structure. Although the molecular long-axis projections look like the same, the modifications are characterized by the displacement perpendicular to the layer (figure 4). If the intermolecular interaction is restricted in one dimension by this displacement, the mobility is reduced by two orders. In the case of 6, the intermolecular interactions are destroyed in all directions, resulting in no transistor functions. The existence of unequivalent molecules also reduces the performance by two orders as in 7. Large displacements also lead to large tilt angles, estimated from XRD, and this tends to result in poor performance. Two independent d-spacings of the XRD peaks suggest the existence of two orientations, and are associated with poor performance. These observations demonstrate that two-dimensional intermolecular interaction is very important in achieving high-performance OFET. Single-crystal structure analysis is powerful for discussing the detailed correlation between the molecular arrangement and the transistor performance, but observation of a simple d-spacing corresponding to the molecular length in the thin-film XRD is a good indicator to the simple layer structure. Since these molecules are strong electron donors, the usual Au electrodes result in normally on states, while small work function metals such as (TTF)(TCNQ) lead to better performance.

Figure 10. XRD profiles of thin films of (a) 1, (b) 2, (c) 3, (d) 4, (e) 5, (f) 6, (g) 8, (h) 9, (i) 10, and (j) 11, deposited on SiO2 substrates.
4. Experimental details

4.1. Preparation

13a: To a solution of 2.7 g 4-ethylacetophenone 12a (20 mmol) in 10 ml acetic acid, 3.2 g bromine (20 mmol) was added dropwise over 90 min. After addition of diethyl ether, the red solution was washed by an aqueous sodium chloride solution, and the ether layer was evaporated to give a yellow oil 13a (2.7 g, 12 mmol, 59%). This compound was used without further purification. Compounds 13b-d were prepared similarly in yields of 13b: 73%, 13c: 87%, and 13d: 44%.

14a: To a suspended solution of o-isopropyl xanthic acid potassium salt (2.1 g, 12 mmol) in 80 ml acetone, 13a (2.7 g, 12 mmol) was added and stirred for 10 min. After filtration, the filtrate was evaporated. A white powder 14a was obtained quantitatively (3.5 g, 12 mmol). Compounds 14b-d were prepared similarly in yields of 14b: 100%, 14c: 91%, and 14d: 97%.

15a: To 15 ml sulfuric acid at 0°C, a solution of 14a (3.5 g, 12 mmol) in 30 ml diethyl ether was added dropwise over 1 h and stirred for 1 h. The yellow solution was poured into 50 g ice, and the ether layer was collected, and washed by an aqueous sodium chloride solution. After evaporation, a white powder 15a was obtained (2.2 g, 9.9 mmol, 79%). Compounds 15b-d were prepared similarly in yields of 15b: 67%, 15c: 100%, and 15d: 85%.

Bis(p-ethylphenyl)tetrathiafulvalene (4). To 15a (2.2 g, 9.9 mmol) under nitrogen atmosphere 10 ml triethylphosphite was added and stirred at 120°C for 4 h. After cooling, the phosphite was removed in vacuo, and recrystallization from toluene resulted in a red powder 3 (240 mg, 0.59 mmol, 12%). Mass m/z 412; 1H-NMR (CDCl3) δ = 1.239 (6H), δ = 2.656 (4H), δ = 7.189 (4H), δ = 7.290 (4H). Analysis calculated for C22H20S4: C, 64.03; H, 4.89; S, 31.08. Found: C, 63.20; H, 4.99; S, 31.08%.

Compounds 5, 10 and 11 were prepared similarly.

Bis(p-propylphenyl)tetrathiafulvalene (5). 15% yield. Mass m/z 440; 1H-NMR (CDCl3) δ = 0.941 (6H), δ = 1.638 (4H), δ = 2.588 (4H), δ = 7.165 (4H), δ = 7.327 (4H). Analysis calculated for C24H24S4: C, 64.03; H, 4.89; S, 31.08. Found: C, 63.20; H, 4.99; S, 30.76%.

Bis(p-trifluoromethylphenyl)tetrathiafulvalene (10). 25% yield. Mass m/z 492; 1H-NMR (CDCl3) δ = 7.515 (4H), δ = 7.622 (4H). Analysis calculated for C24H18F12S4: C, 48.77; H, 2.05; F, 23.14; S, 26.04. Found: C, 48.47; H, 2.03; F, 23.06; S, 26.33%.

Bis(perfluorophenyl)tetrathiafulvalene (11). 14% yield. Mass m/z 536; 1H-NMR (CDCl3) δ = 7.616 (2H). Analysis calculated for C24H10F12S4: C, 40.30; H, 0.38; F, 35.41; S, 23.91. Found: C, 41.42; H, 1.26; F, 29.33; S, 27.23%.

4.2. X-ray structure analysis and device fabrication

The single-crystal x-ray data of TTF derivatives were collected on a Rigaku AFC-7T diffractometer with a rotating anode generator and graphite-monochromated Mo Kα radiation at room temperature, and using the 2θ-ω scan technique to a maximum 2θ of 60°. The structure was solved by the direct method (SIR 92) and refined by full-matrix least-squares analysis. The crystallographic data are listed in Table 2. The CIF files are available from the Cambridge Crystallographic Data Centre, CCDC 634363-634640. The calculations of molecular orbitals were carried out using the extended Hückel method with the same parameters as [21], and the intermolecular overlap integrals of the HOMO were calculated.

The FET devices were fabricated with bottom-contact geometry. Commercially available Si/SiO2 substrates with 300 nm SiO2 were used. The substrates were cut into slices (1 cm x 1 cm), successively washed in acetone, 2-propanol, and pure water respectively for 10 min, dried at 120°C for 10 min, and finally treated with a ozone cleaner for 10 min. For source and drain electrodes, gold/chromium with the thickness of 50–100 nm was vacuum deposited through a shadow mask under high vacuum (<10^-5 Torr). The gold electrodes for 7 were photolithographically patterned. (TTF)(TCNQ) was also used as source and drain electrodes [10]; a powder of the complex was evaporated from a crucible. Values of the channel length/width were 50/300 or 100/2000 μm. Subsequently, TTF derivatives were evaporated to a thickness of 50–100 nm under high-vacuum conditions (<10^-6 Torr). The FET characteristics were measured with a Keithley 4200 semiconductor parameter analyzer. The measurements in air were carried out by using an OYAMA manual prober system model TB-2-H-200, and the in situ measurements were made by connecting copper wires to the device with using silver paste. The field-effect mobility μ was estimated from the linear regime of the transconductance,

\[ g_m = \frac{\partial I_D}{\partial V_G} \bigg|_{V_D=\text{const}} = \frac{W C_m \mu V_D}{L} \]

by plotting the drain current I_D versus source-gate voltage V_G at a constant source-drain voltage V_D [24]. In this equation, \( g_m \), W, C, and L respectively represent the slope of the linear regime of the transconductance, the channel width, the capacitance of the gate dielectric, and the channel length.

AFM images of the evaporated thin films were taken with a SII scanning probe microscope system SPI3800N and SPA 300 by using a Si3N4 cantilever. X-ray diffraction profiles of the thin films were obtained with a Phillips X’Pert-MPD-OEC PW3050 with monochromated Cu Kα radiation (λ = 1.541 Å) at room temperature using the θ–2θ technique for 2θ < 20 < 30°.

Acknowledgments

This work was partly supported by a Grant-in-Aid for Scientific Research (B) (No. 18350095), and on Priority Areas of Molecular Conductors (No. 15073211) from MEXT.

References
