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Molecular aggregation-performance relationship in the design of novel cyclohexylethynyl end-capped quaterthiophenes for solution-processed organic transistors

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ABSTRACT

The synthesis and characterization of cyclohexylethenyl end-capped guaterthiophenes is reported. Additionally, an investigation of the performance of organic field-effect transistors based on these quaterthiophenes in view of the relationship between the solid-state (or aggregate) order and the electronic performance is described. UV-vis absorption measurements revealed that the quaterthiophene with an asymmetrically substituted cyclohexylethynyl end-group induced the formation of H-type aggregates, whereas the quaterthiophene with a symmetrically substituted cyclohexylethynyl end-groups favored the formation of J-type aggregates. Two-dimensional grazing-incidence wide-angle X-ray scattering studies were performed to support the molecular structure-dependent packing of films of the new quaterthiophenes. Solution-processed quaterthiophenes were tested as the active layers of p-type organic field-effect transistors with a bottom gate/top contact geometry. The field-effect mobility of devices that incorporated asymmetric quaterthiophene molecules was quite high, exceeding 0.02 cm²/V s, due to H-aggregation and good in-plane ordering. In contrast, the field-effect mobility of devices that incorporated symmetrical quaterthiophenes, was low, above 5×10^{-4} cm²/(V s), due to the formation of J-aggregates and poor in-plane ordering. A comparison of the symmetrical and asymmetrical quaterthiophene derivatives revealed that the molecular aggregation-dependent packing, determined by the cyclohexylethynyl end groups, was responsible for influencing the organic field-effect transistor performance.

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1. Introduction

Organic semiconductors based on oligomers and polymers have recently received considerable attention for use as active channel materials in organic field-effect transistors (OFETs). Organic semiconductors are compatible with plastic substrates and can potentially be solution-processed using inexpensive fabrication techniques, which would facilitate the commercialization of high-

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performance devices [1,2]. Organic semiconductors can potentially replace inorganic counterparts in the fabrication of organic integrated circuits, sensors, low-cost memories, smart cards, and driving circuits for large-area applications, such as paper-like displays [3-10]. Among the various organic semiconductors developed thus far, thiophene-based oligomers provide an important platform because of their high chemical and electrochemical stability, ease of synthesis, tuneable electronic properties, and the availability of well-developed/regioselective ring-ring coupling methodologies [11,12]. In addition, solution-processable oligomeric semiconductors can be deposited using low-cost solution processing methods, such as spin-coating, inkjet printing, or gravure printing [13–15]. Oligomer solubility and stability toward oxidation can be increased by functionalizing the α - and ω -ends of the conjugated thiophene ring systems [2]. Straight alkyl chain functionalization at

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the α - and ω -ends of the conjugated thiophene oligomers allows the thiophene rings to orient themselves vertically on a substrate, thereby inducing good molecular ordering [16].

In many classes of these oligomers, the molecular ordering and crystallinity can significantly influence the performance of devices, such as OFETs [2], because the hopping of charge carriers between individual organic molecules depends strongly on the molecular ordering and crystallinity [16–18]. Therefore, many research groups have endeavored to control the molecular ordering and crystallinity of structures in organic semiconductor thin films [17]. As a crystalline film forms, organic materials aggregate with various aggregation patterns by combination of H- and J-types. The aggregation types are distinguished by the sign of the resonant electronic (excitonic) coupling [19,20]. H-aggregation yields a positive sign for the resonant electronic (excitonic) coupling, which occurs in a pair of molecules in a parallel orientation [21]. The UV absorption peak for an H-aggregated film is blue-shifted compared to the absorption peak in solution because of cancellation of the transition dipole moments of the lower-lying state [19]. J-aggregation occurs when molecules assume a head-to-tail arrangement. In J-aggregation, couplings are negative, and the UV absorption peak of the film is redshifted compared to the absorption peak in solution [19,22]. Previous studies reported that many organic semiconductors show J-aggregation [22,23]; however, H-aggregation may have several advantages over J-aggregated molecules for high-performance OFETs in view of the area of π -overlap among adjacent semiconductor molecules. H-aggregation includes a parallel adjacent molecular arrangement that yields a large area of π -overlap between adjacent molecules. In contrast, I-aggregation exhibits a head-to-tail arrangement [21] and does not build up a large area of π -overlap between adjacent molecules. H-type aggregation can improve the performance of organic semiconductors in OFETs.

The present study describes a novel synthetic strategy designed to uncover the relationship between molecular aggregation in a film state and OFET performance. To this end, two new compounds were synthesized as shown in Scheme 1: cyclohexylethynylquaterthiophene (CHE4T) and bis-cyclohexylethynylquaterthiophene (BCHE4T). The triple bond in the cyclohexylacetylene provided a special π -conjugated site [24], extended the π -system in the molecule, and improved the molecular rigidity [25]. UV–vis absorption and grazing-incidence wide-angle X-ray scattering (GIWAXS) analysis revealed that CHE4T tended to undergo H-aggregation whereas BCHE4T tended to undergo J-aggregation. To test the utility of the quaterthiophene derivatives as organic semiconductors, FETs of these derivatives were fabricated using a solution process. The field-effect mobility in the H-aggregated material was much higher than in the J-aggregated material. An understanding of the mechanism by which molecular aggregation affected the performance of a transistor is discussed, and the aggregation type-dependent charge carrier mobility is described in detail.

2. Experimental section

2.1. Measurements

The ¹H NMR and ¹³C NMR spectra were recorded using a Bruker AM-200 spectrometer. The FT-IR spectra were measured on a Bomem Michelson series FT-IR spectrometer. The melting points were determined using an Electrothermal Mode 1307 digital analyzer. The thermal analysis was performed using a TA TGA 2100 thermogravimetric analyzer under a nitrogen atmosphere with a heating rate of 20 °C/min. Differential scanning calorimetry (DSC) measurements were conducted under nitrogen using a TA instrument 2100 DSC. The sample was heated with a rate of 20 °C/min from 30 °C to 250 °C. UV–vis absorption spectra were measured using a Perkin Elmer LAMBDA-900 UV/VIS/IR spectrophotometer.

2.2. Materials and synthesis

2-Bromothiophene, *N*-bromosuccinimide(NBS), *n*-butyllithium, 2-isopropoxy-3,3,4,4-tetramethyl-1,3,2-dioxaborolane, 1,3-bis(diphenylphosphinopropane)dichloronickel, *N*,*N*-dimethylformamide (DMF), copper(I), sodium carbonate, 2,2'-bipyridine, 1,5-cyclooctadiene, bis(cyclooctadiene)nickel(0), dichloro-((bis-diphenylphosphino)ferrocenyl)palladium(II), cyclohexylacetylene, and tetrakis(-triphenylphosphine)palladium(0) were purchased from Aldrich.



Scheme 1. Synthetic scheme for preparing the quaterthiophene's cyclohexylacetylene end-capping groups.

The synthesis of the cyclohexylacetylene-end capped oligomers was carried out through a series of cross-coupling reactions that involved Suzuki couplings. The procedure involved treatment of the respective cyclohexylacetylene and 5,5'-dibromo-2,2'-bithiophene starting materials with Pd(dppf)Cl₂ and Cul at 55 °C under Sonogashira reaction conditions. All oligomers were purified by sublimation under high vacuum.

2.2.1. 2,2'-Bithiophene (1)

2,2'-Bithiophene (1) was synthesized according to the procedure reported in the literature. (1) Yield: 48 g (94%). mp: 32 °C (lit mp 32–33 °C), ¹H NMR (300 MHz, CDCl₃, ppm): δ 7.21 (d, 4H, *J* = 3.9 Hz), 7.07 (t, 2H, *J* = 4 Hz) [26].

2.2.2. 5,5'-Dibromo-2,2'-bithiophene (2)

5,5'-Dibromo-2,2'-bithiophene (2) was synthesized according to the procedure reported in the literature. (2) Yield: 4.20 g (84%). mp: 144 °C (lit mp 144–146 °C), ¹H NMR (300 MHz, CDCl₃, ppm): δ 6.84 (d, 2H, *J* = 3 Hz), 6.95 (d, 2H, *J* = 3 Hz) [27].

2.2.3. 2-(2,2'-Bithiophen-5-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3)

Compound 1 (7 g, 42.1 mmol) in THF (150 mL) was added dropwise (18.52 mL, 46.31 mmol) to n-butyllithium (2.5 M solution in hexane) at -78 °C. After the mixture had been stirred at -78 °C for 1 h, 2-isopropoxy-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (8.61 g, 46.31 mmol) was added. The resulting mixture was stirred at -78 °C for 1 h then warmed to room temperature and further stirred overnight. The mixture was poured into water, extracted with diethyl ether, and dried over MgSO₄. The solvent was removed by column chromatography using hexane as the eluent. Yield: 3 g (24%). IR (KBr, cm⁻¹); 3071 (aromtic C–H), 2973 (aliphatic C–H), ¹H NMR (300 MHz, CDCl₃, ppm): δ 1.37 (s, 12H), 7.03 (t, 1H), 7.26 (m, 3H) [28].

2.2.4. 5-Bromo-5'-(cyclohexylethynyl)-2,2'-bithiophene (4)

Diisopropylamine (150 mL), Cul (0.31 g, 1.63 mmol), Pd(dppf)Cl₂ (0.44 g, 0.54 mmol) and 5,5'-dibromo-2,2'-bithiophene (8.82 g, 27.2 mmol) were placed in flask and degassed with nitrogen at 0 °C for 20 min. After cyclohexylacetylene (3 g, 27.7 mmol) was added, the mixture was heated at 55 °C for 16 h. The mixture was poured into water, extracted with diethyl ether, and dried over MgSO₄. The solvent was removed by rotary evaporation. The crude product was purified by column chromatography using n-hexane as the eluent. Yield: 4.5 g (34%). mp: 64 °C, IR (KBr, cm⁻¹); 3083 (aromtic C–H), 2970 (aliphatic C–H), 2217 (C=C) ¹H NMR (300 MHz, CDCl₃, ppm): δ 7.00 (s, 1H), 6.97 (s, 1H), 6.94 (s, 1H), 6.89 (s, 1H), 2.63 (q, 1H), 1.82 (m, 5H), 1.46 (m, 5H). ¹³C NMR (75 MHz, CDCl₃): δ 138.4, 136.2, 131.6, 130.6, 123.8, 123.6, 123.5, 111.2, 100.0, 73.4, 32.4, 30.0, 25.8, 24.9. MS (*m*/*z*): [M⁺] = 349.9.

2.2.5. Cyclohexylethynylquaterthiophene (CHE4T)

Toluene (40 mL), tetrahydrofuran (THF) (10 mL), compound 3 (2 g, 5.6 mmol) and compound 4 (2.1 g, 7.4 mmol) were added to a 2 M aqueous solution (10 mL) of sodium carbonate. After the mixture was bubbled with nitrogen for 30 min, Pd(PPh₃)₄ (0.19 g, 0.17 mmol) was added. The mixture was heated under reflux for 24 h under a nitrogen atmosphere. The reaction mixture was cooled to room temperature and poured into a solution containing aqueous 2 N-HCl (200 mL). The mixture was poured into water, extracted with diethyl ether, and dried over MgSO₄. The solvent was removed by rotary evaporation and purified by column chromatography using n-hexane as the eluent. Yield: 1.18 g (47.5%). mp: 164 °C, IR (KBr, cm⁻¹); 3078 (aromtic C–H), 2980 (aliphatic C–H), 2221 (C≡C). ¹H NMR (300 MHz, CDCl₃, ppm): δ 7.24 (t, 1H, *J* = 4 Hz), 7.19 (d, 1H,

J = 1 Hz), 7.05 (m, 7H), 2.63 (m, 1H), 1.90 (t, 2H, J = 6 Hz), 1.78 (q, 2H, J = 3 Hz), 1.53 (t, 4H, J = 6 Hz), 1.44 (m, 2H). ¹³C NMR (75 MHz, CDCl₃): δ 137.6, 137.0, 136.5, 136.2, 135.9, 135.6, 132.1, 127.9, 124.6, 124.4, 124.3, 123.8, 123.4, 120.4, 96.3, 79.9, 26.9, 25.8, 22.2, 21.4. HR-MS (FAB, C₂₄H₂₀S₄): calculated, 436.0448; found, 436.0424.

2.2.6. Bis-cyclohexylethynylquaterthiophene (BCHE4T)

A mixture of bis(1.5-cvclooctadiene) nickel(0) (Ni(COD)₂, (3.28 g, 11.95 mmol), 2,2'-bipyridine (1.86 g, 11.95 mmol), and 1,5cyclooctadiene (1.29 g, 11.95 mmol) in anhydrous DMF (15 mL) was stirred at 80 °C for 30 min. Compound 4 (1.4 g, 3.98 mmol) in toluene (80 mL) was added in one portion. The reaction mixture was stirred at 80 °C for 48 h. After cooling to room temperature, the mixture was poured into water, extracted with diethyl ether, and dried over MgSO₄. The solvent was removed by rotary evaporation and purified by column chromatography using n-hexane as the eluent. Yield: 0.6 g (55.5%). mp: 231 °C, IR (KBr, cm⁻¹); 3073 (aromtic C–H), 2982 (aliphatic C–H), 2215 (C≡C). ¹H NMR $(300 \text{ MHz}, \text{CDCl}_3, \text{ppm}): \delta 7.07 (t, 4\text{H}, J = 4 \text{ Hz}), 7.02 (q, 4\text{H}, J = 4 \text{ Hz}),$ 2.63 (p, 2H, J = 5 Hz), 1.90 (t, 4H, J = 5 Hz), 1.78 (q, 4H, J = 4 Hz), 1.53 (t, 8H, J = 9 Hz), 1.36 (s, 4H).¹³C NMR (75 MHz, CDCl₃): δ 136.9, 135.9, 131.7, 124.5, 124.3, 123.3, 99.9, 73.5, 32.4, 30.0, 25.8, 24.9. HR-MS (FAB, C₃₂H₃₀S₄): calculated, 542.1230; found, 542.1257.

2.3. Fabrication and characterization of the OFET devices

The electrical properties of CHE4T and BCHE4T films were characterized in a top-contact OFET configuration using a 300 nm thick SiO₂ dielectric on a highly doped n-Si substrate, which served as the gate electrode. Cleaned substrates were modified with hydrophobic octyltrichlorosilane (OTS) by dipping the substrates in an OTS toluene solution for 60 min at room temperature. Solutions of the organic semiconductors were spin-coated at 2000 rpm from a 0.5 wt% solution (CHE4T: chloroform, BCHE4T: chlorobenzene) to form thin films with a nominal thickness of 50 nm, confirmed using a surface profiler (Alpha Step 500, Tencor). Gold source and drain electrodes were evaporated on top of the semiconductor layers (100 nm). For all measurements, the channel lengths (L) were 100 μ m and the channel widths (*W*) were 1000 μ m. The electrical characteristics of the FETs were measured in air using Keithley 2400 and 236 source/measure units. Field-effect mobilities were extracted in the saturation regime from the slope of the sourcedrain current, wherein the slope of a plot of the square root of the drain current versus the gate voltage (V_G) was fit to the following equation: $I_{\rm DS} = (WC_i/2L)\mu(V_{\rm G} - V_{\rm th})^2$, where $I_{\rm DS}$ is the drain current, μ is the carrier mobility, and V_{th} is the threshold voltage. X-ray diffraction (XRD) studies were performed at the 4C2 beamline at the Pohang Accelerator Laboratory (PAL). The measurements were carried out with a sample-to-detector distance of 136 mm. Data were typically collected for ten seconds using an Xray radiation source of $\lambda = 0.138$ nm with a 2D charge-coupled detector (CCD) (Roper Scientific, Trenton, NJ, USA). The samples were mounted on a home-built *z*-axis goniometer equipped with a vacuum chamber. The incidence angle a_i for the X-ray beam was set to 0.14°, which was intermediate between the critical angles of the films and the substrate ($a_{c,f}$ and $a_{c,s}$).

3. Results and discussion

3.1. Thermal properties

The thermal stabilities of CHE4T and BCHE4T were investigated using TGA and DSC techniques (Fig. 1). Good thermal stability is important for device longevity [26]. The CHE4T and BCHE4T displayed excellent thermal stability, with decomposition



Fig. 1. Differential scanning calorimetry curves for (a) CHE4T and (b) BCHE4T; and TGA of (c) CHE4T and (d) BCHE4T.

temperatures of 365 °C and 406 °C, and melting temperatures of 164 °C and 231 °C, respectively.

3.2. UV-vis absorption spectroscopy

Generally, intermolecular interactions between adjacent molecules in the solid state can be characterized by UV–vis absorption spectroscopy. UV–visible spectroscopy is most widely used to study molecular energy levels or molecular aggregation effects. UV–vis absorption spectroscopy can be used to characterize the electronic structure profiles of a thin film [29]. The optical absorption properties for CHE4T and BCHE4T in chloroform and thin films are summarized in Table 1 and Fig. 2.

A comparison of the peaks of the UV–vis spectra of CHE4T and BCHE4T in a dilute solution revealed that the maximum peak of CHE4T was lower than that of BCHE4T. This result was observed because BCHE4T included longer conjugated segments that lowered the $\pi \rightarrow \pi^*$ transition energy gap [30]. CHE4T and BCHE4T are quasi-one-dimensional, so the ground-to-excited-state energy gaps of their π electrons scale inversely with the square of the conjugated length of the molecule [31].

The main absorption peaks of the CHE4T films were blue-shifted by greater than 180 nm relative to the peaks of a dilute solution, indicating that the CHE4T molecules formed H-aggregate structures [19,22]. In contrast, the main absorption peaks of the BCHE4T film were red-shifted by greater than 50 nm. In addition, the absorption peak of BCHE4T was broadened compared with that of the dilute solution. This observation could be explained by the formation of J-aggregated molecules [20].

Table 1

Optical properties of compounds CHE4T and BCHE4T.

	Λ_{abs}^{a} [nm]	$\Lambda_{\rm abs}$ film [nm]
CHE4T	407	225,273
BCHE4T	421	397,447,483

^a CHCl₃ solution.

H- or J-aggregation usually involves excitonic coupling or dipole—dipole interactions between adjacent molecules in a self-assembled film [32,33]. The potential energy of interaction between two dipoles is a complex function of their relative orientation [34]. The potential energy of interaction between two dipoles can be described as follows:

$$V = \frac{\boldsymbol{\mu_1} \cdot \boldsymbol{\mu_2}}{4\pi\varepsilon_0 r^3} - 3\frac{(\boldsymbol{\mu_1} \cdot \boldsymbol{r})(\boldsymbol{\mu_2} \cdot \boldsymbol{r})}{4\pi\varepsilon_0 r^5} = \frac{\mu_1 \mu_2 \left(1 - \cos^2\theta\right)}{4\pi\varepsilon_0 r^3},\tag{1}$$

because $\mu_1 \cdot r = \mu_1 r \cos \theta$ $\mu_2 \cdot r = \mu_2 r \cos \theta$, as shown in Fig. 3 [22]. Equation (1) indicates that a blue shift (H-aggregation) in the UV

absorption corresponds to an increase in energy of the excitonic



Fig. 2. UV–vis absorption spectra of (a) CHE4T and (b) BCHE4T in chloroform and in the solid state.



Fig. 3. Arrangement of the molecular dipoles separated by a distance *r* (the reader is referred to Ref. [22]).

energy states for θ approaching 90°, whereas a red shift (J-aggregation) in the absorption corresponds to a decrease in the energy for θ approaching 0° [33]. Such spectral shifts arise from changes in the energy levels due to the molecular packing geometry [35,36]. The UV absorption results and Equation (1) suggest that the H-aggregated CHE4T tended to stack in a parallel arrangement and the J-aggregated BCHE4T tended to stack in a head-to-tail arrangement [19,22].

The molecular packing structure of the designed semiconductors was examined by GIWAXS. As shown in Fig. 4, the CHE4T and BCHE4T diffraction patterns were observed along the out-of-plane directions. These results indicated that CHE4T and BCHE4T were vertically oriented on the substrate and grew along the out-of-plane direction [37]. The diffraction patterns of CHE4T were also observed along the in-plane direction, but the diffraction patterns of BCHE4T were not obvious along the in-plane direction. In place of a peak in the in-plane direction, diagonal BCHE4T diffraction patterns were observed, suggesting that BCHE4T crystals were diagonally packed on the substrate [38]. From data of GIWAXS and UV-spectrum of CHE4T and BCHE4T, we can estimate the molecular configuration that CHE4T forms an orthorhombic crystal and BCHE4T forms monoclinic or triclinic crystal. These packing trends were similar to those reported previously. The differences in the packing trends were caused by the substituted side groups. The cyclohexylacetylene group generated steric hindrance at the periphery of the molecule. That is, the substituted side groups favored packing of adjacent molecules so that the bulky side groups avoided proximity and minimized steric hindrance [20].

The degree of π -overlap and the molecular ordering among molecules along the in-plane direction is important to highperformance OFETs because charge carriers in an organic medium move along π -overlapping areas along the in-plane direction [39]. The UV—vis absorption data demonstrate that CHE4T assumed a high degree of π -overlap. The GIWAXS data verified that molecular ordering of CHE4T along the in-plane direction was better than that of BCHE4T. Therefore, the performance of an OFET based on a CHE4T thin film was expected to be higher than the performance of an OFET based on a BCHE4T thin film.



Fig. 5. Typical transfer curves for (a) CHE4T and (b) BCHE4T devices; and an output curve for (c) CHE4T.

3.3. Field effect transistor (FET) properties

The potential of the synthesized quaterthiophene derivatives for use as organic semiconductors was tested by fabricating FETs of these derivatives using a solution process. As shown in Fig. 5 and



Fig. 4. GIWAXS scattering results for (a) CHE4T and (b) BCHE4T.

Table 2

Device performance of solution-processed OFETs on CHE4T and BCHE4T (average mobility values are given in parentheses).

	Mobility (cm ² /V s)	On/off	$V_{\mathrm{th}}\left(V\right)$	SS (V/decade)
CHE4T BCHE4T	$\begin{array}{c} 3.21\times 10^{-2}(2.51\times 10^{-2})\\ 5.91\times 10^{-4}(4.76\times 10^{-4})\end{array}$	$\begin{array}{c} 1.15\times10^6\\ 3.11\times10^2\end{array}$	-7.98 -4.11	0.680 12.7



Fig. 6. Schematic diagram showing OFETs based on (a) CHE4T or (b) BCHE4T.

Table 2. FET devices composed of CHE4T and BCHE4T showed p-channel transfer characteristics, and the output curve of the CHE4T showed excellent saturation behavior under ambient conditions. The average field-effect mobilities of the devices based on CHE4T and BCHE4T were 2.51 \times 10⁻² cm²/(V s) and 4.76 $\,\times\,$ 10^{-4} cm^2/(V s) in the saturation regime. The structural analysis and UV-vis absorption spectra revealed a clear correlation between H-aggregation (CHE4T) and a high charge carrier mobility, and between J-aggregation (BCHE4T) and a low mobility. Previously reports of high-performance organic semiconductors, such as 6,13bis(triisopropylsilylethynyl)pentacene and its derivatives, usually described J-aggregation with a head-to-tail molecular stacking [22,23]. However, large-area π -stacking among adjacent molecules is accomplished within H-aggregation and not J-aggregation. As the number of molecules stacked in parallel increased to produce a large area of π -overlap, the hole mobility among adjacent molecules improved [18], thereby producing a higher field-effect mobility in the devices. The area of π -overlap between adjacent molecules was higher in the H-aggregated materials such that they yielded better charge carrier mobilities than the J-aggregated materials.

The GIWAXS studies confirmed that the asymmetric CHE4T molecules were vertically aligned in a face-to-face packing structure, and the symmetric BCHE4T molecules were diagonally oriented normal to the substrate, as shown in Fig. 6 [37,38]. Parallel packing and good ordering along the in-plane direction in the H-type aggregate material (CHE4T) produced a higher FET mobility than was observed in the J-type aggregate material (BCHE4T).

4. Conclusions

The relationship between molecular aggregation and OFET device performance using designed two end-capped quaterthiophene derivatives for use in solution-processed organic transistors was studied. It was shown that the molecular aggregation type

(H- or I-type aggregation) and packing structures were determined by differences in the molecular structures. The bulky cyclohexylacetylene end-capping side groups were found to generate steric hindrance that pushed the molecules apart. The films formed from asymmetrically substituted side groups (CHE4T) tended to stack in such a way that adjacent molecules were parallel, which minimized repulsion. In contrast, films based on symmetrically substituted side groups (BCHE4T) formed with head-to-tail arrangements. These two modes led to H- or J-aggregation, respectively. The GIWAXS analysis showed that the H-aggregated CHE4T included more effective intermolecular π -stacking than the J-aggregated BCHE4T along the in-plane direction. We also found that the field-effect mobility of a CHE4T-based device was two orders of magnitude higher than that of a BCHE4T-based device. The results of our study revealed that H-type aggregation assumed a packing structure that resulted in a better OFET performance than was observed for OFETs based on J-type aggregation.

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