Impact of Noncovalent Sulfur– Fluorine Interaction Position on Properties, Structures, and Photovoltaic Performance in Naphthobisthiadiazole-Based Semiconducting Polymers

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1. Introduction

Semiconducting polymers are an important class of functional materials that can be solution-processed to form thin films on plastic substrates and thus can be applied to various flexible optoelectronic devices.[1–3] One of the devices that are most strongly reliant on the properties of semiconducting polymers is organic photovoltaics (OPVs), in which the semiconducting polymers are typically used as the p-type (electron donor) material in combination with fullerene derivatives or nonfullerene small molecules as the n-type (electron acceptor) material.[4–12] Research of OPVs has seen great advances in the last decade owing to the development of a wide variety of semiconducting polymers with donor–acceptor motifs wherein electron-rich and electron-deficient π-conjugated building units (donor and acceptor) are alternately incorporated in the backbone.[13–22] This design strategy has enabled us to easily tune polymer

Controlling the energetics and backbone order of semiconducting polymers is essential for the performance improvement of polymer-based solar cells. The use of fluorine as the substituent for the backbone is known to effectively deepen the molecular orbital energy levels and coplanarize the backbone by noncovalent interactions with sulfur of the thiophene ring. In this work, novel semiconducting polymers are designed and synthesized based on difluoronaphthobisthiadiazole (FNTz) as a new family of naphthobisthiadiazole (NTz)–quaterthiophene copolymer systems, which are one of the highest performing polymers in solar cells. The effect of the fluorination position on the energetics and backbone order is systematically studied. It is found that the dependence of the solar cell fill factor on the active layer thickness is very sensitive to the fluorination position. It is thus further investigated and discussed how the structural features of the polymers influence the photovoltaic parameters as well as the diode characteristics and bimolecular recombination. Further, the polymer with fluorine on both the naphthobisthiadiazole and quaterthiophene moieties exhibits a quite high power conversion efficiency of 10.8% in solar cells in combination with a fullerene. It is believed that the results would offer new insights into the development of semiconducting polymers.

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properties. Recent studies of nonfullerene n-type materials have further enhanced the performance of OPVs.\textsuperscript[8,12,23–26] In addition, semiconducting polymers as the n-type material have also been intensively studied.\textsuperscript[27–35]

The requirements for semiconducting polymers to improve the power conversion efficiency (PCE) with respect to the electronic properties include a narrow optical bandgap ($E_g$) and a deep highest occupied molecular orbital (HOMO) energy level, which in principle would maximize the short-circuit current density ($J_{SC}$) and the open-circuit voltage ($V_{OC}$), respectively.\textsuperscript[36] Further, the lowest unoccupied molecular orbital (LUMO) energy level is also important because the offset energy of the LUMOs between the p- and n-type materials, particularly when the p-type material has a narrower bandgap than the n-type material, would dictate the photon energy loss ($E_{loss}$), which is calculated by $E_{loss} = eV_{OC}$, where $e$ is the elementary charge.\textsuperscript[37–39] Thus, the LUMO energy level of the p-type material should be deep and as close as that of the n-type material, which would diminish the offset energy and thereby increase $V_{OC}$. In the meantime, the desired structural features for the semiconducting polymers are high crystallinity and backbone orientation with the “face-on” motif.\textsuperscript[40–43] Such favorable structural features would bring about high charge carrier mobility, which is crucial for a high fill factor (FF). It would also enable the use of thick active layers, which are beneficial for increasing light absorption and thus $J_{SC}$.\textsuperscript[44,45]

The incorporation of large π-conjugated building units with strong electron deficiency is an effective way to ensure the coplanarity of the polymer backbone and thereby a high crystallinity as well as deep energy levels.\textsuperscript[13,14,16,20–22] On the other hand, the introduction of substituents with an electron-withdrawing nature that realizes noncovalent intramolecular interactions also brings about these electronic and structural features.\textsuperscript[46] The fluorine atom is one of the most widely used substituents for this purpose in semiconducting polymers because it has the highest electronegativity among all the elements and shows attractive interaction with hydrogen and sulfur atoms.\textsuperscript[47–49] However, the position and the number of substituents largely affect the electronic properties, the ordering structures, and the solubility of the polymers. Therefore, the implications of such substituents have to be carefully examined to design semiconducting polymers with even higher performance.

One good example is a series of semiconducting polymers consisting of a naphtho[1,2-c:5,6-c’]-bis[1,2,5]thiadiazole (NTz)\textsuperscript[27,29,50–52] strongly electron deficient building unit (Figure 1a) and a quaterthiophene moiety with two long branched alkyl groups. We reported that an NTz-based polymer, PNTz4T (Figure 1a), showed crystalline structures with the face-on orientation in the polymer/fullerene blend film, which led to PCEs of $\approx$10% in the PC$_7$BM-based cell.\textsuperscript[53] More recently, we developed fluorinated NTz-based polymers, PNTz4TF2 and PNTz4TF4 (Figure 1b), in which two and four fluorine atoms were introduced into the β-positions of the bithiophene moiety, respectively (Figure 1b).\textsuperscript[54] Both fluorinated polymers had deeper HOMO energy levels than PNTz4T, whereas they had wider optical bandgaps than PNTz4T. Further, as the fluorine number increased, the backbone coplanarity was apparently enhanced but the fraction of the face-on orientation was decreased in the blend film: in particular, PNTz4TF4 oriented rather randomly. Overall, the PNTz4TF2 cell exhibited as high as 10.5% PCE, whereas the PNTz4TF4 cell exhibited a limited PCE of $\approx$6.5%.

Very recently, le and co-workers reported the synthesis of difluorinated NTz (FNTz) (Figure 1a) as well as an FNTz-based small molecule that nicely functioned as an n-type material in an OPV cell.\textsuperscript[53] FNTz would thus allow us to examine the effect of fluorination on the NTz moiety in the PNTz4T backbone. Here, we synthesized for the first time FNTz-based semiconducting polymers, PFN4T and PFN4TF2 (Figure 1c), as new members of the PNTz4T family. Furthermore, we systematically studied the effect of the fluorene substitution position on the polymer electronic structure, the ordering structure, and the photovoltaic properties by comparing with counterpart polymers PNTz4T and PNTz4TF2. PFN4TF2, which has two fluorine atoms each on the NTz moiety and the bithiophene moiety, showed as high as 10.8% PCE and reduced $E_{loss}$ in PC$_7$BM-based OPV cells. To better distinguish the chemical structure, we renamed the polymers as F0–F0, where the first and the second “F” represent fluorine at the NTz moiety and the bithiophene moiety, respectively, and “n” represents the number of substituted fluorine atoms in each moiety. Thus, PNTz4T, PNTz4TF2, PNTz4TF4, PFN4T, and PFN4TF2 will be hereinafter called F0–F0, F0–F2, F0–F4, F2–F0, and F2–F2, respectively (Figure 1a–c).

2. Synthesis of Polymers

The synthetic route to the FNTz-based polymers is displayed in Figure 1d. FNTz, synthesized according to a previous report,\textsuperscript[53] was first brominated by N-bromosuccinimide (NBS) to give 1, and 1 was reacted with stannylated alkyliothiophenes (\textit{2a}: R = 2-decyltetradecyl (DT), \textit{2b}: R = 2-dodecylhexadecyl (DH)) via the Stille coupling reaction to afford 3a and 3b, respectively. Then, 3a and 3b were dibrominated by NBS to provide 4a and 4b, respectively, as the monomers for polymerization. 4a and 4b were copolymerized with distannylated bithiophene (5a) and distannylated difluorobithiophene (5b), respectively, via the Stille coupling reaction under microwave irradiation to afford F2–F0 and F2–F2.

The polymers were soluble in hot chlorinated solvents, such as chlorobenzene (CB) and o-dichlorobenzene (DCB). Whereas the DT group was introduced as the side chain of F2–F0, the DH group, which is longer than the DT group, was introduced to F2–F2. This is because F2–F2 with four fluorine atoms showed reduced solubility and F2–F2 having the DT group as the side chain was barely soluble in the above conditions. Number-average and weight-average molecular weights ($M_n$ and $M_w$) determined by high-temperature gel-permeation chromatography (GPC) were 33.5 and 79.1 kDa with a polydispersity index (PDI) of 2.3 and 66.3 and 529 kDa with a PDI of 8.0 for F2–F0 and F2–F2, respectively (Table S1, Supporting Information). The large PDI for F2–F2 is due to the broad GPC peak that probably originated in the strong aggregation property (Figure S1, Supporting Information).\textsuperscript[54–56] The thermal properties of the polymers were investigated by differential scanning calorimetry.

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Whereas F2–F0 showed a melting peak at 340 °C, F2–F2 did not show any peak below 350 °C (Figure S2, Supporting Information). This indicates that both polymers do not undergo phase transitions under the conditions for cell fabrication and measurements. The properties of F0–F0 and F0–F2 used in this study are also summarized in Table S1 (Supporting Information).

3. Influence of Fluorination Position on Electronic and Optical Properties, and Backbone Order

The HOMO and LUMO energy levels (\(E_H\) and \(E_L\)) of the polymers were examined by photoelectron yield spectroscopy (PYS) (Figure 2a) and low-energy inverse photoelectron spectroscopy (LEIPS)(57,58) (Figure 2b) using the polymer thin films, and
are summarized in Figure 2d and Table 2. F2–F0 had an $E_{\text{H}}$ of −5.14 eV, which was slightly deeper by 0.05 eV than that of F0–F0. However, it had an $E_{\text{L}}$ of −3.28 eV, which was deeper by 0.16 eV than that of F0–F0. This indicates that the fluorination on the NTz moiety affected LUMO more than HOMO. This is fairly consistent with the fact that the LUMOs mainly reside on the NTz moiety according to the computation carried out by the DFT method (B3LYP/6-31g(d)) (Figure S4, Supporting Information). When F2–F2 was compared with F2–F0, the downward shift of $E_{\text{L}}$ was also larger than that of $E_{\text{H}}$: $E_{\text{H}}$ and $E_{\text{L}}$ of F2–F2 were −5.30 and −3.35 eV, respectively, and those of F0–F2 were −5.27 and −3.18 eV, respectively. However, these results contrasted with the results when the fluorine atoms were introduced onto the bithiophene moiety. When F2–F2 was compared with F0–F0, whereas $E_{\text{H}}$ of F2–F2 was downshifted by 0.16 eV, $E_{\text{L}}$ was downshifted by only 0.07 eV. This was consistent with the comparison between F0–F0 and F0–F2, and also with the computation in which the HOMOs mainly resided on the bithiophene moiety (Figure S5, Supporting Information). The energy levels measured by PYS and LEIPS were likely affected by the orientation of the polymer backbone.[59,60] Thus, although the energy levels determined here could be well explained by the electronic effect of the fluorine atom, these values might include some effect from orientation because the backbone orientation of these polymers was altered by the fluorination, as will be discussed later. In addition, cyclic voltammetry (CV) was also carried out to investigate $E_{\text{H}}$ and $E_{\text{L}}$ of the polymers (Figure S5, Supporting Information). $E_{\text{H}}$ and $E_{\text{L}}$ that were calculated using the redox potentials that were determined at the onset of the peaks are summarized in Table 1. Although the values were somewhat different from those determined by PYS and LEIPS, the trend showed good agreement.

Figure 2c displays the UV–vis absorption spectra of the polymers in the thin films. The absorption maximum ($\lambda_{\text{max}}$),
the absorption edge (λ_{edge}), and the optical bandgap (E_g^{opt}) calculated using λ_{edge} are summarized in Table 1 (The E_g^{opt}s are also shown in Figure 2d). All the polymers gave a spectrum with the main band spanning ~500–800 nm, in which two peaks were observed: in F2–F0 and F0–F0, the peak in the shorter wavelength region appeared as a shoulder. The peaks were assigned to the 0–0 (700–760 nm) and 0–1 (620–700 nm) vibrational bands. The intensity ratio of the 0–0 to 0–1 bands was larger in F2–F2 and F0–F2 than F2–F0 and F0–F0, implying that the polymers with fluorine on the bithiophene moiety are more ordered than the polymers with unsubstituted bithiophene. This will be further discussed later. λ_{max} and λ_{edge} of F2–F0 were 760 and 850 nm, respectively, both of which were red-shifted by ~50 nm from those of F0–F0 (λ_{max} = 716 nm, λ_{edge} = 798 nm). Accordingly, E_g^{opt} of F2–F0 was calculated to be 1.46 eV, which was reduced by ~0.1 eV relative to that of F0–F0 (E_g^{opt} = 1.55 eV). As the first excitation is dominated by the electron transition from HOMO to LUMO, the observed shifts in the absorption spectra are consistent with the effects of the fluorine substitution discussed above. Similarly, F2–F2 also gave an absorption band (λ_{max} = 727 nm, λ_{edge} = 810 nm) that was red-shifted from that of F0–F2 (λ_{max} = 694 nm, λ_{edge} = 770 nm) by ~40 nm, resulting in an E_g^{opt} of 1.53 eV that was reduced by ~0.1 eV relative to that of F0–F2. Thus, it is concluded that the fluorination on the NTz moiety can reduce the bandgap of the polymer. This sharply contrasts the fluorination on the bithiophene moiety that enlarges E_g^{opt} of 1.46 eV for F2–F0 to 1.53 eV for F2–F2.

We also measured the UV–vis absorption spectra of the polymers in CB solution by changing the temperature (Figure 2e–h). At room temperature, all the polymers gave a main broad absorption at around 500–800 nm, in which the 0–0 and 0–1 bands were observed, similarly to the film spectrum. Such similarity likely means that the polymer backbones are partially aggregated even in solution. However, these two bands had less features in solution than in film for F2–F0 and F0–F0 suggesting that their backbones are less aggregated than the F2–F2 and F0–F2 backbones. The shapes of the room temperature spectra for F2–F0 and F2–F2 are very similar to those for F0–F0 and F0–F2, respectively, although the peak locations are different. This suggests that the fluorination on the NTz moiety does not affect the coplanarity of the backbone. In F2–F0 (Figure 2e), when the temperature was gradually increased to 100 °C, the spectrum became almost featureless and slightly broadened toward the shorter wavelength region, which implies that disaggregation occurred and the motion of the backbone became large. Such behavior was more significant in F0–F0 (Figure 2g), where its spectrum became a single broad spectrum and largely blue-shifted. This suggests that the F2–F0 backbone is more rigid than the F0–F0 backbone, most likely due to the noncovalent F⋯S interactions between the FNTz moiety and the neighboring alkylithiophene moiety, although the coplanarity is similar at room temperature, as mentioned above. In contrast, F2–F2 did not show such behavior (Figure 2f). In F2–F2, the intensity ratio of the 0–0 band to the 0–1 band slightly decreased by raising the temperature, which implies that disaggregation and/or motion of the backbone was very limited and thus the F2–F2 backbone was more rigid than the F2–F0 backbone. This would originate in the additional noncovalent F⋯S interactions in the bithiophene moiety. F0–F2 showed similar temperature-dependent spectra to F2–F2 (Figure 2h). However, if the sizes of the alkyl side chains were the same for F0–F2 and F2–F2, the behavior would be different, such as the case in F0–F0 and F0–F2. It is also important to carefully compare the difference between F0–F0 and F2–F0, and between F0–F0 and F0–F2. Although the number of fluorine atoms is two for both F2–F0 and F0–F2, the backbone rigidity was larger in F0–F0 than F2–F0. This clearly demonstrates that fluorination on the bithiophene moiety results in more significant intramolecular locking than that on the NTz moiety.

The difference in the fluorination effect on the backbone rigidity can be explained as follows. On the one hand, in F2–F0, there are two locking sites both bonding FNTz and neighboring alkylithiophene, and there is one noncovalent F⋯S interaction at each site (Figure 2i, upper). On the other hand, in F0–F2, there is only one locking site bonding two fluorothiophenes, but there are two F⋯S interactions at this site (Figure 2i, lower). Therefore, it is concluded that although both polymers have two F⋯S interactions in total, the locking effect is stronger when one bond is locked by two interactions than when two bonds are each locked by one interaction. This is further supported by the computation of model compounds: NTz-thiophene (NTz-T), FNTz-thiophene (FNTz-T), bithiophene (T-T), and difluorobithiophene (FT-FT). More specifically, we calculated the total energy of the compounds with different dihedral angles and plotted the energy variation relative to the energy at the dihedral angle of 0° as a function of the dihedral angle (Figure 2j,k). The energy barrier for twisting the chemical bond for NTz-T and FNTz-T was very similar, whereas that for FT-FT was approximately twice as high as that for T-T. In addition, the optimized backbone structure is more coplanar in F2–F2 and F0–F2 than F2–F0 and

Table 1. Optical and electrochemical properties of the polymer thin films.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>E_t [eV]^a</th>
<th>E_t [eV]^b</th>
<th>λ_{max} [nm]^c</th>
<th>λ_{edge} [nm]^c</th>
<th>E_g^{opt} [eV]^e</th>
</tr>
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<tbody>
<tr>
<td>PYS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>F2–F0</td>
<td>−5.14</td>
<td>−5.25</td>
<td>−3.28</td>
<td>−3.55</td>
<td>760</td>
</tr>
<tr>
<td>F2–F2</td>
<td>−5.30</td>
<td>−5.48</td>
<td>−3.35</td>
<td>−3.60</td>
<td>727</td>
</tr>
<tr>
<td>F0–F0</td>
<td>−5.09</td>
<td>−5.20</td>
<td>−3.12</td>
<td>−3.46</td>
<td>716</td>
</tr>
<tr>
<td>F0–F2</td>
<td>−5.27</td>
<td>−5.42</td>
<td>−3.18</td>
<td>−3.49</td>
<td>694</td>
</tr>
</tbody>
</table>

^a HOMO energy levels determined by photoelectron yield spectroscopy (PYS) and cyclic voltammetry (CV); ^b LUMO energy levels determined by low-energy photoelectron spectroscopy (LEIPS) and CV; ^c Absorption maximum; ^d Absorption edge; ^e Optical bandgap determined from the absorption edge.
4. Photovoltaic Properties

We fabricated OPV cells with ITO/ZnO/photoactive layer/MoO3/Ag stacking. The photoactive layer was composed of the polymer and PC71BM. The optimum polymer to PC71BM weight ratio was 1:1.5 for the F2–F0 cell and 1:2 for the other cells. The current density (J)–voltage (V) curves and the external quantum efficiency (EQE) spectra of the optimized cells are displayed in Figure 3a,b, respectively, and the photovoltaic parameters are summarized in Table 2. Here, we compared the photovoltaic parameters between the cells based on NTz polymers and those based on FNTz polymers. As expected from the deeper $E_H$ for the polymers based on FNTz, the F2–F0 and F2–F2 cells exhibited slightly higher $V_{OC}$ values of 0.73 and 0.84 V than the F0–F0 cell (0.71 V) and the F0–F2 cell (0.81 V), respectively. Consequently, $E_{loss}$ was 0.73 eV for the F2–F0 cell and 0.69 eV for the F2–F2 cell, which were reduced by ca. 0.1 eV from that of the F0–F0 (0.84 eV) and F0–F2 (0.80 eV) cells, respectively. In contrast, although F2–F0 and F2–F2 had a somewhat wider absorption range (narrower $E_g$) than F0–F0 and F0–F2, respectively, the short-circuit current density ($J_{SC}$) values of the cells that used F2–F0 ($J_{SC} = 19.2$ mA cm$^{-2}$) and F2–F2 ($J_{SC} = 17.8$ mA cm$^{-2}$) were slightly reduced relative to those of cells that used F0–F0 ($J_{SC} = 19.4$ mA cm$^{-2}$) and F0–F2 ($J_{SC} = 19.3$ mA cm$^{-2}$). This is in good agreement with the result showing that the EQE values are lower nearly throughout the absorption range for the F2–F0 and F2–F2 cells than the F0–F0 and F0–F2 cells, respectively. Nevertheless, overall PCE of the F2–F0 cell was 9.6%, which was the same as that of the F0–F0 cell (PCE = 9.6%), and PCE of the F2–F2 cell was 10.8%, which was reasonably enhanced compared to that of the F0–F2 cell (PCE = 10.1%).

Table 2. Photovoltaic parameters of the optimized polymer/PC$_{71}$BM cells.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Thickness [nm]$^a$</th>
<th>$J_{SC}$ [mA cm$^{-2}$]</th>
<th>$V_{OC}$ [V]</th>
<th>FF</th>
<th>PCE [%]$^b$</th>
<th>$E_{loss}$ [eV]$^c$</th>
</tr>
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<tbody>
<tr>
<td>F2–F0</td>
<td>300</td>
<td>19.2</td>
<td>0.73</td>
<td>0.68</td>
<td>9.6 [9.2]</td>
<td>0.73</td>
</tr>
<tr>
<td>F2–F2</td>
<td>190</td>
<td>17.8</td>
<td>0.84</td>
<td>0.72</td>
<td>10.8 [10.4]</td>
<td>0.69</td>
</tr>
<tr>
<td>F0–F0</td>
<td>320</td>
<td>19.4</td>
<td>0.71</td>
<td>0.71</td>
<td>9.6 [9.2]</td>
<td>0.84</td>
</tr>
<tr>
<td>F0–F2</td>
<td>240</td>
<td>19.3</td>
<td>0.81</td>
<td>0.68</td>
<td>10.1 [9.7]</td>
<td>0.80</td>
</tr>
</tbody>
</table>

$^a$Thickness of the active layer; $^b$Maximum power conversion efficiency. In the brackets are average power conversion efficiencies obtained from more than 10 devices; $^c$Photon energy loss defined by $E_g - E_{VOC}$. 

Figure 3. a) J–V curves and b) EQE spectra of the optimized polymer/PC$_{71}$BM cells. Thickness dependence of c) $J_{SC}$, d) FF, and e) PCE of the cells.
Interestingly, we found clear dependence of the photovoltaic properties on the fluorination position when the active layer thickness was changed (Figures S6 and S7, Supporting Information). Figure 3c–e depict the dependence of $J_{SC}$, FF, and PCE on the active layer thickness. In F2–F0 and F0–F0, $J_{SC}$ increased as the active layer thickness increased to above 300 nm, most likely due to the increased photon absorption, whereas in F2–F2 and F0–F2, $J_{SC}$ increased at first but almost plateaued at around 200 nm thickness (Figure 3c). With respect to FF, in F2–F0 and F0–F0, FF decreased very gently as the thickness increased, whereas in F2–F2 and F0–F2, it decreased steeply (Figure 3d). As a result, F2–F0 and F0–F0 showed gradual increases in PCE with increasing thickness, whereas F2–F2 and F0–F2 showed gradual decreases above 200 nm thickness (Figure 3e). Thus, the optimum thickness for the F2–F0 and F0–F0 cells was >300 nm, whereas that for the F2–F2 and F0–F2 cells was around 200 nm.

5. Thin-Film Structure

Grazing incidence X-ray diffraction (GIXD) measurements were performed to investigate polymer ordering in the thin films. 2D GIXD patterns of the polymer neat films fabricated on the ITO/ZnO substrate are shown in Figure 4. Although the 2D GIXD patterns need to be corrected because the diffraction data along the $q_z$ axis ($q_{xy} = 0$) are not true specular scan,[61] we here show the 2D original patterns without the correction in order to better visualize the polymer order. For F2–F0 and F2–F2 neat films (Figure 4a,b), we observed diffractions in the small angle region along both the quasi-$q_z$ ($\approx q_z$) and $q_{xy}$ axes, which are assignable to the lamellar order for the edge-on and face-on orientations, respectively. Correspondingly, we observed a diffraction in the wide-angle region on both the $q_z$ and $q_{xy}$ axes, which is assignable to the $\pi-\pi$ stacking order for the face-on
and edge-on orientations, respectively.\(^\text{[58]}\) It is notable that the diffraction for the face-on π–π stacking appeared more strongly in F2–F0 than F2–F2. In contrast, for F0–F0 and F0–F2 neat films (Figure 4c,d), the lamellar and π–π diffractions were only observed along the \(q_{\|}\) and \(q_{\perp}\) axes, respectively, as reported previously. The results indicate that the F2–F0 and F2–F2 films were composed of both fractions of the edge-on and face-on orientations, whereas the F0–F0 and F0–F2 films were mostly dominated by the edge-on orientation. Moreover, this means that the fluorination on the NTz moiety drove the polymer backbones to lie flat on the substrate.

The cross-sectional diffraction profiles of the polymer neat films cut along the \(q_{\|}\) and \(q_{\perp}\) axes of the 2D GIXD patterns are depicted in Figure 4m, respectively. The lamellar \(d\)-spacing \((d_{\|})\) of F2–F0 and F2–F2 in the edge-on fraction (along the \(q_{\|}\) axis) was 22.6 Å \((q_{\|} = 0.28 \text{ Å}^{-1})\) and 24.7 Å \((q_{\|} = 0.25 \text{ Å}^{-1})\), respectively (Table S2, Supporting Information). The difference should be due to the difference of the side chain length. Interestingly, \(d_{\|}\) of F2–F0 was shorter than that of F0–F0 (24.7 Å) by \(\approx\) 2 Å, despite the fact that both polymers have the same alkyl side chain. This can be attributed to the interlocked FNTz–alkythiophene bonds in F2–F0. This would afford more effective space between the adjacent side chains than nonfluorinated F0–F0, and thus would enable deeper side chain interdigitation, space between the adjacent side chains than nonfluorinated F2–F0. This would afford more effective despite the fact that both polymers have the same alkyl side chain, the polymer and using films with two different thicknesses, \(\approx\) by the fluorination position, we conducted measurement by performance dependence on the active layer thickness differed films were also measured. As the trend of the photovoltaic q z

Nevertheless, the \(d\)-spacing for the π–π stacking \((d_{\perp})\) of F2–F0 and F2–F2, determined by the edge-on fraction, was 3.53 Å, which was almost the same as those of F0–F0 and F0–F2 (Table S2, Supporting Information).

The 2D GIXD patterns of the polymer/PC71BM blend films were also measured. As the trend of the photovoltaic performance dependence on the active layer thickness differed by the fluorination position, we conducted measurement by using films with two different thicknesses, \(\approx\)100 nm (thin) (Figure 4e–h,n) and 300 nm (thick) (Figure 4i–l, o), for each polymer. In F2–F0 and F2–F2, the polymer π–π stacking diffraction mainly appeared on the \(q_{\|}\) axis, indicating that the polymers predominantly formed the face-on orientation. Both \(d_{\|}\) and \(d_{\perp}\) of all the polymers were almost unchanged by blending with PC71BM (Table 3). Although the predominant orientation in the neat films was different between the polymers with NTz and with FNTz, that in the blend films was mostly the same for all the polymers. However, it is noted that, in F2–F2 and F0–F2 blend films, the polymer π–π stacking diffraction somewhat diffused as ring, suggesting that the degree of face-on orientation is relatively low and that some portions are randomly oriented. The difference in the backbone orientation was further quantified by pole figure analysis using the 2D GIXD patterns of the blend films.\(^{[9,45,62,63]}\) The ratios of the face-on to edge-on orientation were evaluated by calculating \(A_{\|}/A_{\perp}\), where \(A_{\|}\) and \(A_{\perp}\) correspond to the area of the diffraction peak for the face-on and edge-on fractions in the pole figure plots (Figure S8, Supporting Information), and are summarized in Table 3. For the thin films, \(A_{\|}/A_{\perp}\) was higher in F2–F0 (0.60) than F2–F2 (0.42) and F0–F2 (0.26). For the thick films, although \(A_{\|}/A_{\perp}\) was increased in all the polymers, the trend was the same as that for the thin films. These results suggest that fluorination on the bithiophene moiety deteriorates the face-on orientation in the blend film.

Polymer crystallinity was also evaluated by calculating the coherence length \((L_c)\) by the simplified Scherrer’s equation.\(^{[64,65]}\)

\[
L_c = \frac{\pi}{2 \times \text{FWHM}}
\]

where FWHM is the full width at half-maximum of the lamellar diffraction peak in the \(q_{\|}\) axis (face-on fraction) (Table 3). Although the \(L_c\) values evaluated here are not real values, because the FWHM values include broadening due to the instrumental resolution originating in the X-ray footprint at the sample surface, this would be a good measure to discuss the relative difference in crystallinity. Whereas all the polymers in the thin film gave similar \(L_c\) values (42–48 Å), F2–F0 and F0–F2 gave \(L_c\) values larger than 50 Å and F2–F2 and F0–F2 gave \(L_c\) values smaller than 40 Å in the thick film. The result was somewhat interesting because the polymers with the difluorinated bithiophene moiety (F2–F2 and F0–F2) should have more coplanar backbones due to the noncovalent F–S interactions as discussed above. A plausible reason is that these polymers have relatively lower solubility due to the more coplanar backbones, which makes them solidify more quickly before self-organizing to pack in order during the spin coating, resulting in the lower crystallinity. Another possible reason is the influence of dipoles.\(^{[60]}\) Although the dipoles are cancelled throughout the backbone due to the symmetric structure, there are certainly some local dipoles at each moiety (Figure S9, Supporting Information). Seemingly, fluorination on the bithiophene moiety changes the local dipole more significantly than on the NTz moiety. Such difference might affect the polymer crystal packing and/or orientation.

Table 3. Structural parameters of the polymers in the blend films and charge carrier mobilities of the blend films.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>(d_{|} \text{[Å]})</th>
<th>(d_{\perp} \text{[Å]})</th>
<th>(A_{|}/A_{\perp})</th>
<th>FWHM (\text{[Å]})/(L_c \text{[Å]})</th>
<th>(\mu \text{[cm}^2\text{V}^{-1}\text{s}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>F2–F0</td>
<td>22.6</td>
<td>3.53</td>
<td>0.60</td>
<td>1.28</td>
<td>2.2 × 10^{-3}</td>
</tr>
<tr>
<td>F2–F2</td>
<td>24.7</td>
<td>3.53</td>
<td>0.42</td>
<td>0.52</td>
<td>1.36 × 10^{-3}</td>
</tr>
<tr>
<td>F0–F0</td>
<td>24.7</td>
<td>3.55</td>
<td>0.66</td>
<td>0.90</td>
<td>1.31 × 10^{-3}</td>
</tr>
<tr>
<td>F0–F2</td>
<td>24.7</td>
<td>3.53</td>
<td>0.26</td>
<td>0.46</td>
<td>1.37 × 10^{-3}</td>
</tr>
</tbody>
</table>

\(d\)-Spacing corresponds to the lamellar structure of the face-on crystallite, (100) along the \(q_{\parallel}\) axis; \(d\)-Spacing corresponds to the π–π stacking of the face-on crystallite, (010) along the \(q_{\perp}\) axis; the ratio of face-on to edge-on orientation determined by pole figure analysis; FWHM and coherence length \((L_c)\) estimated from the simplified Scherrer’s equation; Hole mobilities for the polymer-neat and polymer/PC71BM blend films and electron mobilities for the blend films evaluated by the space-charge-limited current model.
6. Charge Carrier Mobility

The charge carrier mobility was evaluated with a hole-only device using the polymer neat film and polymer/PC$_{71}$BM blend film, and with an electron-only device using the blend film based on the space-charge-limited current (SCLC) model (Figure S10, Supporting Information and Table 3). In the polymer-neat film, the mobilities for F2–F0 and F2–F2 (1.3–1.6 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$) were slightly higher than those for F0–F0 and F0–F2 (2.2–2.6 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$), which is consistent with the backbone orientation. However, due to the very small difference, we regard as that these hole mobilities are basically the same. In the blend film, F2–F0 (1.2 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$) and F0–F0 (2.1 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$), having larger face-on fraction, showed higher hole mobilities than F2–F2 (1.1 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$) and F0–F2 (0.8 × 10$^{-3}$ cm$^2$ V$^{-1}$ s$^{-1}$). However, the difference of the mobility was again very small, and we regard as that all the polymers have similar mobilities. Thus, it is concluded that although the GIXD studies showed that the polymers with the unsubstituted bithiophene moiety (F2–F0 and F0–F0) had larger fraction of the face-on orientation and higher crystallinity than the polymers with the difluorinated bithiophene moiety (F2–F2 and F0–F2), the mobility determined by the SCLC model was insensitive to such difference. The electron mobilities were also similar in all the blend films, which is quite reasonable considering that the major electron carrier is PC$_{71}$BM.

7. Charge Recombination Dynamics

Charge recombination is an important factor that determines the photovoltaic performance: suppressed charge recombination leads to efficient charge collection and hence high FFs.[67] In this section, in order to discuss how the fluorination position and the resulting polymer order affect the charge recombination in these polymers, we studied charge recombination dynamics by measuring transient photovoltage/transient photocurrent (TPV/TPC) of these solar cells with a thin or thick active layer (Figures S11–S13, Supporting Information).

Figure 5a displays the dependence of charge carrier lifetime ($\tau_n$) on charge carrier density ($n$) for the thin devices. On the basis of these values, the bimolecular recombination rate constant ($k_{rec}$) is given by $k_{rec} = 1/\tau_n$. The bimolecular recombination reduction factor ($\zeta$) is given by the ratio of $k_{rec}$ to diffusion-limited Langevin recombination rate constant ($k_L$), $\zeta = k_{rec}/k_L$, which has been widely employed as a measure of how charge recombination is suppressed in bulk heterojunction OPVs.[70] Here, $k_L$ is given by $k_L = e\mu/\varepsilon_0\varepsilon_r$, where $\mu$ is the slower charge carrier mobility,[71] $\varepsilon_0$ is the vacuum permittivity, and $\varepsilon_r$ is the relative dielectric constant, which was assumed to be 3.5. Note that the SCLC-based charge carrier mobilities for the blend films as described above were used. Figure 5b displays the dependence of $\zeta$ on $n$ for the thin devices. In all cases, $\zeta$ was evaluated to be on the order of 10$^{-2}$, which indicates that bimolecular recombination was substantially suppressed.

Figure 5c,d displays the results for the thick devices. $\zeta$ was evaluated to be on the order of 10$^{-2}$ for F0–F0, F2–F0, and F0–F2, and to be on the order of 10$^{-1}$ for F2–F2. This indicates that bimolecular recombination was still suppressed in the F2–F0-, F0–F0-, and F0–F2-based devices, but was enhanced in the F2–F2-based device and was close to the Langevin recombination when the active layer was thickened. More interestingly, $\zeta$ was larger in the F2–F2- and F0–F2-based devices than in the F2–F0- and F0–F0-based devices, which means that bimolecular recombination can be enhanced more significantly when the fluorine atoms were introduced on the bithiophene moiety. This trend correlates well with the fact that F2–F2 and F0–F2 had lower degree of polymer crystallinity particularly in the thick film than F2–F0 and F0–F0, as revealed by the GIXD studies.
8. Diode Characteristics of Cells

It has been known that FF and Voc are closely related. In this section, we study the diode parameters of the cells by the dark J–V characteristics, and discuss the relationship between FF and Voc and diode parameters by using the following empirical equations:\(^\text{[72]}\)

\[
\text{FF}_s = \frac{\text{V}_{\text{OC}} - \ln(\text{V}_{\text{OC}} + 0.72)}{\text{V}_{\text{OC}} + 1} \quad (1)
\]

\[
\text{FF}_t = \text{FF}_s (1 - 1.1r_t) + \frac{r_s^2}{5.4} \quad (2)
\]

\[
\text{FF}_{\text{calc}} = \text{FF}_t \left( 1 - \frac{\text{V}_{\text{OC}} + 0.7 \text{FF}_t}{\text{V}_{\text{OC}} r_s} \right) \quad (3)
\]

Here, FF\(_s\) is the fill factor of ideal solar cells with negligibly small series and shunt resistances. FF\(_t\) is the fill factor in consideration of only series resistance, and FF\(_{\text{calc}}\) is the fill factor in consideration of both series and shunt resistances. Voc is the normalized open-circuit voltage expressed by \(eV_{\text{OC}}/k_BT\), where \(n_{id}\) is the ideality factor. \(r_s\) and \(R_{sh}\) are the normalized resistances expressed by \(R_{\text{SC}}/V_{\text{OC}}\) and \(R_{\text{ID}}/V_{\text{OC}}\), respectively, where \(R_s\) and \(R_{sh}\) are actual series and shunt resistances, respectively. \(n_{id}\) can be evaluated by intensity-dependent J–V measurements, and \(R_s\) and \(R_{sh}\) can be evaluated by dark current analysis (Figures S14–S16, Supporting Information). Table S4 (Supporting Information) summarizes the diode parameters and experimental FF (FF\(_{\text{exp}}\)) and FF\(_{\text{calc}}\) of the cells. Although FF\(_{\text{calc}}\) values were higher than FF\(_{\text{exp}}\) values because the loss processes of photogenerated charges were not taken into account, these would be a good measure of the upper limit of FF. For thin cells, the FF\(_{\text{calc}}\) values of F2–F0 (0.79) and F0–F0-based cells (0.80) were lower than those of F2–F2 (0.82) and F0–F2-based cells (0.83). This is ascribed mainly to the lower Voc, because \(n_{id}\) and \(R_s\) of the devices are comparable and \(R_{sh}\) is sufficiently large. For thick devices, however, the difference between FF\(_{\text{calc}}\) values (0.78 for F2–F0, 0.79 for F2–F2 and F0–F2, and 0.80 for F0–F0) became smaller probably due to the larger \(R_s\) originating from the thick active layer.

9. Discussion on Thickness Dependence of FF

As we have shown above, the thickness dependence of FF was different between the polymers with the unsubstituted bi thiophene moiety and the difluorinated bithiophene moiety: the latter showed more significant decrease in FF than the former by increasing thickness of the cell. We here discuss the correlation between FF and polymer order as well as charge recombination.

For the thin devices, FF was the highest for the F0–F0 cell (0.75). For the other cells, the FF values of the F2–F0 cell (0.68) and the F0–F2 cell (0.69) were lower than that of the F2–F2 cell (0.72) (Figure 3). The highest FF for the F0–F0 cell would be explained by the favorable orientation and the high crystallinity of the polymer in the blend film and the substantially suppressed bimolecular recombination. On the other hand, it is interesting that the F2–F0 cell exhibited a low FF in spite of the favorable orientation and the high crystallinity of F2–F0, both of which were apparently similar to F0–F0. Although the SCLC-based hole mobility in the blend film was lower for F2–F0 than for F0–F0, the difference was not significant when compared with other polymers as discussed above. The low FF in F2–F0-based cell compared to the F0–F0 cell would rather be ascribed to the increased bimolecular recombination as proven by the larger \(\zeta\), although the origin is yet unclear. It is possible that the relatively low molecular weight of F2–F0 compared to F0–F0 might be the origin for the increase bimolecular recombination.

In addition, FF in the F2–F0 cell was even lower than the F2–F2 and F0–F2 cells, despite the fact that F2–F0 had desirable backbone orientation and high crystallinity as well as reduced bimolecular recombination compared to F2–F2 and F0–F2. This could, in part, be ascribed to the relatively low Voc for the F2–F0 cell compared to the F2–F2 and F0–F2 cells. According to the empirical equation (see Equation (3) in the above section), a lower Voc leads to a lower FF (FF\(_{\text{calc}}\)) particularly in a thinner cell. In fact, the calculated FF using the diode characteristics of the cells for the F2–F0 cell was lower than that for the F2–F2 and F0–F2 cells by 0.03–0.04 (Table S4, Supporting Information), which is in good agreement with the difference in the experimental FF.

The lower FF for the F0–F2 and F2–F2 cells than for the F0–F0 cell would be due to the relatively unfavorable orientation, as evidenced by the small fraction of the face-on orientation, and the relatively large \(\zeta\). The low FF for the F0–F2 cell compared to the F2–F2 cell should be attributed to the smaller fraction of the face-on orientation in F0–F2.

With increasing thickness of the active layer, FF decreased very gently for the F0–F0 and F2–F0-based cells, whereas FF decreased steeply for the F2–F2 and F0–F2-based cells. This is clearly explained by the difference in polymer order: the face-on fraction and crystallinity for F2–F0 and F0–F0 were much larger than those for F2–F2 and F0–F2 in the thick film. Further, bimolecular recombination was more suppressed in the F2–F0 and F0–F0 cells. For F2–F2 and F0–F2, such an unfavorable polymer order as well as the large \(\zeta\) would result in the low FF of the cell with a thick active layer. Note that the FF\(_{\text{calc}}\) values of the thick devices were almost the same, and thus this effect would be negligible. Thus, in the present polymer system, fluorination on the NTz moiety does not affect much on FF, whereas fluorination on the bithiophene moiety reduces FF particularly for the thick film, which is well-correlated with the polymer order as well as the bimolecular recombination.

10. Conclusions

We have synthesized new semiconducting polymers that incorporate difluoronaphthobisthiadiazole (FNTz), F2–F0 and F2–F2, and discussed the influence of the substitution position of the fluorine atoms in the NTz and quaterthiophene copolymer system. The fluorination on the NTz moiety mainly deepened the LUMO energy level of the polymer, whereas the fluorination on the bithiophene moiety mainly deepened the HOMO energy level, which could be understood from the geometry of the LUMOs and HOMOs. Overall, the polymers with FNTz
(F2–F0 and F2–F2) had narrower optical bandgaps than their NTz counterparts (F0–F0 and F0–F2). The fluorination gave rise to the intramolecular locking of the polymer backbone by the noncovalent F⋯S interactions between the fluorine atom and the sulfur atom in the thiophene ring. However, the intramolecular locking was found to be stronger when the fluorine atoms were introduced on the bithiophene moiety rather than when they were introduced on the NTz moiety, which was likely due to the fact that the bithiophene moiety was locked with two F⋯S interactions whereas the NTz moiety had only one F⋯S interaction with the neighboring alkylthiophene moiety.

The photovoltaic performance of the polymers was studied by fabricating solar cells that used polymer/PC_{71}BM films as the active layer. With the increased $V_{OC}$ and thus the reduced $J_{SC}$, the F2–F2 cell exhibited the highest power conversion efficiency of 10.8% among these polymers, which is one of the highest values reported so far for polymer/fullerene solar cells. Notably, the value was far higher than that of F0–F4 having the same four fluorine atoms on the same polymer backbone but at different positions. However, it is interesting to note that the cell that used F2–F2, similarly to F0–F2, showed lower $J_{SC}$ and FF than the cells that used F2–F0 and F0–F0 in particular when thick active layers were employed. The thickness dependence of FF was explained by the polymer order and the bimolecular recombination reduction factor, along with the empirical equation of FF. First, although F2–F2 and F0–F0 should have more planar backbones, the polymer crystallinity in the blend film was lower than that in the other films, particularly for the thick film. Then, these polymers had less favorable backbone orientation, in which the face-on fraction was smaller. Such polymer order in these polymers apparently led to the larger bimolecular recombination, resulting in the lower FF in the thick cells.

Although it has been shown in various semiconducting polymer systems that fluorination can effectively improve polymer electronic properties as well as polymer order, these results clearly show that the fluorination position must be carefully considered. Therefore, we believe that although the newly synthesized polymer, F2–F2, exhibited improved performance, careful molecular design would lead to new related polymers with even higher photovoltaic performance.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

fluorination, noncovalent interaction, organic photovoltaics, semiconducting polymers, $\pi$-conjugated polymers

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