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Unveiling Excitonic Dynamics in High-Efficiency Nonfullerene Organic Solar Cells to Direct Morphological Optimization for Suppressing Charge Recombination

Xiaoyu Liu, Yajie Yan, Alireza Honarfar, Yao Yao, Kaibo Zheng,* and Ziqi Liang*

Nonfullerene acceptors (NFAs)-based organic solar cells (OSCs) have recently drawn considerable research interests; however, their excitonic dynamics seems quite different than that of fullerene acceptors-based devices and remains to be largely explored. A random terpolymer of PBBF11 to pair with a paradigm NFA of 3,9-bis(2-methylene-1,1-dicyanomethylene)-indanone)-5,5,11,11-tetrakis[4-hexylphenyl]-dithieno-[2,3-d:2′,3′-d′]-s-indaceno[1,2-b:5,6-b′]dithiophene (ITIC) such that both complementary optical absorption and very small offsets of both highest occupied molecular orbital and lowest unoccupied molecular orbital energy levels are acquired is designed and synthesized. Despite the small energy offsets, efficient electron/hole transfer between PBBF11 and ITIC is both clearly observed from steady-state photoluminescence and transient absorption spectra and also supported by the measured low exciton binding energy in ITIC. Consequently, the PBBF11:ITIC-based OSCs afford an encouraging power conversion efficiency (PCE) of 10.02%. Although the good miscibility of PBBF11 and ITIC induces a homogenous blend film morphology, it causes severe charge recombination. The fullerene acceptor of PC71BM with varying loading ratios is therefore added to modulate film morphology to effectively reduce the charge recombination. As a result, the optimal OSCs based on PBBF11:ITIC:PC71BM yield a better PCE of 11.4% without any additive or annealing treatment.

1. Introduction

In recent several years, nonfullerene acceptors (NFAs)-based solution-processed bulk heterojunction (BHJ) organic solar cells (OSCs) have drawn vast attention with increasingly rapid developments.[1–10] In principle, NFAs possess tunable molecular structures, allowing for a fine control of optical bandgap ($E_g$), energy levels, light absorption, and crystallinity to match well with a variety of organic donor semiconductors. The record power conversion efficiencies (PCEs) in NFAs-based single-junction binary OSCs have now reached $\approx 14\%$, which has surpassed those of fullerene acceptor (FA)-based counterparts.[10] The superior photovoltaic performance of NFA OSCs is believed to originate from not only the prominent structural and optical characteristics in NFAs but also the favorable morphological and charge dynamic properties in the blend, the latter of which are however still obscure and require in-depth understanding.

In FA-based OSCs, a large energy offset[11] of lowest unoccupied molecular orbital (LUMO) levels between organic semiconductor donor (D) and acceptor (A) is generally needed to overcome the high exciton binding energy ($E_B$) of donor—typically within 0.33–0.7 eV[12,13] which becomes an inevitable origin of the energy loss.[14] Different from FA analogs, owing to the light absorption of both D and A components in NFA-based systems, there exist two possible charge transfer channels—not only electron transfer from D to A but also hole transfer from A to D via highest occupied molecular orbital (HOMO) energy levels. Numerous studies have indicated that high driving force seems unnecessary for efficient hole transfer in NFA systems. For example, in the...
benchmark NFA systems based on 3,9-bis(2-methylene-(3-(1,1-dicyanomethylene)-indanone)-5,5,11,11-tetrakis(4-hexylphenyl)dithieno[2,3-d:2’,3’-d’]-s-indaceno[1,2-b:5,6-b’]dithiophene (ITIC) and its derivatives, small HOMO energy offsets ranging from 0.04 to 0.2 eV were confirmed as sufficient to drive hole transfer by the means of photoluminescence (PL) quenching efficiency, transient absorption (TA) spectra, and so on.[7,8,15–17]

We consider such a phenomenon is presumably stemmed from the unique A–D–A-type structure of NFAs, which permits the electron/hole pairs to be partly separated within the molecules by forming charge transfer excitons between the neighboring units and thus leads to a reduction of $E_B$. However, whether the electron transfer can occur efficiently under a comparatively small LUMO offset in NFA-based systems remains to be answered.

Despite the favorable energy level alignment of NFAs in OSCs, one major limiting factor is their high energetic loss caused by severe charge recombination induced by the non-ideal film morphology. For instance, Wang and coworkers found that the charge recombination loss in the ITIC-based OSCs was considerably worse than that in FA-based counterparts due to the poor phase-separation morphology induced by well miscibility of polymer donor and ITIC.[18] One feasible approach to solve the problem is then the construction of ternary blend OSCs by judiciously selecting three components and tuning their ratio that can synergistically optimize film morphology, enhance optical absorption, and promote charge transport, which has attracted increasing research interest.[19–28]

This contribution aims to gain a better understanding of efficient charge transfer and address the issue of morphology-induced charge recombination in NFA-based OSCs. We first designed and synthesized the random terpolymer donor based on one benzothiophene (BDT) donor moiety and two well-chosen acceptor units of benzothiophene-4,8-dione (BDD)[29] and fluorine-substituted benzotriazole (FTAZ).[30] At a molar ratio of BDT:BDD:FTAZ = 2:1:1, the resulting terpolymer donor named as PBBF11 exhibits complementary light absorption and very small HOMO/LUMO energy offsets with ITIC, the latter of which can still ensure efficient hole and electron transfer between them. The BHJ OSCs based on the PBBF11:ITIC blend yield the maximum PCE of 10.02%. However, the homogeneous film morphology caused by the well miscibility between PBBF11 and ITIC in the blend would induce severe charge recombination. Therefore, PC$_7$BM was added into the PBBF11:ITIC system as the third component to modulate film morphology and improve charge transport. As a consequence, the optimal ternary OSC based on the PBBF11:ITIC:PC$_7$BM (1:1:0.3, wt%) blend delivers an outstanding PCE of 11.4%.

2. Results and Discussion

Chemical structures of random terpolymer donor PBBF11 and ITIC are depicted in Figure 1a. PBBF11 was synthesized via one-pot Stille coupling reaction, and its synthetic route is shown in Figure S1 in the Supporting Information. As displayed in Figure 1b, the PBBF11 neat film shows strong absorption in the visible region, suggesting its potential application in photovoltaic devices. The UV–vis absorption spectra of PBBF11:ITIC blend films are also shown in Figure 1b, indicating a complementary absorption to ITIC. The band gap ($E_B$) of ITIC was determined by temperature-dependent PL measurements with a linear fitting curve, as shown in Figure 1c. The inset shows a simulation of the free charge fraction over the total excitation density at 300 K under thermal equilibrium. The shaded area represents PV operating conditions (PV regime). The TRPL decay of ITIC neat film is depicted in Figure 1d, with a lifetime ($\tau$) of 0.8 ns.

Figure 1. a) Molecular structures and b) UV–vis absorption spectra of PBBF11 and ITIC neat, and PBBF11:ITIC blend films. c) Determination of $E_B$ of ITIC by temperature-dependent PL measurements with a linear fitting curve. Inset: A simulation of the free charge fraction over the total excitation density at 300 K under thermal equilibrium. The shaded area represents PV operating conditions (PV regime). d) TRPL decay of ITIC neat film.
optical absorption ranging from 450 to 650 nm, which complements that of ITIC, and therefore the PBBF11:ITIC (1:1, wt%) blend film exhibits a broad coverage in the visible light region. The HOMO/LUMO energy levels of PBBF11 are estimated to be $-5.48/-3.66$ eV while those of ITIC was reported as $-5.51/-3.78$ eV.\[28\] It is noticed that the HOMO offset ($\Delta E_{\text{HOMO}}$) between PBBF11 and ITIC is negligible as only 0.03 eV, which is however enough to achieve efficient hole transfer from ITIC to PBBF11. This is evidenced by the high PL quenching efficiencies over 90% for PBBF11 to ITIC in the blend films (Figure S2, Supporting Information). Despite a small $\Delta E_{\text{HOMO}}$, it has been widely reported that ITIC-based OSCs have demonstrated excellent device performance.\[7,8,15–17,31\] We therefore tend to believe ITIC should possess such unique features that differ from organic donors and FAs.

We for the first time characterized the exciton $E_0$ of ITIC by measurements of temperature-dependent PL intensity.\[1,32\] The PL spectra of ITIC thin film were measured at low temperatures ranging from 140 to 200 K and the integrated PL intensities, $I(T)$, were calculated. With increasing temperature, $I(T)$ is decreased due to the thermal dissociation of excitons at higher temperature, and it can be expressed in Equation (1)\[1,32;\]

$$I(T) = I(0) + A e^{-\frac{E_0}{kT}}$$

where $I(T_0)$ is the PL intensity at the lowest temperature, and $k_B$ is the Boltzmann constant. The linear fitting of $\ln(I(T_0)/I(T)-1)$ versus $1/(k_B T)$ is plotted in Figure 1c and, from the fitting slope, the $E_0$ of ITIC is estimated to be $117$ meV that is considerably low when comparing it to organic semiconductors which typically present an $E_0$ of 0.2–0.4 eV.\[33\] In this case, the photogenerated excitons might be intra-charge transfer excitons along the neighboring D–A units rather than the Frenkel-type excitons. Note that free charges and weak coupled excitons coexist under thermodynamic equilibrium with a stable molar ratio which resembles the ion–electron balance in a hot plasma expressed by using the Saha–Langmuir equation where the ratio which resembles the ion–electron balance in a hot plasma coexists under thermodynamic equilibrium with a stable molar ratio.

conductivity $p$ (Equation (2))\[34\]:

$$p = \frac{n e^2}{\pi \mu k_B T}$$

where $\mu$ is the charge mobility and $e$ is the electric quantity of elementary charge. Consequently, ITIC affords an $L_D$ of $\approx 14.4$ nm, which is larger than that of P3HT ($L_D = \approx 10.2$ nm), indicating there are more chances for excitons to diffuse to the D/A interfaces which might enhance the toleration of blend film morphology on device performance in ITIC-based systems.

Grazing-incidence wide-angle X-ray scattering (GIWAXS) measurements were then conducted to evaluate the crystallinity properties of neat PBBF11 and ITIC in solid state and their respective π-stacking structures in the blend film. As shown in Figure 2a, PBBF11 exhibits a moderate (100) lamellar reflection peak located at 0.28 Å$^{-1}$ along with a weak (010) π–π stacking peak at 1.73 Å$^{-1}$ along the out-of-plane direction, which reflects its amorphous nature. On the contrary, ITIC displays two distinct (100) and (010) peaks at 0.52 and 1.62 Å$^{-1}$ along out-of-plane direction, respectively, indicative of its relatively higher crystalline property than PBBF11 (Figure 2b). Additionally, the ITIC neat film shows multiple signals along both in-plane and out-of-plane directions, which are presumably attributed to various ITIC crystalline phases. In the PBBF11:ITIC blend film (Figure 2c), the signal intensities of ITIC are remarkably lower than that of ITIC neat film. This suggests that PBBF11 is readily miscible with ITIC due to their similar chemical structures. Concurrently, the phase-separated morphology and surface topography of the blend film were examined by transmission electron microscope (TEM) and atomic force microscope (AFM) techniques, respectively. A homogeneous blend film morphology is observed in Figure 2d, indicating the good miscibility of PBBF11 and ITIC, which can also be confirmed from its low root-mean-square (RMS) surface roughness of 0.91 nm as shown in Figure 2e.

The additive- and annealing-free BHJ OSCs were fabricated with an inverted configuration of ITO/ZnO/PBBF11:ITIC (1:1, wt%)/MoO$_3$/Al and the resulting current–density–voltage ($J$–$V$) curve is displayed in Figure 3a. An impressive PCE of 10.02% was achieved with $J_{SC} = 17.42$ mA cm$^{-2}$, $V_{OC} = 0.92$ V, and a fill factor (FF) of 62.50%. The current integrated from the external quantum efficiency (EQE) spectrum (Figure 3b) is 17.1 mA cm$^{-2}$, which is about the same as $J_{SC}$. High photocurrent is originated from the strong and complementary optical absorption of PBBF11 and ITIC (Figure 1b) and efficient charge transfer between them as evidenced from the PL results (Figure S2, Supporting Information). Meanwhile, high $V_{OC}$ is obtained because of the small $\Delta E_{\text{HOMO}}$ between PBBF11 and ITIC.

$$L_D = \sqrt{D \tau}$$

where $D$ is the diffusion coefficient and $\tau$ is the average PL lifetime in thin film, and $D$ can be further calculated in Equation (4)$[36]$:

$$D = \frac{\mu k_B T}{e}$$

where $\mu$ is the charge mobility and $e$ is the electric quantity of elementary charge. Consequently, ITIC affords an $L_D$ of $\approx 14.4$ nm, which is larger than that of P3HT ($L_D = \approx 10.2$ nm), indicating there are more chances for excitons to diffuse to the D/A interfaces which might enhance the toleration of blend film morphology on device performance in ITIC-based systems.
To unveil the detailed pathways of charge carrier transporta-
tion and recombination, ultrafast TA spectroscopy was utilized
for mechanistic studies. The first factor to be confirmed is
hole transfer from ITIC to PBBF11, which can be identi-
fied from the comparison of TA spectrograms among neat
PBBF11 (Figure 4a), ITIC (Figure 4b), and PBBF11:ITIC blend
(Figure 4c). After excitation above the $E_g$s of both PBBF11 and
ITIC, the characteristic ground state bleaches (GSB) can be
observed for both PBBF11 (620 nm) and ITIC (720 nm) repre-
senting the population of the HOMO and LUMO energy levels
as shown in Figure 4a,b, respectively. In the PBBF11:ITIC blend
film (Figure 4c), the GSB of the PBBF11 still appears when
only ITIC is expected to be excited using 700 nm excitation. As
the optical $E_g$ of ITIC is comparatively narrower than that of
PBBF11 (as shown in Figure 1a), the shortened GSB recovery of
PBBF11 in the binary blend compared with that in neat
PBBF11 can be attributed to the efficient hole transfer from
the HOMO energy level of ITIC to that of PBBF11.\cite{16} Such fast
hole transfer can be further clarified from the extracted kinetics
at the maximum bleach in Figure 4e where the TA kinetics in
the blend exhibit faster decay for ITIC GSB (green curve) and
slower rising for PBBF11 GSB (blue curve) compared to neat
samples (red and black curves), respectively. The hole transfer
time can be estimated to be 1 ps from the fitting of the rising
of TA kinetics for PBBF11:ITIC (blue line). Such efficient hole
transfer in spite of low $\Delta E_{\text{HOMO}}$ is consistent with the reported
results for ITIC, which will significantly increase the $V_{OC}$ of
OSC devices.\cite{7,8,15-17,31}

Apart from hole transfer, electron transfer from the LUMO
level of PBBF11 to ITIC is also essential to the generation of
photocurrent. Thus, we first compared the TA spectrograms
of the PBBF11:ITIC blend excited at 700 and 400 nm shown
in Figure 4c,d, respectively. The TA kinetics at the maximum
ITIC GSB (725 nm) of both cases are extracted into Figure 4f.
When pumped at 700 nm, only ITIC in the blend would be
excited and the GSB decay at 700−750 nm only reflects the
depopulation of photoexcited charges in ITIC. However, by
400 nm pumping, both ITIC and PBBF11 would be excited and
the GSB dynamics in ITIC would be additionally contributed by
either electron transfer or energy transfer from PBBF11 as they
are both energetically favorable in the blend system. In this sce-
nario, the decay of ITIC GSB (blue line in Figure 4f) is much
slower. Next, we extracted the differential curve (gray curve in
Figure 4f) between two decays with 700 and 400 nm excitation.

![Figure 2. GIWAXS images of a) PBBF11 and b) ITIC neat film, and c) PBBF11:ITIC (1:1, wt%) binary blend film. d) TEM and e) AFM images of PBBF11:ITIC (1:1, wt%) binary blend film.](image)

![Figure 3. a) $J$−$V$ curve and b) EQE spectrum of the PBBF11:ITIC-based optimal OSC.](image)
It can be fitted by two exponential rising components with lifetimes of 0.2 and 11 ps, respectively. The ultrafast component (0.2 ps) should be attributed to the electron transfer process which is notably faster than hole transfer from ITIC to PBBF11. The slower component (11 ps) is hard to assign at this stage since both the energy transfer and the dissociation of the intermediate charge transfer state (CTS) state could occur within this timescale in the blend system. However, efficient electron transfer from PBBF11 to ITIC within 10 ps can still be qualitatively confirmed. In summary, we proved both electron and hole transfer in ITIC-based blend film can be extremely efficient regardless of low driving force at both HOMO and LUMO energy levels.

Despite superior charge separation in the above PBBF11:ITIC blend film, the lifetime of separated charges in either donor or acceptor components is still ≈1–2 ns as evidenced by the TA decay at PBBF11 GSB (625 nm) after ITIC is excited at 700 nm (Figure 4e, blue curve). This indicates that the interfacial geminate recombination still exists hindering charge transportation, which would be stemmed from the well miscibility between PBBF11 and ITIC. In this respect, we set out to employ a third component to regulate the blend film morphology and further separate the electrons and holes from the D/A interfaces to retard the geminate recombination. PC71BM, which possesses strong electron-withdrawing capability and lower LUMO energy level [24] than ITIC (Figure 5a), appears to be a suitable candidate. It can accept the electrons from both PBBF11 and ITIC while the holes remain in PBBF11, thereby preventing the electrons and holes to be recombined at the interfaces of PBBF11 and ITIC. Figure 5b shows the light absorption spectra of PBBF11:ITIC:PC71BM ternary blend films with various PC71BM loading ratios. It can be seen that PC71BM contributes little to light absorption due to its weak visible light harvesting characteristics and low addition amount.

Ternary PBBF11:ITIC:PC71BM and binary PBBF11:PC71BM OSCs were fabricated and compared with the same device structure and processing conditions as the PBBF11:ITIC-based cells. Their J–V curves and EQE spectra are displayed in Figure 5c,d, respectively, and the corresponding photovoltaic parameters are collected in Table 1. The JSC deviations between J–V curves and EQE spectra are very low. Note that the ternary devices exhibited a bit lower EQE values in short wavelength regions than those of the binary PBBF11:ITIC devices, which might be ascribed to both the weak optical absorption of PCBM and the blend film morphology variation caused by the PCBM addition. Compared to the PBBF11:ITIC (1:1, wt%) binary device, the ternary systems based on PBBF11:ITIC:PC71BM (1:1:0.1 and 1:1:0.3, wt%) exhibit a steady increase of JSC, giving rise to prominent PCE enhancements. Note that the slightly enhanced optical absorption in ternary blends may not be the main contributor for the JSC improvements (Figure 5b). Instead, the simultaneously boosted JSC is believed to originate mainly from morphological and dynamic reasons induced by fullerene addition. When further increasing the weight ratio of PC71BM to 1:1:0.5, the device performance however begins to degrade with simultaneously reduced JSC, VOC, and FF. As a result, the optimal ternary blend OSCs based on PBBF11:ITIC:PC71BM (1:1:0.3, wt%) yield an outstanding PCE of 11.40% with JSC = 19.17 mA cm⁻², VOC = 0.92 V, and FF = 64.65%.

To reveal the morphological function of PC71BM, GIWAXS, TEM, and AFM measurements of ternary blend films were successively conducted. The GIWAXS diffractograms of
PBBF11:ITIC:PC71BM-based blend films are presented in Figure 6a–d. The characteristic diffraction ring of PC71BM (at ≈ 1.40 Å−1; see Figure S3, Supporting Information) becomes gradually distinct with an increase of PC71BM addition amount, indicative of the formation of individual PC71BM aggregates. Additionally, it is interesting to note that in the PBBF11:ITIC:PC71BM (1:1:0.3, wt%) ternary blend, several extra diffraction peaks appear along the in-plane direction, which could be ascribed to the enhanced crystallinity of ITIC, implying that an addition of PC71BM might further induce the ITIC crystallization. TEM and AFM images offer more morphological evidences as shown in Figure 6e–l. In the ternary blends, an introduction of PC71BM is found to afford additional PC71BM phases as seen by the existence of black dots (~10 nm) in the TEM images (Figure 6e–g) with various fullerene loading ratios, in which an increasing PC71BM ratio leads to rougher surface (Figure 6i–k). By varying the amount of PC71BM aggregates, the blend film morphology can be finely regulated, and thus a remarkable enhancement of device performance is achieved with an appropriate PC71BM ratio (30 wt% vs ITIC). However, the PBBF11:PC71BM binary blend shows distinctive PC71BM aggregates (Figure 6h) with the highest RMS roughness of 1.85 nm (Figure 6l), which would impede charge separation at D/A interfaces.

To comprehend the difference of charge carrier transportation and recombination dynamics between PBBF11:ITIC:PC71BM and PBBF11:ITIC-based systems, ultrafast TA spectroscopy studies were then performed as shown in Figure 7. When PC71BM is added into the binary blend, the lifetime of injected holes in PBBF11 becomes longer as shown in the GSB of PBBF11 at 620 nm in Figure 7a. The underlying mechanism can also be analyzed by the singular value decomposition (SVD) fitting of TA spectra in the ternary blends as summarized in Figure 7b. During the SVD fitting, we first obtained the rate constants of each component from the conventional multi-exponential fitting of all the main bleaching bands as the initial parameters. It should also be noted that we have minimized the excitation intensity down to the fluence of

Table 1. Summary of photovoltaic parameters of PBBF11:ITIC:PC71BM-based devices under simulated light irradiation of 100 mW cm−2.

<table>
<thead>
<tr>
<th>Blend ratio [w/w/w]</th>
<th>JSCa) [mA cm−2]</th>
<th>JSCb) [mA cm−2]</th>
<th>Vocca) [V]</th>
<th>FFca) [%]</th>
<th>PCEca) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:1:0</td>
<td>17.58 ± 0.42 (17.42)</td>
<td>17.1</td>
<td>0.91 ± 0.01 (0.92)</td>
<td>61.90 ± 0.59 (62.50)</td>
<td>9.94 ± 0.10 (10.02)</td>
</tr>
<tr>
<td>1:1:0.1</td>
<td>18.20 ± 0.24 (18.04)</td>
<td>17.3</td>
<td>0.91 ± 0.02 (0.92)</td>
<td>60.81 ± 1.31 (60.49)</td>
<td>10.07 ± 0.14 (10.15)</td>
</tr>
<tr>
<td>1:1:0.3</td>
<td>19.14 ± 0.77 (19.17)</td>
<td>18.0</td>
<td>0.92 ± 0.01 (0.92)</td>
<td>61.51 ± 1.94 (64.65)</td>
<td>10.88 ± 0.29 (11.40)</td>
</tr>
<tr>
<td>1:1:0.5</td>
<td>17.44 ± 0.37 (17.83)</td>
<td>17.1</td>
<td>0.90 ± 0.01 (0.90)</td>
<td>58.09 ± 0.56 (58.02)</td>
<td>9.01 ± 0.13 (9.21)</td>
</tr>
<tr>
<td>1:0:1</td>
<td>10.72 ± 0.17 (10.51)</td>
<td>10.2</td>
<td>0.90 ± 0.01 (0.90)</td>
<td>51.49 ± 2.40 (54.65)</td>
<td>4.97 ± 0.19 (5.17)</td>
</tr>
</tbody>
</table>

a)The average values of photovoltaic parameters were obtained from at least five devices and the values in parentheses are the highest values; b) The JSC values were calculated from the EQE results.
Thus, the contribution of all high-order nongeminate recombination within ITIC or PBBF11 should be neglected in our case. Besides the 1 ps component denoted for hole transfer, three more components with lifetime of 240 ps (blue), 3.7 ns (black), and 10 ns (green) can also be extracted. Among them, the blue component of 240 ps consists of negative signals at the positions of GSB for both ITIC and PBBF11. Such a component can also be extracted in the binary PBBF11:ITIC blend (Figure S4a, Supporting Information) with similar spectral feature and lifetime after hole transfer occurs from ITIC to PBBF11. This means it should reflect a status with electron residing in ITIC and hole locating in PBBF11 concurrently. In addition, we notice the spectral feature of the negative bleach around 600 nm in this 240 ps component is different from that in neat PBBF11 film (Figure S4b, Supporting Information). This suggests the holes are not directly injected into the HOMO energy level of PBBF11, which is a signature feature of the intermediate CTS. The other two slow components with lifetimes of 3.7 and 10 ns share the same spectral feature of the TA spectrum for neat PBBF11 (Figure S4b, Supporting Information), which can be thus attributed to the injected holes on the HOMO energy level of PBBF11. We also note that the 3.7 ns component can also be extracted in the SVD fitting of the binary PBBF11:ITIC blend (Figure S4a, Supporting Information), while the 10 ns component is not observed. This means the former refers to the charge dynamics within PBBF11 and ITIC whereas the long-lived component should reflect that induced by the addition of PC71BM. Based on the above analysis, we propose all the photoexcited charge carrier recombination pathways in the ternary blend as schematically shown in Figure 7c. The ultrafast (1 ps) hole transfer to PBBF11 directly from the photoexcitation in ITIC leads to the formation of the interfacial CTS with a dissociation time of 240 ps. After dissociation, the free charges in PBBF11 and ITIC still have a chance to recombine at the interface within 3.7 ns. The role of PC71BM is then to extract the remaining electron carriers in ITIC after hole transfer to PBBF11, which reduces the possibility for them to recombine with hole carriers in PBBF11 due to both the long distance between free electrons and holes and the lowered driving force for charge recombination. We believe these two factors account for prolonged charge lifetime and improved device efficiency afforded by PC71BM addition.

Despite the fact that a small addition of fullerene can boost the device performance of NFA-based systems has been widely
reported,[24–27,37–39] the role FA plays in ternary NFA blends and devices, particularly in relation to the loading percent of fullerene, has yet to be systematically explored. We therefore investigated the influence of the PC71BM addition ratio on charge dynamics by TA studies. In order to simplify the analysis, we conducted the global fitting of the TA kinetics at the PBBF11 bleach maximum (625 nm) for the blend films with various PC71BM ratios along with PBBF11 neat film. The evolution of the corresponding amplitude for each component is summarized in Figure 7d. In binary PBBF11:ITIC, only recombination within the CTS (orange) and between interfacial free charges (green) can be found with the major contribution from the free charges (78%). When 10 wt% PC71BM (relative to ITIC) is added, the recombination of the most dissociated charges from CTS between PBBF11 and ITIC is replaced by charge recombination between PBBF11 and PC 71BM (purple 50%) with the contribution of CTS unchanged. Further addition of PC71BM to 30 wt% increases charge recombination between PBBF11 and PC71BM (65%) and reduces CTS (geminate) recombination (15%). When the ratio of PC71BM reaches 50 wt%, the interfacial charge recombination between PBBF11 and ITIC becomes pronounced again (38%). In short, inserting PC71BM into the binary blends initially retards the charge recombination paths between PBBF11 and ITIC; yet an increasing addition of PC71BM would then reverse such an effect.

According to the literature, the influence of the D/A ratio in the BHJ blends of OSCs on charge transport dynamics is mainly originated from the microscopic film morphologies.[40] Although further structural characterization is needed to reveal such a correlation, we can still propose one of the most reasonable morphologic models as illustrated in Figure 8 to interpret the obtained photophysics. In the binary blend, both ITIC and amorphous-like PBBF11 phases are homogeneously mixed, which ensures the efficient interfacial charge separation (Figure 8a). Then, a small amount of added PC71BM is more likely embedded merely within either ITIC or PBBF11 domains where only electron transfer from ITIC to PC71BM is energetically favorable and thus feasible (Figure 8b). When the ratio of PC71BM is increased to 30 wt% versus ITIC, the chance is that the PC71BM phase can reach the interfaces of ITIC and PBBF11 (Figure 8c). In this scenario, electron transfer should occur not only for free charge carriers but also for interfacial CTS. In other words, the separation of charge carries would be maximized. Overaddition of PC71BM, however, would induce extra recombination pathways for the electrons in PC71BM and the holes in PBBF11 if they are encountered (Figure 8d).

Figure 7. a) TA kinetics (open dots) of the blends with various PC71BM weight ratios along with their global fitting (solid lines) of tri-exponential functions, b) SVD fitting of the TA spectrogram of optimal blend, c) schematics of the charge recombination pathways, and d) evolution of the amplitudes among three decay components in the blend samples.

3. Conclusions

In conclusion, we have designed and synthesized a terpolymer donor of PBBF11 which affords complementary absorption regions and small HOMO/LUMO offsets with ITIC NFA. Efficient electron and in particular hole transfer between them are verified by both PL and TA studies along with the small
$E_b$ of ITIC. Consequently, PBBF11:ITIC-based OSCs yield a high PCE of 10.02%. Severe charge recombination is however found and therefore we introduce a small amount of PC$_{71}$BM to optimize the blend film morphology and effectively extract the photogenerated electrons. At the optimal addition ratio of PC$_{71}$BM, the fullerene aggregates can connect both ITIC domains and PBBF11:ITIC interfaces in the blend, which ensures the swift separation of CTS and the efficient extraction of free electrons, thereby largely suppressing charge recombination. As a result, the optimized PBBF11:ITIC:PC$_{71}$BM (1:1:0.3, w/w/w) ternary OSCs achieved the best PCE of 11.4% with $V_{OC} = 0.92$ V, $J_{SC} = 19.17$ mA cm$^{-2}$, and FF = 64.65%. Therefore, this work not only fundamentally reveals the reasons why efficient hole transfer occurs under negligible HOMO offset in ITIC-based OSCs but also manifests the great promise of exploiting FA into NFAs-based OSCs.

**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.

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**Figure 8.** Schematics of charge transportation pathways in a) PBBF11:ITIC (1:1, wt%) binary, b) PBBF11:ITIC:PC$_{71}$BM (1:1:0.1, wt%) ternary, c) PBBF11:ITIC:PC$_{71}$BM (1:1:0.3, wt%) ternary, and d) PBBF11:ITIC:PC$_{71}$BM (1:1:0.5, wt%) ternary blends.

**Keywords**

charge recombination, film morphology, hole and electron transfer, nonfullerene acceptors, organic solar cells

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