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Excitation Wavelength Dependent Internal Quantum Efficiencies in a P3HT / Non-Fullerene Acceptor Solar Cell

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ABSTRACT

Solar cells based on blends of the donor polymer, P3HT, with the non-fullerene acceptor, O-IDTBR, have been shown to exhibit promising efficiencies and stabilities for low cost organic photovoltaic (OPV) devices. We focus herein on the charge separation and recombination dynamics in such devices. By employing selective wavelength excitations of P3HT and O-IDTBR, we show that photoexcitation of the P3HT results in lower internal quantum efficiency (IQE) for photocurrent generation than observed for photoexcitation of the O-IDTBR. Transient absorption and photoluminescence quenching studies indicate that this lower IQE results primarily from higher geminate recombination losses of photogenerated charges following P3HT excitation compared with O-IDTBR excitation, rather than from differences in exciton separation efficiency. These higher geminate recombination losses result not only in a lower photocurrent generation efficiency at short circuit, but also a lower device J-V fill factor upon selective excitation of the P3HT donor, when compared with O-IDTBR excitation.

INTRODUCTION

Non-fullerene acceptors (NFAs) are increasingly attracting attention for organic photovoltaic (OPV) applications due to their readily tunable energetics and absorption properties, low cost syntheses, promising device efficiencies and stabilities.¹⁻⁴ These

acceptors have been demonstrated in many cases to achieve better device performance than fullerene based acceptors such as PCBM, which have dominated the field until very recently. This performance enhancement is primarily due to the higher-lying LUMO levels that are available from these new, easily tailored non-fullerene acceptors, resulting in increased output voltages compared to fullerene-based devices. However, attaining higher photocurrent generation with such NFAs has proven more challenging, despite these acceptors often exhibiting stronger and broader visible light absorption than PCBM. In this study, we focus on one polymer/NFA blend that offers great promise for low-cost OPV technologies, namely the industry standard donor polymer, P3HT, with the rhodanine based acceptor, O-IDTBR (see Figure 1 for structure). We have previously reported that OPV devices based on this binary blend yield device efficiencies of 6.4%,⁵ as well as promising stabilities, and ternary devices offer efficiencies of up to 7.8% when a second NFA is added to the blend.⁶ The main reason for the improved device performance achieved with P3HT:O-IDTBR compared to the analogous fullerene-based device is its higher device voltage, with photocurrent generation quantum efficiencies being relatively modest at circa 55%. Herein, we address the origin of this modest photocurrent generation efficiency in these blends and find that photocurrent is primarily limited by geminate recombination losses, with these losses being most severe upon excitation of the P3HT, rather than O-IDTBR excitation.

The geminate recombination losses discussed herein refer to the monomolecular recombination of charges following exciton separation at polymer/acceptor interfaces. This recombination typically derives from coulombically bound polaron pairs localized at the interface, and primarily impacts the device J_{SC} . It is distinct from the non-geminate recombination of dissociated charges, which accelerates at high charge densities and is a key

loss pathway under open circuit conditions. Several studies have addressed the factors determining the magnitude of geminate recombination losses in OPV devices, including blend nanomorphology and domain formation,⁷⁻⁹ energy offset differences (ΔE_{CS}),^{10,11} dipole moment,¹² and dielectric constant.^{13,14} Such studies, to date, have focused on geminate recombination losses following donor photoexcitation and photoinduced electron transfer from the donor to the acceptor. In the P3HT/O-IDTBR blend studied herein, the donor and acceptor absorptions are complementary and distinct (O-IDTBR absorption is red-shifted relative to P3HT absorption), with each contributing significantly to photocurrent generation. This allows for selective excitation of either the donor or acceptor in transient kinetic studies and thus evaluation of geminate recombination losses following either donor or acceptor excitation in the same blend. To the best of our knowledge, an analysis of this phenomenon has not been reported before, despite the importance to OPV device performance in blends comprising donor and acceptor materials which both exhibit strong visible absorption.

EXPERIMENTAL METHODS

Materials

O-IDTBR acceptor was synthesized according to the previous procedure reported.⁵ P3HT was obtained from Flexink Ltd. All solvents used are from Sigma Aldrich.

Device fabrication, J-V characteristics and EQE measurements

OPV devices were fabricated in an inverted architecture (glass/ITO/ZnO/P3HT:O-IDTBR/MoO₃/Ag). ITO substrates were used as received and cleaned by sonicating in

detergent, deionized water, acetone and isopropanol. The substrates were then treated with oxygen plasma and layers of ZnO were deposited using a zinc acetate dihydrate precursor solution (60 μL monoethanolamine in 2 mL 2-methoxyethanol), which was spin-coated followed by annealing at 150 $^{\circ}\text{C}$ for 10–15 min, resulting in a thickness of around 30 nm. P3HT:O-IDTBR (1:1) solutions were prepared in chlorobenzene (24 mg mL^{-1}) and left stirring overnight before spin coating at 2,000 r.p.m. on the substrates, followed by thermal annealing at 130 $^{\circ}\text{C}$ for 10 min. The active layer thickness was around 80 nm, with a rms roughness of 15 nm (see Figure S7). MoO_3 (10 nm) and Ag (100 nm) electrode layers were deposited by thermal evaporation through a shadow mask yielding device active areas of 0.045 cm^2 . J-V characteristics were measured using a Xenon lamp at AM1.5 solar illumination (Oriel Instruments) calibrated to a silicon reference cell with a Keithley 2400 source meter. External quantum efficiency (EQE) was measured using a 100 W tungsten halogen lamp (Bentham IL1 with Bentham 605 stabilized current power supply) coupled to a monochromator and a stepping motor controlled by software. The incident illumination was calibrated using a UV-enhanced silicon photodiode for spectral mismatch correction before devices were tested. A 590-nm long-pass glass filter was used to block irradiation as a result of second-order diffraction. Measurement duration for a given wavelength was sufficient to ensure the current had stabilized.

Film Preparation

The same recipe for the active layer (P3HT:O-IDTBR) was used as mentioned in the device fabrication section. The solution was deposited onto acetone-cleaned glass substrates by spin coating and kept in an N_2 atmosphere.

Steady-state UV-Visible and Photoluminescence (PL) spectroscopy

UV-Vis absorption spectroscopic measurements were performed to obtain UV-visible spectra from 200 to 1400nm using a UV-2600 Shimadzu UV-Vis spectrophotometer with an integrating sphere attached. Transmission and diffuse reflectance measurements were taken on the samples.

Steady-state photoluminescence measurements were carried out employing excitation wavelength of 500 nm and 680 nm on neat P3HT and O-IDTBR blend films with a Fluorolog FM-32 spectrofluorometer using a visible detector. The signals were corrected for absorbance at the excitation wavelength.

Ultra-fast transient absorption spectroscopy (fs-TAS)

Ultrafast transient absorption spectroscopy measurements were carried out with a commercial setup that comprises of a 1 kHz Solstice (Newport Corporation) Ti:sapphire regenerative amplifier with 800 nm, 90 fs pulses. The output of this laser was split to generate the pump and probe pulses. The tunable pump pulse was generated in a TOPAS-Prime (Light conversion) optical parametric amplifier and used to excite the samples with excitation wavelengths of 500 nm and 680nm and densities between 1 and 15 $\mu\text{J cm}^{-2}$. The probe light was used to generate a near-IR continuum (900-1450 nm) in a sapphire crystal. A HELIOS transient absorption spectrometer (Ultrafast Systems) was used for collecting transient absorption spectra and decays up to 6 ns. The time resolution of this set-up was 200 fs. The samples were kept at all time under a nitrogen atmosphere. Blend TA spectra obtained were deconvoluted by fitting the spectra of P3HT exciton (S_{exciton}), O-IDTBR exciton (S_{exciton}) and polaron (P_{polaron}) using:

$$\Delta OD = D * S_{exciton}(1260\text{ nm}) + A * S_{exciton}(1120\text{ nm}) + P * P_{polaron}(950\text{ nm})$$

where D, A and P are linear coefficients of donor exciton, acceptor exciton and polaron respectively in a blend spectrum.

Excitation spectra

Excitation spectra were acquired with a spectrofluorometer (Horiba Fluoromax-4) equipped with a broadband pulsed UV xenon lamp and Horiba R928P photomultiplier tube. Measurements were taken by probing at 850 nm, which is the limit of the detector. Although there is emission from P3HT and also O-IDTBR at this probing wavelength, the emission from P3HT emission is negligible compared with that from O-IDTBR. Fluorescence resonance energy transfer (FRET) was calculated by comparing the magnitudes of excitation spectrum and absorption at 450 nm after both the spectra are normalized at the maximum amplitude (730 nm). This is mainly because that at this wavelength, the contribution of P3HT is insignificant, we can deduce that any amplitude arises at this wavelength is due to the contribution from O-IDTBR direct excitation. In addition, we show that the excitation and 1-T spectra for non-annealed O-IDTBR film are very similar and can be used to compare the results (Figure S6). Given all the reasons mentioned above, the FRET equation is modified to suit this study.

$$\begin{aligned}
 FRET(\%) &= \frac{k_{ET}}{k_f + k_{ET} + \sum k_i} = \frac{I_{ET}}{I_f + I_{ET} + \sum I_i} = \frac{I_{ET}}{I_{non-radiative}} \quad (\text{for OPV systems}) \\
 &= \frac{\text{Excitation Intensity probed at } 850 \text{ nm}_{blend} - \text{Excitation Intensity probed at } 850 \text{ nm}_{acceptor}}{PLQE \times \text{Excitation Intensity}_{donor}} \\
 &= \frac{\text{Excitation Amplitude at } 450 \text{ nm}_{blend} - \text{Excitation Amplitude at } 450 \text{ nm}_{acceptor}}{PLQE \times \text{Excitation Amplitude at } 450 \text{ nm}_{donor}} \\
 &= \frac{\text{Exc. Amp. at } 450 \text{ nm}_{blend} / \text{Exc. Amp. at } 730 \text{ nm}_{blend} - \text{Exc. Amp. at } 450 \text{ nm}_{acceptor} / \text{Exc. Amp. at } 730 \text{ nm}_{acceptor}}{PLQE \times \text{Exc. Amp. at } 450 \text{ nm}_{donor} / \text{Exc. Amp. at } 730 \text{ nm}_{donor}} \\
 &= \frac{\text{Exc. Amp. at } 450 \text{ nm}_{blend} / \text{Exc. Amp. at } 730 \text{ nm}_{blend} - 1 - T \text{ at } 450 \text{ nm}_{acceptor} / 1 - T \text{ at } 730 \text{ nm}_{acceptor}}{PLQE \times 1 - T \text{ at } 450 \text{ nm}_{donor} / 1 - T \text{ at } 730 \text{ nm}_{donor}}
 \end{aligned}$$

Ellipsometry

P3HT:O-IDTBR solutions were spin coated onto silicon wafers which were coated with 25 nm SiO₂. The J.A. Woollam M2000 ellipsometer was used to collect the raw ψ and Δ values that describe polarization change over the visible range. The n and k values were obtained using Complete EASE software. Models were developed and fitted to the ψ and Δ data until a suitable fit was found, indicated by a mean squared error (MSE) value <2.

RESULTS AND DISCUSSION

The study herein employs O-IDTBR as the acceptor (See Figure 1a for chemical structure and 1b for depiction of frontier molecular orbitals) and P3HT as the donor, blended in a 1:1 ratio. Upon thermal annealing for of 10 min, the peak absorption of this molecule in the visible region is red-shifted by about 20 nm. This O-IDTBR molecule has LUMO and HOMO energy levels of -3.88 eV and -5.51 eV respectively, calculated from a combination of cyclic

voltammetry and optical band gap measurements. In this study, we focus on a comparison of the exciton and charge dynamics following either donor or acceptor photoexcitation and infer that the observed differences are primarily related to differences in film nanomorphology.

Figure 1. a) Chemical structure and b) the illustration of LUMO and HOMO energy levels⁵ of donor P3HT and acceptor O-IDTBR molecule; c) J-V curves of O-IDTBR blend device in the architecture glass/ITO/ZnO/O-IDTBR:P3HT/MoO₃/Ag.

Figure 1c illustrates the photovoltaic device performance for the devices studied herein. The same device architecture of glass/ITO/ZnO/P3HT:O-IDTBR/MoO₃/Ag and conditions (post annealing of 130 °C for 10 min) were adopted as described previously,⁵ resulting in a short circuit current (J_{sc}) of 14.1 mAcm⁻², open circuit voltage (V_{oc}) of 0.73 V, fill factor (FF) of 62% and overall power conversion efficiency (PCE) of 6.4% for the P3HT:O-IDTBR blend under simulated one sun irradiation (AM1.5G).

Figure 2. a) EQE and IQE (calculated from $\text{IQE} = \text{EQE} / (1 - \text{reflectance} - \text{parasitic absorption})$) of P3HT:O-IDTBR devices, b) normalized absorbance of P3HT, O-IDTBR and P3HT:O-IDTBR, c) photoluminescence spectra of neat P3HT and P3HT:O-IDTBR blend exciting mainly at P3HT (500 nm) and d) FRET from P3HT to O-IDTBR in blend calculated by comparing normalized 1-T spectra of neat O-IDTBR and neat P3HT films (inset) with normalized excitation spectrum of P3HT:O-IDTBR blend film, probed at the emission of O-IDTBR (850 nm) in the blend (see Experimental Methods for details).

The external quantum efficiency (EQE) spectrum of P3HT:O-IDTBR devices is plotted in Figure 2a, overlaid on the IQE spectrum which is determined from the $\text{IQE} = \text{EQE} / (1 -$

reflectance – parasitic absorption) where reflectance and parasitic absorption are calculated using n and k values obtained from ellipsometry (see Figure S5 and Experimental Methods for more details). The EQE spectrum is relatively flat across the visible range, with values between 54–58%. The IQE spectrum, on the other hand, shows a pronounced dip between 450 and 500 nm (the lowest IQE of 54% at 460 nm), where P3HT absorbs mainly (refer to the neat material absorption in Figure 2b), and the highest IQE of 74% at 690 nm in the region of O-IDTBR absorption. In contrast, by comparing the absorption spectra of the neat materials with the blend shown in Figure 2b, the absorbance is higher for the region in which P3HT absorbs significantly (500 nm) in comparison to the region where O-IDTBR absorbs (680 nm). This suggests that P3HT has a higher absorption coefficient compared with O-IDTBR in the blend film. We note that the ratio between donor and acceptor is 1:1 in the blend and attempts to enhance the acceptor light absorption by either increasing the O-IDTBR composition in the blend or increasing the blend thickness resulted in lower device efficiencies. The IQE and absorption data suggest that the material absorption properties are not the reason for their respective IQEs. Instead, the IQE spectrum strongly suggests that P3HT excitons are less efficient at generating photocurrent, when compared with O-IDTBR excitons. This is particularly surprising given that P3HT excitons have higher energies than O-IDTBR excitons, which corresponds to a blend LUMO-LUMO offset of ~ 0.7 eV (driving P3HT exciton separation) being almost twice as large as the HOMO-HOMO offset of 0.4 eV (driving O-IDTBR exciton separation).

We focus now on understanding the difference in the IQEs between P3HT and O-IDTBR upon photo-excitation, employing photoluminescence quenching efficiency (PLQE) and transient absorption spectroscopy (TAS) with excitation wavelengths of 500 nm and 680

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3 nm, corresponding to P3HT and O-IDTBR excitations respectively. The P3HT:O-IDTBR blend
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5 exhibited reasonably efficient PLQE for excitation of either material, 85% for P3HT
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7 excitation at 500 nm and 83% for O-IDTBR excitation at 680 nm (see Figure 2c and S1a
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9 respectively), indicating similar efficiencies for exciton separation in both cases.
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12 We note that the PL spectrum of P3HT overlaps strongly with the absorption spectrum of
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14 O-IDTBR, (see Figure S1b), opening up the potential for energy transfer from P3HT to O-
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16 IDTBR. This possibility was investigated by determining PL excitation spectra, monitoring
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18 O-IDTBR emission at 850 nm. A significant O-IDTBR emission was observed following P3HT
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20 excitation (Figures 2d). From these data, the quantum efficiency for resonant energy transfer
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22 from P3HT to O-IDTBR was estimated to be ~9% in the blend (refer to Experimental
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24 Methods for details).
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Figure 3. TA spectra of a) neat P3HT and b) P3HT:O-IDTBR blend exciting at 500 nm (P3HT region) with a density of $1 \mu J cm^{-2}$ in an N_2 atmosphere; c) the deconvoluted rise and decay dynamics of polarons generated from P3HT and O-IDTBR excitons (500 nm and 680 nm excitations respectively) in P3HT:O-IDTBR blend.

We turn now to transient absorption studies of the exciton and polaron kinetics in the blend, employing ultrafast transient absorption (TA) spectroscopy. The measurements again used selective excitation of either P3HT at 500 nm or O-IDTBR at 680 nm, probing photoinduced absorption signals in the near-infrared on timescales from 300 fs to 6 ns. Figure 3a and 3b show TA spectra employing 500 nm pulses to excite either neat P3HT

(Figure 3a) or P3HT:O-IDTBR (Figure 3b). Further data, including TA spectra for neat O-IDTBR films, are shown in Figure S2. The neat P3HT sample exhibits only P3HT exciton absorption, with a maximum at 1300 nm.¹³ This signal, employing the lowest excitation density of the instrument ($1 \mu\text{J cm}^{-2}$), decays to near zero with a time constant of 63 ps and can be assigned to exciton decay to ground, with only a very weak residual absorbance being observed, which is assigned to a low yield of P3HT polarons.^{9,15,16} In the blend film (Figure 3b), the initial P3HT exciton absorbance rapidly evolves into a new photoinduced absorption feature at 1000 nm which is assigned to P3HT polaron absorption, indicative of photoinduced charge separation. We note that at the excitation wavelength of 500 nm, while the majority of excitation is from the P3HT (about 80%), there is about 20% O-IDTBR excitons (excluding energy transfer from P3HT to O-IDTBR) at the probe wavelength of around 1150 nm. This can be understood with reference to the absorption spectrum in Figure 2b and TA peak of neat O-IDTBR films, employing an excitation wavelength of 680 nm to solely excite O-IDTBR in Figure S2.

A deconvolution method was used as described in the Experimental Methods to separate the kinetics of P3HT and O-IDTBR excitons, and P3HT polarons, following our previous study.⁵ Figure 3c shows the deconvoluted polaron signals in the blend following P3HT and O-IDTBR excitations at picosecond timescales. The rise of the polaron signal data while exciting at 500 nm is fitted with double exponentials because of the different lifetimes of P3HT and O-IDTBR excitons. Owing to the rapid decay of excitons faster than the instrument response (~ 100 fs), the corresponding rise of polarons from the excitons is similarly rapid as shown in Figure 3c. This is apparent from the TA spectra of the blend, of which the exciton signal is six times lower than that of the neat spectra at the same timescale and excitation

density ($1 \mu\text{J cm}^{-2}$) (Figure 3a and 3b). We assign the residual exciton signal, which is apparent at these timescales, to the slow phase of P3HT and O-IDTBR exciton separation (Figure 3a and 3b). The different rates of decay have been shown in a previous study wherein the rate of exciton decay was observed to depend on the regio-regularity of P3HT used.¹⁷ In this regard, we note that the regio-regularity of the P3HT we employ herein is the same as published before.⁵ The rise of the fast phase of the polaron generated from O-IDTBR excitons is also limited by the instrument response, however, this accounts only for about 20% of the polaron rise. The rise of the slow phase (the remaining $\sim 80\%$) has a half-life of around 2.6 ps. By comparing the amplitude of exciton absorption between neat and blend films (refer to Figure 3a, 3b and S2), P3HT exciton quenching efficiency calculated at 1250 nm is 87% and O-IDTBR exciton quenching efficiency at 1120 nm is 84%, both of which are similar to the PLQEs following P3HT and O-IDTBR excitations respectively. Both TAS and PL data suggest a rather highly intermixed donor/acceptor blend, which in turns allows a faster exciton separation.

We then compare the decay of polarons generated from the excitons of P3HT and O-IDTBR in the blend (Figure 3c). These decays, apparent on the timescale studied (up to 6 ns), are fitted with a single exponential lifetime. Polarons generated from P3HT excitons exhibit a decay lifetime of around 700 ps in the blend, which is shorter than the polaron decay time of ~ 10 ns apparent from O-IDTBR excitons. This difference of an order of magnitude between the decay times of polarons generated from P3HT and O-IDTBR excitons (700 ps and 10 ns, respectively) indicates that the charges generated from P3HT excitons recombine faster than those of generated by the acceptor excitation.

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3 The decays of polarons generated from the excitons of P3HT and O-IDTBR, following an
4 excitation density dependence study (refer Figure S3), show that they are excitation density
5 independent, suggesting a geminate recombination (a loss pathway from forming fully
6 separated charges for efficient photocurrent generation) of polarons upon exciting either
7 P3HT or O-IDTBR. These geminate losses have been observed in blends with another small
8 molecule acceptor FBR (Figure S4) which was previously reported to have a lower
9 photocurrent compared with PCBM and form a highly intermixed blend with P3HT.¹⁸
10 Analogous geminate recombination losses have also been reported for blends of un-
11 annealed P3HT:PCBM, with these losses being suppressed by annealing, correlated with
12 increased blend crystallinity.¹⁹ The slower lifetime (10 ns) for geminate recombination of
13 charges generated from O-IDTBR excitons correlates well to the higher IQE (73%) compared
14 with P3HT excitation (lifetime of 700 ps and IQE of 64%) in the blend.
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Figure 4. J-V curves of P3HT:O-IDTBR blend device measured using band pass filters exciting at P3HT (520 nm) and O-IDTBR (670 nm) regions.

Figure 4 shows normalized J-V curves of P3HT:O-IDTBR device measured using band pass filters of 520 nm and 670 nm, focusing on either the donor or acceptor respectively. This simple method directly measures the photocurrent generation and FF that results from exciting either P3HT or O-IDTBR. We observe that superior device short circuit photocurrent is achieved upon the excitation of O-IDTBR in comparison to the excitation of P3HT in the blend device (J_{sc} of 0.50 and 0.42 mAcm^{-2} respectively). The difference in the photocurrent generation exciting at P3HT and O-IDTBR is consistent with the difference in IQEs as well as

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3 in the lifetimes of polaron decay in the blend, and is indicative of field dependent geminate
4 recombination losses being most pronounced following P3HT excitation.
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8 Considering all of the above results, we deduce that the reason for the lower photocurrent
9 in O-IDTBR blend devices, compared to fullerene-based devices, is related to the dip in the
10 P3HT region of the IQE spectrum. The relatively strong absorption strength of P3HT and
11 rather high PLQE of P3HT:O-IDTBR blend indicates that this dip is not caused by a low rate
12 of exciton dissociation. Furthermore, the fast polaron generation from P3HT excitons, as
13 observed by TAS measurements, demonstrates that the highly efficient exciton quenching is
14 because of a fast exciton dissociation process (as well as some resonant energy transfer to
15 O-IDTBR). However, even with an efficient charge generation process, our data clearly shows
16 that there are higher geminate losses upon selective excitation of P3HT. These losses are
17 shown to impact not only the photocurrent generation but also the FF of the devices where
18 more geminate losses result in lower photocurrent generation and FF. Since the LUMO-
19 LUMO offset in this system is almost twice the magnitude of the HOMO-HOMO offset, this
20 difference is unlikely to be linked to an insufficient driving force for charge separation.
21 Rather, we propose that the lower IQE in the P3HT region of the IQE spectrum originates
22 predominantly from morphology effects, most probably associated with some molecular
23 mixing in P3HT-rich domains.
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47 CONCLUSIONS

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52 In summary, although P3HT:O-IDTBR devices are more efficient than fullerene-based
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only around 60% using this donor. While PLQE experiments have shown that there is an efficient exciton separation in both donor and acceptor in this blend, TAS measurements show that the efficient exciton quenching is due to the fast exciton decay or polaron generation. The lower photocurrent and FF obtained from selectively exciting at P3HT is due to the higher geminate losses of polarons in this blend compared with exciting at O-IDTBR (the decay of polarons from O-IDTBR excitons is also assigned to the same monomolecular type of recombination). This, in turn, results in poorer device performance when selectively exciting P3HT compared with that following selective excitation of O-IDTBR. As far as we know, this is the first time that distinct, field dependent geminate losses have been observed following either donor or acceptor excitation. The difference in geminate losses results in differences in IQE and FF, depending upon donor or acceptor excitation. We recently observed a suppression of geminate recombination leading to almost 90% IQE for another IDTBR blend device.²⁰ These results provide further evidence of the importance of geminate recombination losses in determining the performance of organic solar cells employing non-fullerene acceptors, and how these losses can differ depending upon donor or acceptor excitation.

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SUPPORTING INFORMATION

The Supporting Information contains PL spectra of neat O-IDTBR, P3HT and O-IDTBR:P3HT blend; normalized 1-T spectra of O-IDTBR; TA spectra of O-IDTBR neat films; TA kinetics of P3HT:O-IDTBR blend films; normalized optical density difference of an excitation density dependence study of FBR:P3HT blend films. Reflectance and parasitic absorption of a P3HT:O-IDTBR device; and 1-T and excitation spectra of O-IDTBR film.

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