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Introduction

Organic photovoltaics (OPVs) are under development as a potential source of low-cost solar energy capable of being fabricated on flexible, lightweight substrates. The efficiency of these devices has increased considerably in the past several years,^{1,2} but further increases in efficiency, as well as improvements to device lifetime and manufacturing costs, will aid in bringing this technology to market.^{3–5} A primary strategy for increasing efficiency is the design of novel semiconductors that have specific, desirable optoelectronic and morphological properties.^{6–9}

Tetrabenzoporphyrin (BP) has been used as a donor material to achieve power conversion efficiencies (PCEs) of 5% in OPV devices with a three-layer p–i–n device structure.¹⁰ In order to expand on this class of materials, various metal-centered tetrabenzoporphyrins have been synthesized, including those with

Effect of copper metalation of tetrabenzoporphyrin donor material on organic solar cell performance†

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The effects of copper metalation of tetrabenzoporphyrin on the properties and performance of organic solar cells are studied. Tetrabenzoporphyrin (BP) and copper tetrabenzoporphyrin (CuBP) are both solution processed from soluble precursor materials and thermally converted in the thin film. Despite high field-effect hole mobility above $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, the power conversion efficiency (PCE) of solar cell devices with CuBP is severely diminished compared to those with BP. Conducting atomic force microscopy (c-AFM) is used to show that CuBP films are highly conductive in the direction perpendicular to the substrate, relative to those comprising BP. By analyzing the donor absorption characteristics as well as the external quantum efficiency and short-circuit current density of bilayer OPV devices as a function of donor layer thickness, it is determined that the differences in performance are likely due to a prohibitively short effective exciton diffusion length (L_D) in the metalated derivative. By modeling the external quantum efficiency of bilayer OPV devices, we are able to approximate this difference in effective L_D to be 15 nm for BP and 2 nm for CuBP.

copper, zinc, nickel and iron cores.¹¹ By incorporating a metal into the tetrabenzoporphyrin structure, the frontier energy levels may be modified, which can allow for tuning of the energy levels to optimize the open circuit voltage ($V_{\rm OC}$) and short-circuit current density ($J_{\rm SC}$).¹²⁻¹⁴ Additionally, it was found that the charge carrier mobility measured in field effect transistors (FETs) with metalated tetrabenzoporphyrin derivatives is relatively high, over 1 cm² V⁻¹ s^{-1,15,16} making metalated tetrabenzoporphyrins promising potential OPV materials.

Despite favorable electronic tunability and high charge carrier mobility, metalated tetrabenzoporphyrins perform very poorly in OPVs, both in bilayer and bulk heterojunction devices. While the metalated and non-metalated tetrabenzoporphyrins only differ in structure by several atoms, it has been shown that even single-atom substitution in organic semiconductors may broadly affect the morphological and optoelectronic properties that govern performance in devices.^{7,17-20}

The purpose of this work is to investigate the differences in optoelectronic properties between metalated and non-metalated tetrabenzoporphyrins that can lead to loss processes in the devices prepared from metalated derivatives. Among the tetrabenzoporphyrins synthesized, BP and CuBP have the starkest contrast in their respective OPV performance (as reported herein) and FET mobility,^{16,21,22} and so we focused on comparing these two materials. We designed a series of experiments to probe factors that limit the performance of devices comprising CuBP. Conducting atomic force microscopy (c-AFM) is used to characterize vertical charge transport and reveals high vertical conductivity in neat CuBP films relative to those

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comprising BP. Analysis of current density-voltage (I-V) characteristics provide further evidence that non-geminate recombination does not account for the difference in the performance of OPV devices. Likewise, UV-Vis spectroscopy and spectroscopic ellipsometry are used to demonstrate that the light absorption characteristics of both donor materials are similar. The two tetrabenzoporphyrin materials are further compared in bilayer OPVs with [6,6]-phenyl-C₆₁-butyric acid methyl ester (PCBM) as the electron acceptor, varying the donor layer thickness. Differences in the dependence of the external quantum efficiency (EQE) and J_{SC} on the donor film thickness for bilayer OPVs with the two different donors suggest a short effective exciton diffusion length $(L_{\rm D})$ in CuBP as the factor limiting solar cell performance. The EQE spectra of the bilayer OPV devices with both donors are then modeled to quantify the differences in effective $L_{\rm D}$ of the photoactive materials.

Results and discussion

The structures of BP and CuBP are shown in Fig. 1a. Both donor materials contain porphyrin cores with four fused benzene rings. Both BP and CuBP thin films are prepared by solution processing from a soluble precursor molecule, 1,4:8,11:15,18:22,25-tetraethano-29*H*,31*H*-tetrabenzo[*b*,*g*,*l*,*q*]porphyrin and [1,4,8,11,15, 18,22,25-octahydro-1,4:8,11:15,18:22,25-tetraethano-29H,31H-tetrabenzo[b,g,l,q]porphinato(2-)- $\kappa N^{29},\kappa N^{30},\kappa N^{31},\kappa N^{32}$]-copper(II) (CP and CuCP, respectively). The precursor film is annealed at temperatures between 180 °C and 210 °C in order to induce a retro Diels-Alder reaction, which produces gaseous leaving groups and four conjugated, fused benzene rings.10 The precursor materials are soluble, insulating, and amorphous but, once the conversion has taken place, the BP and CuBP films are insoluble in organic solvents, semiconducting, and



Fig. 1 (a) Chemical structures of BP and CuBP. (b) J-V curves and (c) device performance characteristics of bilayer OPVs with the architectures: ITO/PEDOT:PSS/BP/PCBM/Al and ITO/PEDOT:PSS/CuBP/PCBM/BCP/Al. Bilayer OPV devices with BP were prepared with and without the BCP layer and found to have equivalent J-V curves.

polycrystalline.^{16,23,24} These characteristics allow for facile solution processing of additional layers without dissolving of the underlying donor film, enabling fabrication of solution-processed bilayer OPV devices with a well-defined donor/acceptor interface. By examining bilayer OPVs, we can focus on the materials properties of the tetrabenzoporphyrins that result in widely different OPV performance without the additional complexity of a bulk heterojunction blend morphology.^{25,26}

The FET hole mobility (μ_h) of BP is roughly 0.1 cm² V⁻¹ s⁻¹ while that of CuBP is an order of magnitude higher, 1.3 ${\rm cm}^2\,{\rm V}^{-1}$ s^{-1} , as measured in our lab and by Mitsubishi Chemical Group Science and Technology Research Center (data not shown) and consistent with trends observed in the literature.16,21,22 As shown in Fig. 1b and c, the average PCE of bilayer OPV devices using BP is 2.6%, while that of devices using CuBP is only 0.3%. Specifically, comparing the bilayer OPV performance characteristics that determine PCE, the $V_{\rm OC}$ drops from 0.61 V to 0.38 V, the $J_{\rm SC}$ falls dramatically from -6.3 to -1.3 mA cm⁻², and the fill factor (FF) decreases slightly from 0.67 to 0.61 for devices with BP and CuBP, respectively. The lower V_{OC} of devices with CuBP is likely attributable to the relatively shallow HOMO level of -4.4 eV, compared to that of BP, -4.8 eV, as determined by ultraviolet photoelectron spectroscopy (UPS) (see Fig. S1, ESI⁺). The most significant difference in the performance of bilayer OPV devices with BP and CuBP is the J_{SC} , which decreases by roughly a factor of five. JSC in an OPV device can be curtailed by inefficient photon absorption,27 exciton decay to the ground state prior to reaching a donor/acceptor interface,28 geminate recombination of charge transfer states,29 or non-geminate recombination of charge carriers prior to sweep out.29,30

Several recent studies have found that charge transport limitations in OPV devices can lead to significant non-geminate recombination, thereby limiting the J_{SC} and FF.^{29,31–33} Thus, we begin by addressing non-geminate recombination and charge transport in these two OPV systems with BP and CuBP. Nongeminate recombination in a bilayer OPV device occurs primarily at the planar donor/acceptor interface and is thus mitigated in systems with suitably high charge carrier mobility.³⁰ While the FET mobility of CuBP is quite high, and an order of magnitude higher than that of BP, it is possible that the FET mobility does not reflect the charge transport characteristics during solar cell operation. FET mobility is measured in the plane of the substrate, while charge carriers in an OPV travel perpendicular to the substrate. In order to evaluate the charge transport of BP and CuBP in the vertical direction, we employ c-AFM, a technique that can be used to image the nanoscale morphology while simultaneously collecting a current image under an applied bias.34-36 In a c-AFM experiment, unlike FET measurements, the current can be measured in the direction perpendicular to the substrate, making it more applicable to a study of OPV devices. Additionally, unlike bulk space charge limited current (SCLC) measurements, which also probe vertical charge transport, c-AFM does not require very thick films; in fact, the same neat donor films used to make bilayer OPVs (${\sim}50$ nm thick) can be used for c-AFM measurements. Making neat films of crystalline small molecules several hundred nanometers thick in order to rigorously measure the SCLC mobility can

be challenging and results in a solid state morphology that is different from that of a thin film. While it is difficult to quantitatively measure the charge carrier mobility using c-AFM, it can be used to qualitatively compare the charge transport characteristics of different samples or different morphological features on the same sample.³⁵ For these reasons, c-AFM was found to be the most effective tool for comparing the charge transport characteristics of BP and CuBP.

Current images obtained by c-AFM of neat BP and CuBP films are shown in Fig. 2. Current images collected over large areas (covering 40 μ m \times 40 μ m) and corresponding topography images of both films are shown in the ESI (Fig. S2 and S3[†]). The average diameter of both topographic features and conductive domains is much larger for CuBP (14 \pm 10 μ m) compared to BP $(4 \pm 2 \mu m)$. The c-AFM current magnitude for both samples can differ significantly from domain to domain. For BP, the magnitude of the current generally depends on the shape of the topographic feature, with higher current in the flat, smooth domains and lower current in the rough domains, as has been described previously.35 For the neat CuBP films, there is less correlation between topographic feature shape and current: some rough domains have high current; some have low current. Grazing incidence wide-angle X-ray scattering (GIWAXS) images (Fig. S4[†]) indicate that both BP and CuBP films are crystalline, and that these crystallites lack a preferred orientation. The crystal structures reported for both BP and CuBP are also extremely similar.37,16 Thus, we do not see evidence of significant differences in the solid state order between the two materials, however, this does not rule out the possibility that contrasting morphologies may influence charge generation and exciton diffusion properties in these materials.

Most importantly, for the purposes of this study, the overall average current under the same applied bias of +0.01 V (relative to the substrate) is an order of magnitude higher for CuBP films (260 ± 100 pA) than for BP films (14 ± 7 pA) of very similar thicknesses. Note the scales of the color bars in the images as well as the current histogram on a log–log plot in Fig. 2c. The trend displayed here was repeated across several sets of samples and under different applied biases. The difference in magnitude between the current images of BP and CuBP films

This is further corroborated by the relatively high FF of both devices with BP and CuBP and the linear light intensity dependence of the J_{SC} (Fig. S5a†). The J_{SC} light dependence in particular suggests that bimolecular recombination is not a significant loss mechanism at least at short-circuit.³⁹ Interestingly, the light dependence of the V_{OC} indicates that both BP and CuBP devices exhibit a combination of bimolecular and trap assisted recombination (Fig. S5b†). However, a reduction in J_{SC} due to trap assisted recombination would likely be accompanied by a significant reduction in FF, which we do not observe.³⁸ The relatively high FF and the fact that BP also shows trapping behavior indicate that it is unlikely that the low J_{SC} of CuBP devices is primarily due to trap assisted recombination.

In order to further examine the origin of the low J_{SC} of bilayer OPVs with CuBP, the UV-Vis absorption of neat films and the EQE spectra of bilayer OPV devices are shown in Fig. 3. The spectral shapes and absorption intensities of films with 55 nm BP or CuBP are very similar, indicating that both materials have similar absorption coefficients and that the band gaps of the two donor materials are similar. Optical constants were also obtained from spectroscopic ellipsometry (data not shown), with very similar resulting spectra. Despite similar light absorption characteristics, the EQE in Fig. 3b shows that the conversion of incident photons to collected electrons is extremely inefficient precisely in the spectral region where CuBP absorption dominates (650-690 nm). Thus, photons are absorbed by CuBP, but are not efficiently converted to electrical current. There are several explanations for this inefficient exciton harvesting in the CuBP system. CuBP could have a short exciton diffusion length $(L_{\rm D})$, such that only a limited number of excitons are able to reach the donor/acceptor interface to generate charges.⁴⁰ Alternatively, the metal center of CuBP could facilitate intersystem crossing (ISC) to a triplet level of insufficient energy to separate across the donor/acceptor interface.14 Finally, devices with CuBP could be limited by



Fig. 2 Current images collected by c-AFM of neat BP (a) and CuBP (b) films on ITO/PEDOT:PSS substrates and histogram (c) of the current values in parts (a) and (b). Images were collected with a Au-coated probe, under an applied bias of +0.01 V relative to the substrate.



Fig. 3 UV-Vis absorption spectra of neat thin films (dashed) and EQE spectra of bilayer OPVs (solid) for films and devices with BP (a) and CuBP (b).

geminate recombination of charge transfer states at the donor/ acceptor interface.^{29,41}

We sought to elucidate which of the mechanisms described above is responsible for the low quantum efficiency of devices with CuBP by fabricating bilayer OPV devices with varying donor thicknesses of BP or CuBP, shown in Fig. 4. The plot of J_{SC} as a function of donor thickness for devices with BP resembles behavior that would be expected for an efficient bilayer OPV with adequate exciton diffusion length: as film thickness increases, more photons are absorbed and thus J_{SC} increases proportionally, peaking at -6.5 mA cm⁻² for a device with a BP layer thickness of 55 nm, after which the J_{SC} is somewhat saturated. Eventually, at very high BP thicknesses, the J_{SC} decreases, due, in part, to the absorption of photons in the part of the BP film farthest (more than an exciton diffusion length)



Fig. 4 J_{SC} from light J-V curves (colored lines with markers) and from integrated EQE spectra (black markers) as a function of donor layer thickness of bilayer OPVs with BP (red, circles) and CuBP (blue, squares) with the same device architecture as those shown in Fig. 1.

from the donor/acceptor interface attenuating the number of photons that can be absorbed closer (within an exciton diffusion length) to the donor/acceptor interface.⁴² For OPVs with CuBP of varying thicknesses, the $J_{\rm SC}$ is very low and does not increase with increasing film thickness, never exceeding -1.6 mA cm⁻², and eventually decreasing further, likely due to the same "filter effect" described for the BP devices. Bilayer OPV devices with thinner CuBP films than those shown in Fig. 4 were also fabricated in order to observe the thickness-limited $J_{\rm SC}$ behavior in CuBP devices, however, below approximately 15 nm the crystallization behavior of CuBP changes significantly. Thus, while the data agree with our analysis, data from extremely thin films would not be a valid comparison to the data we report, due to this difference in morphology.

If a device is limited by a very short $L_{\rm D}$ of the donor material, one would expect to see a J_{SC} that is independent of donor film thickness, because only photons absorbed within the $L_{\rm D}$ of the photoactive materials could contribute to photocurrent. This trend would also be consistent with the formation of low energy triplets with insufficient energy to split across the donor/ acceptor interface. Low photoluminescence (PL) quantum yield renders it challenging to directly measure the triplet energy in CuBP films, however, there is some indication from low temperature PL measurements (data not shown) of a triplet energy at roughly -3.1 eV, which should have a sufficient energy offset with the LUMO of PCBM (-3.7 eV) to allow charge separation. Finally, if charge transfer state recombination limited device performance, the J_{SC} would once again be low but would increase with increasing donor thickness as the exciton density at the donor/acceptor interface is increased. In other words, the probability of CT state recombination would likely be relatively constant with respect to donor layer thickness, but because more excitons reach the donor/acceptor interface, more separated charges would be generated.29 Thus, the most likely explanation for the low J_{SC} and, in turn, PCE of bilayer OPVs with CuBP is a short L_D of CuBP.

Next, we calculated the $L_{\rm D}$ of the photoactive materials in these two systems. The $L_{\rm D}$ of organic semiconducting materials has been probed by a number of techniques, many of which rely on measurement of the photoluminescence of the material of interest.43,44 Very low photoluminescence quantum yield in both BP and CuBP films prevents us from using these quenching techniques, however, we were able to calculate the effective $L_{\rm D}$ of both materials by modeling the EQE spectra of bilayer OPVs. The model, introduced by Pettersson et al.,40,45 uses the complex indices of refraction and the layer thicknesses determined by spectroscopic ellipsometry, implemented with a transfer matrix approach,46 to calculate the internal optical electric field within the device, from which the exciton generation rate is determined. The exciton diffusion lengths of the semiconducting materials are then varied in order to fit the experimental EQE spectrum. Importantly, because $L_{\rm D}$ is extracted from bilayer device quantum efficiency spectra, the obtained $L_{\rm D}$ is an effective value rather than an intrinsic property of the materials. Exciton traps arising from an inhomogeneous energetic landscape in the photoactive materials and ISC to a low energy triplet state with insufficient energy to donate electrons to

PCBM would not be differentiated from L_D with this model. The model also assumes efficient charge separation at the donor/ acceptor interface, which has not been conclusively determined for bilayer OPVs with CuBP but is suggested by the independence of the J_{SC} on donor film thickness in Fig. 4. Additionally, the donor/acceptor interface is taken to be flat, however, in this system, the surfaces of neat donor films (and thus the donor/ acceptor interfaces) are somewhat textured, as measured by AFM (Fig. S3^{\dagger}), which could result in overestimation of $L_{\rm D}$. For neat BP and CuBP films, the root mean square roughness values are similar, thus relative differences in the $L_{\rm D}$ calculated by this technique can be compared. The experimental and simulated EQE spectra are shown in Fig. 5. An effective $L_{\rm D}$ of 14.6 \pm 2.2 nm for BP and 5.5 \pm 1.1 nm for PCBM were calculated. The $\mathit{L}_{\rm D}$ of PCBM calculated here is consistent with other reports.⁴⁰ The $L_{\rm D}$ of BP compares favorably to other high performing electron donating materials.14,40,47 For the bilayer OPV with CuBP, we calculate an effective $L_{\rm D}$ of 2.0 \pm 0.7 nm for CuBP and 4.3 \pm 1.5 nm for PCBM. Notably, the extracted $L_{\rm D}$ of PCBM is consistent between the BP and CuBP devices as would be expected. The effective $L_{\rm D}$ of CuBP is very short relative to that of BP, in agreement with the thickness dependent J_{SC} behavior exhibited by bilayer OPVs with both materials. These results further suggest that the metal center of CuBP limits the effective $L_{\rm D}$, leading to poor OPV device performance.

Conclusion

We have studied the different optoelectronic and morphological characteristics of two electron donors that differ only by the presence or absence of a metalated core: BP and CuBP. The



Fig. 5 Experimental and calculated EQE spectra of bilayer OPVs with the device architecture ITO/PEDOT:PSS/BP/PCBM/Al (a) and ITO/PEDOT:PSS/CuBP/PCBM/BCP/Al (b).

charge transport properties in both the in plane and out of plane directions relative to the substrate are substantially higher in CuBP films compared to BP films, yet the performance of OPVs with CuBP is severely limited by low J_{SC} . While both tetrabenzoporphyrin materials have similar absorption profiles, the EQE of devices with CuBP is lowest in the spectral region where CuBP absorbs the most, indicating that CuBP absorbs photons but cannot efficiently convert them to free charge carriers. Further, we found that while increasing the thickness of BP films in bilayer OPV devices results in significant increases in J_{SC} up to thicknesses of ~55 nm, increasing the thickness of CuBP films in bilayer OPVs has no positive effect on the J_{SC} . This suggests that CuBP has a very short effective L_{D} . We modeled the EQE spectra of bilayer OPV devices with BP and CuBP in order to calculate the effective L_{D} , which we found to be 14.6 nm and 2.0 nm for BP and CuBP, respectively. Thus, a short effective $L_{\rm D}$ is likely the primary cause for the low photovoltaic performance of CuBP. Our study highlights the profound effect of few-atom changes to molecular structure on the materials properties and performance of OPVs. While structural modification can be used to realize a specific characteristic, it is likely to change more than one property. Thus, molecular design must be approached holistically, with care to identify unintended changes to material properties. Continuing to develop structure-property relationships for novel materials will strengthen the ability to anticipate the effects of molecular design on future OPV systems.

Experimental

Bilayer OPV devices

OPV devices were characterized by collecting current densityvoltage (*J*–*V*) curves in light and dark conditions and by measuring the external quantum efficiency (EQE) under a nitrogen atmosphere. *J*–*V* curves were measured using a Keithley 2602 source-measure unit, under solar simulation conditions of 100 mW cm⁻² AM 1.5G using a 300 W Xe arc lamp with an AM 1.5 global filter. The illumination intensity of the solar simulator was measured using a standard silicon photovoltaic diode with a protective KG1 filter calibrated by the National Renewable Energy Laboratory. EQE spectra measurements were done using a 75 W Xe arc lamp, monochromator, optical chopper (Newport Oriel Instruments), Stanford Research Systems lock-in amplifier, and a National Institute of Standards and Technology traceable silicon photodiode for monochromatic power-density calibration.

All materials were used as received. 1,4:8,11:15,18:22,25-Tetraethano-29*H*,31*H*-tetrabenzo[*b*,*g*,*l*,*q*]porphyrin (CP) and 1,4:8,11:15,18:22,25-tetraisobutano-29*H*,31*H* copper tetrabenzo [*b*,*g*,*l*,*q*]porphyrin (CuBP) were received from Mitsubishi Chemical Corporation and stored in a refrigerator. [6,6]-Phenyl-C₆₁-butyric acid methyl ester (PCBM) (99.5%) was purchased from Solenne and stored in a glovebox. ITO (~150 nm thick) coated patterned glass substrates were cleaned by scrubbing with soap and sonicating in D.I. water, acetone, and IPA for at least 15 min each. Cleaned substrates were blown dry with a nitrogen gun, oven-dried for 15 min, and cleaned by UV–O₃ for

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30 min. PEDOT:PSS (Clevios P VP Al 4083) was drop-filtered from a 0.45 µm PVDF filter atop the cleaned ITO-coated glass and spun at 2500 rpm to produce a 50 nm thick film, which was then annealed on a hotplate set at 120 °C for 10 min, transferred into a glovebox, and annealed for another 3 min at 180 °C. Unless otherwise noted, a 20 $\mbox{ mg}\ \mbox{mL}^{-1}$ solution of CP (the precursor to BP) or a 30 mg mL⁻¹ solution of CuCP (the precursor to CuBP) in 1:2 chloroform : chlorobenzene was batch-filtered using a 0.22 µm PTFE filter, spun at 1500 rpm, and subsequently annealed on a hotplate set to 180 °C for BP or 210 °C for CuBP for 20 min. For donor thickness dependent bilayer OPV devices, precursor solution concentrations ranged from 2 to 30 mg mL⁻¹, otherwise using the same processing conditions. Films were allowed to cool before casting PCBM. PCBM films were cast from 0.22 µm PTFE batch-filtered solutions of 12 mg mL⁻¹ PCBM in chlorobenzene at 1500 rpm. Where noted, a 3 nm thick layer of bathocuproine (BCP) was deposited in an Angstrom Engineering thermal evaporator at a pressure below 1×10^{-6} Torr at a rate of 0.2 Å s⁻¹ using an open mask that exposed most of the film surface. All bilayer OPVs were completed by evaporating a patterned top electrode of 100 nm Al evaporated at a pressure below 1×10^{-6} Torr at a rate of 0.3 Å s⁻¹ for the first 10 nm and then gradually increasing to 2.3 Å s^{-1} .

Conducting atomic force microscopy (c-AFM)

Topographic and current c-AFM images were collected on an Asylum MFP-3D AFM under a nitrogen atmosphere in contact mode using a conductive, Au-coated silicon probe with a resonant frequency of \sim 13 kHz and a force constant of \sim 0.2 N m⁻¹ (Budget Sensors).

Scan sizes of 20 \times 20 μ m collected at a rate of \sim 2 lines per second were used for this study. The device structure of ITO/PEDOT:PSS/donor/Au tip was used to selectively probe hole current through the donor film. After compensating for parasitic voltages and subtracting the baseline current, a bias of +0.01 V was applied. This corresponds to hole injection into the donor film from the ITO/PEDOT:PSS substrate.

Samples for c-AFM were prepared by following the procedure described above for bilayer OPVs with BP or CuBP, but omitting the procedure after the donor layer deposition and annealing (PCBM and top electrodes were not added).

Exciton diffusion length modelling

The external quantum efficiency was calculated by modeling the optical field in the bilayer OPVs using the indices of refraction of the materials from ellipsometry measurements. The exciton generation rate in each layer of the device was factored into fitting the computed EQE to the experimental EQE, using the effective exciton diffusion length of the donor material and the effective exciton diffusion length of the acceptor material as the two variables in the fitting process. The reported values are the average $L_{\rm D}$ and standard deviation across several samples of varying donor film thickness.

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