Comparison of Conventional and Inverted Organic Photovoltaic Devices with Controlled Illumination Area and Extraction Layers

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The impact of device architecture on organic photovoltaic device performance has been problematic to quantify due to extraction layer materials and device testing issues. In particular, published reports have used different pairs of hole and electron extraction layer materials for conventional versus inverted devices. The origins of the large apparent discrepancy in device J-V characteristics become difficult to understand, arising from differences in built-in potentials and in the extraction layers' conductivities that can affect collection of stray current outside of device

area. Here, we show that by using an identical pair of hole and electron extraction layers, and by precisely defining illuminated device area with a shadow mask, most of the differences in the performance of conventional and inverted P3HT:PCBM organic photovoltaic devices are eliminated. The remaining difference in short-circuit current density and EQE spectral shape can be explained primarily by the ratio of hole and electron mobility that leads to more efficient carrier extraction in the inverted devices, with a minor contribution from unintentional p-type doping of the active layer that influences the drift field profile.

1. Introduction

Organic photovoltaics (OPVs) have generated significant research interest over the past decade due to the promise of low-cost, lightweight renewable energy generation [1,2]. However, accurate measurements of the power conversion efficiency (PCE) of OPVs have been complicated by various factors, including spectral mismatch between light source and reference photodiode [3], stray current due to high conductivity transport layers [4-7], and unintentional absorption of reflected or scattered light [7-9]. The uncontrolled illumination and variation in ambient temperature and humidity can be minimized through the use of enclosed sample holders.[10-12] The device architecture itself may also affect PCE. Extraction layers (ELs) are often inserted between the active layer and the electrodes of OPVs to determine polarity and improve performance [13,14]. OPVs with conventional versus inverted architectures, where the holes collected by the front versus back electrode, have been shown to exhibit discrepancy in performance that have been attributed to vertical phase separation during active layer drying [15-17], mismatched electron and hole mobility in the active layer [18-21], resistive losses between different ELs and electrode [22], and unwanted absorption of incident light by the EL [23-25]. Furthermore, even direct experimental comparisons of conventional versus inverted OPVs utilize different pairs of ELs [20,22,23], due to the competing requirements of optical transparency, electrical conductivity, wettability, and chemical miscibility between subsequent layers, and mild deposition conditions to maintain active layer nanostructure. As a result, the two device architectures may also exhibit significant differences in e.g. built-in potential and EL conductivities, and the observed differences in J-V response may be a combination of active layer and EL effects. In this report, we present a quantitative experimental-computational study of the effect of device architecture on poly(3-hexylthiophene): [6,6]-phenyl-C61-butyric acid

methyl ester (P3HT:PCBM) OPV performance. In particular, we use, for the first time, an identical pair of transparent metal oxides as ELs for conventional and inverted devices, and combine them with a shadow mask to explicitly define illumination area, hence eliminating any discrepancy due to stray current [8]. While most device performance parameters become equal for the two architectures, differences beyond experimental uncertainties remain in short-circuit current density and the external quantum efficiency (EQE) spectra. After examining built-in potential and light absorption and performing drift-diffusion modeling with varying doping density and carrier mobility, we find that the observed discrepancy is primarily due to the ratio of hole and electron mobility that leads to more efficient carrier extraction in inverted devices, with a minor contribution from unintentional p-type doping of the active layer that affects the electric field profile inside the device.

2. Materials and Methods

OPVs fabrication. Conventional and inverted P3HT:PCBM OPVs were fabricated following published procedure [26] with modifications. All chemicals were used as received, and all processing was performed in a N₂ glove box (Innovative Technology) unless otherwise noted. For conventional devices, 10 nm MoO₃ (99.999% Alfa Aesar) was thermally evaporated (Angstrom Engineering) on patterned ITO on glass (20 $\Omega/\square$, Thin Film Devices) that has been cleaned with UV-ozone (ProCleaner Plus, BioForce) for 20 min to form the hole EL (HEL). P3HT (RMI-001E, Rieke) and PC₇₁BM (Solenne BV) were dissolved at 23:23 mg/mL in chlorobenzene (Aldrich) and spin coated at 1200 rpm to form 250 nm thick BHJ. A suspension of ZnO nanocrystals in n-butanol was synthesized [26] and spin coated at 4000 rpm twice to form the electron EL (EEL) on top of the active layer. The sample was then annealed in N₂ at 170 °C for 10 min. Finally, 100 nm Ag was thermally evaporated to complete the OPVs. For

inverted OPVs, ZnO nanocrystals and P3HT:PCBM were subsequently spin coated on patterned ITO at the previously noted conditions, and the sample was annealed in N₂ at 170 °C for 10 min.

10 nm MoO₃ and 100 nm Ag layers were thermally evaporated on to complete the OPVs. The electrode intersection area is 0.11 cm² (3.2 mm ITO x 3.6 mm Ag).

OPVs characterization. The light source was a class AAA solar simulator (Sun 3000, Abet Technologies) with AM1.5G filter, at intensity of 100 mW cm⁻² set using a calibrated Si photodiode with KG5 filter (RR_227 KG5, Abet Technologies). The sample holder was a modified anodized aluminum KF50 vacuum flange, as previously reported (Fig. 1a) [11]. The illumination area was further limited to 0.049 cm² by inserting a shadow mask consisting of a 150 µm thick stainless steel film with 0.25 cm diameter laser cut holes, inserted between the sample holder and the device. Two aperture geometries were tested: one with six apertures aligned to the six devices (“6 ap”, Fig. 1b), and one with only a single aperture aligned to one device at a time (“1 ap”, Fig. 1c). J-V measurements were performed in N₂ using a low-noise sourcemeter (2635A, Keithley) controlled by LabView (National Instruments). All data shown represent the average of at least six devices. External quantum efficiency (EQE) spectra was collected at room temperature under one-sun white-light bias using a homemade system [21]. Capacitance-voltage (C-V) measurements were carried out at room temperature in dark using a Zahner IM6 electrochemical workstation. Varying AC modulation frequency (10Hz to 1MHz) and DC bias (-1 to 0.5 V) were used, while the amplitude of AC modulation was fixed at 20 mV. Capacitance was directly calculated from the imaginary component of the complex impedance at 1 kHz assuming negligible inductance.

OPVs simulation. Simulation of carrier generation inside the active layer was calculated using the transfer matrix method (TMM) implemented in MATLAB (MathWorks) [27]. n , k , and thickness of each OPV layer (ITO, P3HT:PCBM, MoO₃, ZnO nanocrystal) on Si wafer were obtained from spectroscopic ellipsometry (M-2000DI, J. A. Woollam) data fitted to a built-in model (“B-Spline”). Optical absorption as a function of position within the P3HT:PCBM layer was calculated using a layer stack of ITO (140 nm)/MoO₃ (10 nm)/P3HT:PCBM (250 nm)/ZnO nanocrystals (30 nm)/Ag (100 nm) for conventional devices and ITO (140 nm)/ZnO nanocrystals (30 nm)/P3HT:PCBM (250 nm)/MoO₃ (10 nm)/Ag (100 nm) for inverted devices. A profile of generation rate versus position in active layer was calculated for each wavelength between 400 nm and 700 nm at 10 nm increments by integrating the absorption data with 100 mW cm^{-2} AM1.5G spectral intensity. 1-D drift-diffusion simulation of OPVs was performed using SCAPS [28] to calculate J-V curves and band diagrams of conventional and inverted devices, using total generation profiles calculated by TMM as input and assuming bimolecular recombination. Wavelength dependent generation profiles calculated by TMM were used to simulate EQE spectra.

3. Results and Discussion

Fig. 2 shows the J-V data of conventional and inverted OPVs under three illumination conditions: with no shadow mask, with 6 ap mask, and with 1 ap mask. The mask dimensions are ideal according to the recommendations from Gevorgyan and co-workers, who systematically studied the effect of shadow mask geometry on measured performance of OPVs and found that an opaque mask adjacent to the device, with a thickness of $< 0.4 \text{ mm}$ and aperture size at least $\sim 0.5 \text{ mm}$ smaller than electrode size, minimized the effect of solar simulator beam divergence and yielded high accuracy in measurement of OPV performance [8]. However, Gevorgyan and co-

workers only studied single apertures centered on individual devices, i.e. similar to our 1 ap mask. Because OPV sample typically contain multiple devices per substrate, the shadow mask would need to be repositioned between measurements of different devices, which significantly increase measurement time and complexity. Thus, we compare OPVs with 6 ap mask versus 1 ap mask to determine the impact, if any, on device parameters. We find that for conventional OPVs, a change from no mask (Fig. 2a, dotted) to 6 ap mask (Fig. 2a, dashed) decreases short circuit current density J_{sc} from 9.66 to 9.04 mA cm⁻², while increasing factor FF from 0.576 to 0.591 (Table 1). Further changing to 1 ap mask (Fig. 2a, solid) does not modify J_{sc} or FF. When the performance parameters are normalized to the no mask condition, we see that application of either 6 ap mask or 1 ap mask causes a 7% decrease in J_{sc} , compensated by a 3% increase in FF (Fig. 2b). For inverted devices, a change from no mask (Fig. 2c, dotted) to 6 ap mask (Fig. 2c, dashed) decreases J_{sc} from 10.99 to 10.11 mA cm⁻² and increases FF from 0.533 to 0.565 (Table 1). Unlike the conventional devices, changing to 1 ap mask (Fig. 2c, solid) further decreases J_{sc} to 9.69 mA cm⁻² and increases FF to 0.576 (Table 1), which represents a 12% decrease and 8% increase respectively compared to the no mask condition (Fig. 2d). A decrease in J_{sc} and increase in FF with more restrictive illumination conditions agree with suppressed collection of stray current arising from absorption outside the electrode overlapping region.

Despite using identical EL pair and illumination conditions (1 ap mask), a difference is still observed between conventional and inverted OPVs, particularly the 6% higher J_{sc} of the inverted devices (Table 1). When we integrate the EQE response with 100 mW cm⁻² AM1.5G spectral intensity, we find that the inverted OPV exhibits 5% higher J_{sc} compared to the conventional OPV, which is reasonable given that the EQE illumination spot is a focused beam with diameter of ~ 1 mm, most similar to 1 ap mask. In addition, when EQE spectra of conventional and

inverted OPVs are compared, the inverted OPV (Fig. 3a, red) displays higher EQE response between 450 nm and 600 nm compared to the conventional OPV (Fig. 3a, blue).

To understand this difference, we first examine the quasi-flat band potential V_{pos} for the devices, which corresponds to the voltage at which the photocurrent density $J_{\text{ph}} = J_{\text{light}} - J_{\text{dark}}$ contains an inflection point [29]. At V_{pos} , the majority of the active layer experiences zero electric field. Due to the significant band bending at the interface of electrodes and organic active layer, V_{pos} is a more accurate measure of the built-in potential across the active layer than the work function difference between the contacts or the voltage determined from Mott-Schottky analysis (Fig. 5a, arrow) [29]. When we plot dJ_{ph} / dV versus V and located the maximum (Fig. 3b), we find that V_{pos} is (0.55 ± 0.01) V for all devices independent of conventional or inverted architecture, consistent with the use of identical EL pair. Thus, a difference in built-in potential is not responsible for the difference in J_{sc} between conventional and inverted OPVs.

We then calculate the fractional absorption spectra for the P3HT:PCBM active layer using TMM (Fig. 4a), which shows that the conventional OPV exhibits the same general spectral shape compared to the inverted OPV, but with higher absorption between 400 and 600 nm, resulting in a 4% higher generation current in the conventional OPV when integrated with AM1.5G spectral intensity. In other words, absorption of light cannot explain the higher experimental J_{sc} or the enhanced EQE response between 450 nm and 600 nm for the inverted OPV. From the curves in Fig. 4a, we derive the normalized cumulative generation as a function of position in the active layer by adding generation rates up to the position and dividing by the total generation rate (Fig. 4b). It is clear that the majority of carriers are generated within 100 nm of the front electrode for both conventional and inverted OPVs.

To fully understand the effect of possible carrier loss during extraction on device performance, we perform drift-diffusion simulation of conventional and inverted OPVs using SCAPS, with the material parameters summarized in Table 2. To enable convergence of SCAPS simulation, the active layer/ZnO EEL interface is approximated as a metallic contact with hole recombination velocity of 1×10^{-5} cm/s. Where possible, the material parameters are measured in our laboratory. For example, we determine the acceptor dopant concentration N_A of the P3HT:PCBM active layer from C-V measurements. Since P3HT is a p-type semiconductor [30], the cathode forms a Schottky contact with the P3HT:PCBM BHJ and a corresponding depletion region. Therefore, N_A of the active layer can be determined from the bias dependent depletion layer capacitance [31,32]:

$$N_A = \frac{2}{q\epsilon A^2} \left(\frac{1}{d(C^{-2})/dV} \right) \quad (1)$$

where q is elemental charge, ϵ is dielectric permittivity, A is device area, C is capacitance, and V is applied bias. Fig. 5a illustrates the Mott-Schottky plot of a conventional OPV with capacitance measured at 1 kHz from impedance spectroscopy. A straight line is fitted between -0.5 V and 0.3 V, from which N_A of $7 \times 10^{15} \text{ cm}^{-3}$ is obtained. An inverted OPV gives similar results. J-V curves of hole-only devices and electron-only devices are used to extract mobilities [33]: we obtain a hole mobility μ_h of $5 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ and an electron mobility μ_e of $2 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (Supplemental Data, Fig. S1). Drift-diffusion simulation using these material parameters shows that the conventional and inverted OPVs exhibit similar V_{oc} and FF (Table 3), but the inverted device shows a 2% higher J_{sc} compared to the conventional device, in good agreement with the experimental data. We note again that the higher J_{sc} for inverted OPVs is unexpected, given that the inverted architecture fosters lower absorption of incident light according to TMM

calculations. Thus, drift-diffusion simulation clearly shows that photogenerated carriers in conventional OPV suffer greater recombination loss during extraction. In addition, the simulated EQE spectra for inverted OPV display higher response between 450 nm and 600 nm compared to conventional OPV (Fig. 5b), exhibiting the same trend as the experimental data.

Additional drift-diffusion simulations are performed to pinpoint the underlying cause for the differences in J_{sc} and EQE shape. It has been reported previously that high levels of p-type doping in the active layer can lead to asymmetric band bending such that the depletion is confined to the EEL/cathode [34-39], which can change the shape of the EQE spectra [38]. However, simulated band diagrams for conventional (Fig. 5c, blue) and inverted (Fig. 5c, red) OPVs at short circuit show that for $N_A = 7 \times 10^{15} \text{ cm}^{-3}$, the depletion region extends through the entire active layer, with drift field magnitude greater than $1 \times 10^4 \text{ V cm}^{-1}$ (Fig. 5d). We find that N_A must be increased to $4 \times 10^{16} \text{ cm}^{-3}$ for both conventional and inverted OPVs to exhibit asymmetric band bending similar to published results for OPVs with different donors [36,38,39], with a field-free region near the HEL and a high-field region near the EEL. Simulated J_{sc} values as a function of N_A (Fig. 6a) show that inverted device exhibit significantly higher J_{sc} ($> 20\%$) over conventional device only when $N_A \geq 4 \times 10^{16} \text{ cm}^{-3}$, i.e. above the asymmetric band bending threshold. This is consistent with the fact that the high field and high carrier generation regions overlap in inverted OPV but are offset in conventional OPV, resulting in higher carrier extraction efficiency in inverted OPV. On the low N_A range ($\leq 2 \times 10^{15} \text{ cm}^{-3}$), simulation shows that J_{sc} of conventional OPV is slightly higher than that of inverted OPV, as would be expected from the higher absorption of incident light (Fig. 4b); in this case, the potential drops uniformly as a function of distance from the HEL for both device architectures. At our experimental N_A value of $7 \times 10^{15} \text{ cm}^{-3}$ (line in Fig. 6a), while the p-type doping is insufficient to create a field-free region,

it does contribute to additional band bending near the EEL for both device architectures (Fig. 5c). As a result, the inverted OPV exhibits higher drift field magnitude within 100 nm of the front EL compared to the conventional OPV (Fig. 5d), and qualitatively explains the higher J_{sc} . Nevertheless, while band bending becomes asymmetric as N_A increases, the effect is small at our experimentally determined N_A value. We also varied bimolecular recombination coefficient k using drift-diffusion simulation, but found that it has minimal effect on J_{sc} for both inverted and conventional OPVs near the experimentally measured k value (Supplementary Data, Fig. S2). Thus, another factor must play a dominant role in determining the efficiency of carrier extraction.

We then vary μ_h while holding electron mobility μ_e at $2 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, which mimics the real behavior for P3HT:PCBM active layer, where μ_h depends strongly P3HT crystallinity and μ_e is relatively insensitive to processing [40]. We find that changes in μ_h have a large and non-monotonic effect on J_{sc} due to accumulation of unextracted carriers. As μ_h increases, a shorter time is required for holes to reach the anode and be extracted. As a result, the active layer shifts from an accumulation of holes at low μ_h to an accumulation of electrons at high μ_h , both of which screens the built-in field [40,41]. An optimal μ_h value should exist where balanced carrier extraction minimizes accumulation of both electrons and holes, and maximizes J_{sc} . Indeed, a plot of J_{sc} as a function of μ_h (Fig. 6b) shows maxima for both device architectures with the corresponding optimal μ_h value being higher for inverted OPV ($3 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$) than for conventional OPV ($1.5 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$). The difference in optimal μ_h value is due to the fact that holes in inverted OPV have to travel a greater distance to reach the HEL/anode since the majority of carriers are generated near the front electrode (Fig. 4b). Thus, it is understandable that a higher μ_h is needed to maintain balanced carrier extraction in inverted OPVs. At the

experimental μ_h of $5 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$, carrier extraction is relatively balanced, particularly for the inverted OPV. This can be seen in the bimolecular recombination rate profile for the inverted OPV (Fig. 6d, solid). Because bimolecular recombination rate depends on the product of hole and electron concentrations, a flat recombination rate profile away from the contacts indicates that neither type of carriers is accumulating in the bulk of the active layer. A decrease in μ_h to $1 \times 10^{-4} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ caused the inverted OPV to exhibit 14% lower J_{sc} (Fig. 6b). The corresponding recombination rate profiles show that for both conventional (Fig. 6c, dotted) and inverted (Fig. 6d, dotted) OPVs, recombination rate near the EEL significantly increases due to accumulation of unextracted holes in the front of the inverted device and in the rear of the conventional device. Because the high recombination and the high carrier generation regions overlap in the inverted OPV but are offset in the conventional OPV, carrier extraction and J_{sc} decrease more in the inverted device. On the other hand, an increase in μ_h to $2 \times 10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ caused the conventional OPV to exhibit 6% lower J_{sc} (Fig. 6b). In this case, recombination rate near the HEL increases for both conventional (Fig. 6c, dot dash) and inverted (Fig. 6d, dot dash) OPVs from fast extraction of holes and resulting accumulation of electrons. Due to the overlap of the high recombination and high carrier generation regions in the conventional OPV, carrier extraction and J_{sc} decrease more in the conventional device.

Comparing Figs. 6a and 6b, it is clear that J_{sc} depends more strongly on μ_h than on N_A , particularly near the experimentally measured values for typical devices. We should note that drift-diffusion simulation presents a simplified model of carrier transport in OPVs, since it assumes the bulk heterojunction as a homogenous medium, with no microscopic information on the donor/acceptor morphology and a single bimolecular recombination coefficient. Thus, one cannot expect perfect matching between simulated and experimental results. Nevertheless, drift-

diffusion simulation allows us to vary individual material parameters and establish their relative impact on measured device properties. In summary, drift-diffusion simulation gives good agreement with experimental data in showing a higher J_{sc} and enhanced EQE response between 450 nm and 600 nm for inverted versus conventional OPVs. Moreover, J_{sc} is found to depend strongly on hole mobility and moderately on dopant concentration near the experimentally measured values, suggesting that ratio of hole to electron mobility primarily determines the performance discrepancy for the two device architectures.

4. Conclusions

We find differences beyond experimental uncertainties for performance of P3HT:PCBM OPVs of conventional and inverted architectures with identical ELs under controlled illumination conditions that eliminate stray photocurrent contributions. The differences are examined using transfer matrix method and drift-diffusion simulation. The higher J_{sc} and enhanced EQE response between 450 nm and 600 nm for inverted OPVs are successfully reproduced using drift-diffusion simulation. Systematic variations of material parameters used for simulation reveal that the experimentally observed performance difference between the two architectures results primarily from carrier mobilities that are serendipitously optimized in the case of inverted OPVs, with a minor contribution of band bending due to unintentional p-type doping of the active layer. We show that an approach which combines accurate measurements of OPV performance and careful numerical simulations of carrier generation and recombination is essential to explain and predict the response of OPVs with different active layer and EL materials, as well as other solar cells.

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Device	V_{oc} [V]	J_{sc} [mA cm ⁻²]	FF	PCE [%]
Conv. no mask	0.558 ± 0.004	9.66 ± 0.17	0.576 ± 0.018	3.11 ± 0.13
Conv. 6 ap	0.559 ± 0.005	9.04 ± 0.09	0.591 ± 0.015	2.99 ± 0.09
Conv. 1 ap	0.563 ± 0.005	9.10 ± 0.14	0.596 ± 0.015	3.05 ± 0.12
Inv. no mask	0.570 ± 0.000	10.99 ± 0.12	0.533 ± 0.014	3.34 ± 0.08
Inv. 6 ap	0.569 ± 0.003	10.11 ± 0.14	0.565 ± 0.015	3.25 ± 0.06
Inv. 1 ap	0.570 ± 0.000	9.69 ± 0.10	0.576 ± 0.012	3.18 ± 0.06

Table 1. OPV device parameters measured under AM1.5G 100 mW cm⁻² illumination for conventional and inverted devices with different aperture configurations.

Parameter	Conventional	Inverted
P3HT:PCBM thickness [nm]	250	
Relative permittivity	3.8	
^a Electron affinity [eV]	3.7	
^b Effective bandgap [eV]	1.1	
^b CB & VB effective density of states [cm ⁻³]	1 x 10 ²⁰	
^b Anode work function [eV]	4.5	
^a Cathode work function [eV]	4.0	
^c Bimolecular recombination coefficient k [cm ³ s ⁻¹]	2 x 10 ⁻¹²	
^{b,d} Surface recombination velocity [cm s ⁻¹]	1 x 10 ⁵	
^c Electron mobility μ_e [cm ² V ⁻¹ s ⁻¹]	2 x 10 ⁻³	
^c Hole mobility μ_h [cm ² V ⁻¹ s ⁻¹]	5 x 10 ⁻⁴	
Dopant concentration N _A [cm ⁻³]	7 x 10 ¹⁵	
Series resistance [Ω cm ²]	2.9	2.7
Shunt resistance [Ω cm ²]	8.4 x 10 ⁴	4.8 x 10 ³

^aFrom[42]

^bFrom[32]

^cSee Supplemental Data

^dHole recombination velocity at active layer/ZnO EEL interface is 1 x 10⁻⁵ cm/s

Table 2. Material parameters used for drift-diffusion simulation of conventional and inverted OPVs.

Device	V_{oc} [V]	J_{sc} [mA cm ⁻²]	FF	PCE [%]
Conv.	0.524	11.57	0.587	3.56
Inv.	0.524	11.66	0.583	3.56

Table 3. SCAPS simulated OPV device parameters under AM1.5G 100 mW cm⁻² illumination for conventional and inverted devices.

Fig. 1. (a) Assembled OPV holder with device and no mask. (b) Shadow mask with six 2.5 mm diameter apertures (“6 ap”) in holder. (c) Shadow mask with one 2.5 mm diameter aperture (“1 ap”) in holder. All views are from the solar simulator.

Fig. 2. (a) J-V under AM1.5G 100 mW cm⁻² of conventional OPVs with no mask (dotted), 6 ap mask (dashed), and 1 ap mask (solid). (b) OPV device parameters for conventional OPVs with no mask (dotted), 6 ap (striped), and 1 ap (solid) devices, normalized to the no mask device. (c) J-V under AM1.5G 100 mW cm⁻² of inverted OPVs without mask (dotted), with 6 ap mask (dashed), and with 1 ap mask (solid). (d) OPV device parameters for conventional no mask (dotted), 6 ap (striped), and 1 ap (solid) devices, normalized to the no mask device.

Fig. 3. (a) Experimental EQE spectra for conventional (blue) and inverted (red) OPVs. (b) dJ_{ph}/dV versus V for conventional (blue) and inverted (red) OPVs.

Fig. 4. (a) Fractional absorption spectra calculated using transfer matrix method for the active layer in conventional (blue) and inverted (red) OPVs. (b) Profiles of cumulative generation normalized to total generation, calculated from curves in Figure 4a for conventional (blue) and inverted (red) OPVs. 0-nm in the position corresponds to front EL/active layer interface.

Fig. 5. (a) Mott–Schottky curve showing the $A^2 C^{-2}$ (measured at 1 kHz) vs. V for a conventional OPV. Lines represent the fitting according to Eq. 1, from which N_A of $7 \times 10^{15} \text{ cm}^{-3}$ is obtained. Arrow indicates x-intercept voltage. (b) Simulated EQE spectra for conventional (blue) and inverted (red) OPVs. (c) Simulated band diagrams for conventional (blue) and inverted (red) OPVs at short circuit. (d) Simulated electric field magnitude for conventional (blue) and inverted (red) OPVs at short circuit. 0-nm in the position corresponds to front EL/active layer interface.

Fig. 6. Dependence of J_{sc} for conventional (blue) and inverted (red) OPVs on (a) N_A and (b) μ_h .

Dashed lines correspond to values used in (c) and (d). Simulated recombination rate profiles for (c) conventional and (d) inverted OPVs with $\mu_h = 1 \times 10^{-4}$ cm² V⁻¹ s⁻¹ (dotted), $\mu_h = 5 \times 10^{-4}$ cm² V⁻¹ s⁻¹ (solid), and $\mu_h = 2 \times 10^{-3}$ cm² V⁻¹ s⁻¹ (dashed). 0-nm in the position corresponds to front EL/active layer interface (HEL for (c) and EEL for (d)).

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