Tandem Organic Solar Cells



Nonfullerene Tandem Organic Solar Cells with High Performance of 14.11%

Yamin Zhang, Bin Kan, Yanna Sun, Yanbo Wang, Ruoxi Xia, Xin Ke, Yuan-Qiu-Qiang Yi, Chenxi Li, Hin-Lap Yip, Xiangjian Wan, Yong Cao, and Yongsheng Chen*

Fabricating solar cells with tandem structure is an efficient way to broaden the photon response range without further increasing the thermalization loss in the system. In this work, a tandem organic solar cell (TOSC) based on highly efficient nonfullerene acceptors (NFAs) with series connection type is demonstrated. To meet the different demands of front and rear sub-cells, two NFAs named F-M and NOBDT with a whole absorption range from 300 to 900 nm are designed, when blended with wide bandgap polymer poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)-benzo[1,2-b:4,5-b'] dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'-bis(2-ethylhexyl)benzo[1',2'c:4',5'-c']dithiophene-4,8-dione))] (PBDB-T) and narrow bandgap polymer PTB7-Th, respectively, the PBDB-T: F-M system exhibits a high V_{oc} of 0.98 V and the PTB7-Th: NOBDT system shows a remarkable J_{sc} of 19.16 mA cm⁻², which demonstrate their potential in the TOSCs. With the guidance of optical simulation, by systematically optimizing the thickness of each layer in the TOSC, an outstanding power conversion efficiency of 14.11%, with a V_{oc} of 1.71 V, a J_{sc} of 11.72 mA cm⁻², and a satisfactory fill factor of 0.70 is achieved; this result is one of the top efficiencies reported to date in the field of organic solar cells.

Solution processed organic solar cells (OSCs), as a green energy conversion technology for sustainable development, have received tremendous attentions in the past decade.^[1–5] Recently, a great number of single-junction organic solar cells with power conversion efficiencies (PCEs) beyond 10% and even up to 13% were reported,^[6–22] making this technology more promising. However, there is still large room to make high performance

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OSCs ready for the market. One of the feasible strategies is to construct photovoltaic devices with tandem architecture to tackle the main losses in single-junction devices and further improve the performances.^[23-25] Typically, a tandem organic solar cell (TOSC) connects multiple photoactive layers with complementary absorption by highly transparent interconnecting layers (ICLs),^[26-28] offering more efficient photon utilization than a single-junction OSC. Great efforts have been paid to developing new photovoltaic materials and ICLs ever since Heeger and co-workers reported the first solution-processed TOSC.^[24] Also, the connection types of the multiple layers were divided into series and parallel forms.^[29,30] Up to now, TOSCs have made huge leaps in device performances, PCEs of 11.83%^[31] and 11.20%^[32] were achieved by the triple junction series-connected tandem structure and double junction parallel-connected tandem device, respectively. Notably, during these two years, the PCEs

of double junction series-connected TOSCs have been achieved to reach 12.7% for fullerene acceptors (FAs) based $OSCs^{[33]}$ and 13.8% for nonfullerene acceptors (NFAs) based $OSCs^{[34]}$

In series-connected tandem solar cells, the open-circuit voltage (V_{0c}) is expected to be the sum of the sub- V_{0c} s and the short-circuit current (I_{sc}) is pinned to the smallest I_{sc} among those sub-cells, which suggest that highest possible V_{oc} for each sub-cell and balanced J_{sc} between them are essential to achieve high PCEs. Furthermore, for highly efficient TOSC, minimizing the absorption overlap is also a critical factor.^[35-37] In bulk-heterojunction (BHJ) OSCs that employ fullerene derivatives as the acceptor materials, due to the weak absorptions of FAs, most of light-absorbing tasks were undertaken by the donors.^[30] However, these donor molecules with intrinsic narrow absorption width can cover with only a small fraction of the entire solar spectrum. In contrast, NFA based OSCs can derive benefit from both the donors and acceptors, which make them absorb sufficient photon in the specific range of solar emission spectrum. Moreover, since the V_{oc} of the BHJ OSCs mainly depends on the energy level difference between the highest occupied molecular orbital (HOMO) of the donor and the lowest unoccupied molecular orbital (LUMO) of the acceptor, when use FAs as n-type semiconductors, the $V_{\rm oc}$ can only be tuned by modification the donor materials, which significantly limit the $V_{\rm oc}$ values of the rear cells

^{Y. Zhang, B. Kan, Y. Sun, Y. Wang, X. Ke, Y.-Q.-Q. Yi, Dr. C. Li,} Dr. X. Wan, Prof. Y. Chen
State Key Laboratory and Institute of Elemento-Organic Chemistry
Centre of Nanoscale Science and Technology and Key Laboratory of
Functional Polymer Materials
College of Chemistry
Nankai University
Tianjin 300071, China
E-mail: yschen99@nankai.edu.cn
R. Xia, Prof. H.-L. Yip, Prof. Y. Cao
State Key Laboratory of Technology
Guangdong, Guangzhou 510640, P. R. China
The ORCID identification number(s) for the author(s) of this article can be found under https://doi.org/10.1002/adma.201707508.





with narrow bandgaps for near infrared (NIR) absorptions. On the contrary, NFAs based OSCs are much more convenient to tune the energy offset between the donor and acceptor, as their energy levels can be readily changed through rational modification.^[12,22,38–42] Recent progress also proved that NFA-based OSCs have allowed a smaller voltage loss to be demonstrated,^[43,44] thus, a higher V_{oc} can be obtained in such devices than in those of FAs based OSCs with a similar optical bandgap. All above indicate that NFAs based sub-cells have unique advantages in TOSCs.^[45]

In our previous work, two promising NFAs named 2,9-bis(2-methylene(3-(1,1-dicyanomethylene)indanone))7,12-dihydro-4,4,7,7,12,12-hexaoctyl-4H-cyclopenta[2",1":5,6;3",4":5',6'] diindeno[1,2-b:1',2'-b']dithiophene (FDICTF) (F-H)^[38] and 4,4,10,10-tetrakis(4-hexylphenyl)-4,10-dihydrodithienyl[1,2b:4,5b']benzodi-thiophene-2,8-diyl)bis(2-(3-oxo-2,3-dihydroinden-1-ylidene)malononitrile (NFBDT)^[39] were successively reported,

the chemical structures of these molecules are shown in Figure 1a,b. When blended with extensively used wide bandgap polymer. poly[(2,6-(4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b:4,5-b']dithiophene))-alt-(5,5-(1',3'-di-2-thienyl-5',7'bis(2-ethylhexyl)benzo[1',2'-c:4',5'-c']dithiophene-4,8-dione))] (PBDB-T), F-H based OSCs demonstrated a PCE of 10.06% with a relatively high Voc of 0.94 V. Meanwhile, NFBDT exhibits efficient absorption ability in the NIR range of 700-800 nm, which benefits for obtaining high J_{sc} . The relatively high V_{oc} of F-H and outstanding Isc achieved by NFBDT showed their potential in use of TOSCs for front sub-cell and rear sub-cell, respectively. However, the optical bandgap of F-H and NFBDT was 1.63 and 1.56 eV, respectively, inferred that their energy loss (E_{loss}) (which can be calculated by the equation $E_{\text{loss}} = E_{\text{g}} - eV_{\text{oc}}$, where E_{g} is the bandgap of the devices, e is the elementary charge, and V_{oc} is the open-circuit voltage)^[46] were both around 0.70 eV. The



Figure 1. Chemical structures of electron donor and electron acceptor materials in the a) front (PBDB-T: F-M) and b) rear (PTB7-Th: NOBDT) subcells. Device architecture of the c) single and d) tandem OSCs. e) Normalized absorption spectra of PBDB-T: F-M and PTB7-Th: NOBDT blend films. f) Schematic energy level diagram of each material used in the tandem OSCs. g) EQE curves of PBDB-T: F-M and PTB7-Th: NOBDT OSCs.

ADVANCED MATERIALS

Table 1. The optical and electrochemical data of F-H, F-M, NFBDT, and NOBDT.

Molecules	λ _{max} ^{sol.} [nm]	λ _{max} ^{fil.} [nm]	λ _{edge} ^{fil.a)} [nm]	E ^{optb)} [eV]	HOMO [eV]	LUMO [eV]	E _g cv [eV]
F-H	665	689	760	1.63	-5.43	-3.71	1.72
F-M	662	687	752	1.65	-5.42	-3.70	1.72
NFBDT	703	731	795	1.56	-5.43	-3.88	1.55
NOBDT	744	781	890	1.39	-5.26	-3.89	1.37

^{a)}Calculated from the onset absorption of these molecules; ^{b)} $E_{g}^{opt} = 1240/\lambda_{edge}$ (eV).

comparatively higher $E_{\rm loss}$ values of these two materials indicated that there is still considerable space for the relevant TOSCs.

To make them more suitable for TOSCs, it is necessary to broaden the whole absorption range and decrease their E_{loss} . Herein, we modified these two molecules and rematched the polymer donors in the sub-cells. In the first place, in order to increase the absorption of front-cell in the low wave number direction and obtain a higher $V_{\rm oc}$, methyl was introduced as a weak electron-donating unit on the end-group 2-(3-oxo-2,3-dihydroinden-1-ylidene) malononitrile (INCN) to elevate both the LUMO and HOMO levels of F-H, the methyl substituted molecule was named as F-M (see Figure 1a). The energy levels of F-H and F-M measured by electrochemical cyclic voltammetry (Figure S1, Supporting Information) are shown in Figure 1f and Table 1. Due to the electron-donating effect of the methyl group, the HOMO and LUMO levels of F-M are all elevated by 0.01 eV compared to those of F-H and turned into -5.42 and -3.70 eV, respectively. The normalized thin-film UV-vis absorption spectra of F-H and F-M are presented in Figure 2a. F-M exhibits a maximum absorption peak absorption at 687 nm (with an absorption coefficient of 2.31×10^5 ${\rm M}^{-1}$ cm⁻¹ in

the solution state), which has a small blueshift compared to that of F-H due to the upshifted LUMO level.

BHJ devices were fabricated using these two molecules with a conventional device structure. The optimum current density versus voltage (I-V) curves are shown in Figure 2b and Table 2. The device based on PBDB-T: F-M processed from chlorobenzene with trace amount of diiodooctane (0.2% in volume ratio) as solvent additive showed a PCE of 10.08% with a $V_{\rm oc}$ of 0.98 V, a moderate I_{sc} of 14.56 mA cm⁻², and a fill factor (FF) of 0.71. Under the same batch of PBDB-T, the optimal F-H based devices presented a PCE value of 9.59% with V_{oc} of 0.94 V, which is similar to our reported results. The higher Voc value of F-M compared to F-H indicate that the $E_{\rm loss}$ decreased from 0.69 to 0.67 eV. From the external quantum efficiency (EQE) spectra (Figure 2c), it can be seen that relative to PBDB-T: F-H device, the PBDB-T: F-M device exhibits a slightly narrower photoresponse spectrum with an enhanced EQE in the short-wavelength range from 470 to 580 nm and shows a photo-to-current response from 300 to 750 nm with a maximum value of 77% and over 70% across the range of 490-610 nm. All these results indicate that PBDB-T: F-M is more appropriate for the use in TOSCs as the front sub-cell. The plots of photocurrent (J_{ph}) versus the effective applied voltage $(V_{\rm eff})$ for the devices were measured to study the charge collection properties in the PBDB-T: F-M-based optimal devices. From **Figure 3**d, when V_{eff} values arrived at ≈ 2 V, J_{ph} values reached saturation (J_{sat}) , suggesting that charge recombination is minimal at higher voltage due to the high internal electric field in the devices. The charge extraction probabilities were estimated by calculating $J_{\rm ph}/J_{\rm sat}$,^[47,48] under both the short circuit and maximal power output conditions, F-M based devices exhibited more efficient charge collection efficiency compared to F-H based devices (94%/83% for F-M vs 91%/74% for F-H) (see Figure 2d). The



Figure 2. a) Normalized absorption spectra of PBDB-T, F-H, and F-M. b) Optimal current density–voltage (*J*–*V*) curve of the device based on PBDB-T: F-H/F-M under the illumination of AM 1.5G (100 mW cm⁻²). c) EQE spectra of devices based on PBDB-T: F-H/F-M. d) Photocurrent density versus effective voltage (J_{ph} – V_{eff}) characteristics for the devices under constant incident light intensity (AM 1.5G, 100 mW cm⁻²).

Table 2. Photovoltaic parameters of single-junction OSCs based on PBDB-T: F-H, PBDB-T: F-M, PTB7-Th: NFBDT, and PTB7-Th: NOBDT active layers.

Active layer	V _{oc} [V]	J _{sc} [mA cm ⁻²]	FF	PCE ^{a)} [%]	Eloss
PBDB-T: F-H ^{b)}	0.94 ± 0.01	15.81 ± 0.28	0.66 ± 0.01	10.06 (9.81)	0.69
PBDB-T: F-H ^{c)}	0.94 ± 0.01	15.02 ± 0.26	$\textbf{0.67} \pm \textbf{0.01}$	9.59 (9.38)	0.69
PBDB-T: F-M	$\textbf{0.98} \pm \textbf{0.01}$	14.56 ± 0.22	0.71 ± 0.01	10.08 (10.29)	0.67
PTB7-Th: NFBDT ^{d)}	0.80	14.59	0.58	6.74	0.75
PTB7-Th: NOBDT	$\textbf{0.77} \pm \textbf{0.01}$	19.16 ± 0.23	$\textbf{0.70} \pm \textbf{0.01}$	10.26 (10.55)	0.62

^{a)}The average PCE was obtained from 20 devices and the best results are provided in parentheses; ^{b)}Data from ref. [38]; ^{c)}Parameters measured by same batch of PBDB-T; ^{d)}Data from ref. [39] (used same batch of PTB7-Th).

charge mobilities of the optimized PBDB-T: F-M blend films were measured by the space-charge limited current method. The hole and electron mobilities were measured with device structures of indium tin oxide (ITO)/poly(3,4-ethylenedioxythiopene):poly(styrenesulfonate) (PEDOT: PSS)/active layer/Au and ITO/ZnO/ active layer/Al, respectively. As shown in Figure S3 in the Supporting Information, for PBDB-T: F-M blend films, the hole and electron mobilities were 2.86×10^{-4} and 9.04×10^{-5} cm⁻² V⁻¹ s⁻¹, respectively, which are higher than those of PBDB-T: F-H based films,^[38] and this might have contributed to the higher FF for corresponding devices. Morphological characterizations of their optimal active layers were studied by tapping-mode atomic force microscopy (AFM) and transmission electron microscopy (TEM). As shown in the AFM images (Figure S4a, Supporting Information), PBDB-T: F-M film exhibited a uniform and smooth surface morphologies with a root-mean-square (rms) surface roughness values of 2.13 nm. From the TEM images (Figure S4c, Supporting Information), PBDB-T: F-M film displayed a clearer phase

separation of donor and acceptor compared to the film of PBDB-T: F-H, which is favorable for the exciton dissociation and charge transport, and thus leading to higher FF.

At the same time, to further expand the absorption of NFBDT in NIR area, an acceptor named NOBDT (see Figure 1) was designed and synthesized. A strong electron-donating ability (octyloxy) was incorporated on the benzo[1,2-b:4,5-b']dithiophene core unit to elevate the HOMO level of the molecule. Synchronously, a fluorine atom was utilized to enhance the electronegativity of INCN end-group, thus a lower LUMO

level was obtained. Overall, a low bandgap of 1.37 eV was achieved for NOBDT, making the absorption edge redshifted 100 nm (with an absorption coefficient of 1.93×10^5 M⁻¹ cm⁻¹ in the solution state) (Figure 3a) compared to NFBDT. When blended with narrow-bandgap polymer donor poly[4,8-bis(5-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b:4,5-b']dithiophene-co-3-fluorothieno[3,4-b]thio-phene-2-carboxylate] (PTB7-Th), the device with solvent vapor annealing treatment demonstrated a $V_{\rm oc}$ of 0.77 V with a low $E_{\rm loss}$ of 0.62 eV, a high $J_{\rm sc}$ of 19.16 mÅ cm⁻², and an FF of 0.70 (Figure 3b and Table 2). The EQE values reach a maximum value of 71% and over 70% across the range 630-750 nm (Figure 3c). All above indicate that NOBDT is an applicable material for the rear sub-cell. PTB7-Th: NOBDT based devices demonstrated excellent charge extraction properties under the short circuit and maximal power output conditions with values of 95% and 85%, respectively (Figure 3d). The hole and electron mobilities for PTB7-Th: NOBDT blend film were 5.56×10^{-4} and $1.92\times10^{-4}~\text{cm}^{-2}~\text{V}^{-1}~\text{s}^{-1},$ respectively



Figure 3. a) Normalized absorption spectra of PTB7-Th, NFBDT, and NOBDT. b) Optimal current density–voltage (J–V) curve of the device based on PTB7-Th: NOBDT under the illumination of AM 1.5G (100 mW cm⁻²). c) EQE spectra of devices based on PTB7-Th: NOBDT d) Photocurrent density versus effective voltage (J_{ph} – V_{eff}) characteristics for the devices under constant incident light intensity (AM 1.5G, 100 mW cm⁻²).



J_{sc} (mA cm⁻²) a) b) c) 80 - Front cell - 800 nm light bias Front cell thickness (nm) Current density (mA cm⁻²) 20 -40 -Rear cell - 600 nm light bias The Optimized Tandem Devices 60 -80 -60 EQE(%) -3 100 -40 120 -1.64 mA cm⁻² 11.29 mA 140 -20 160 180 0.00 0.25 0.50 0.75 1.00 1.25 1.50 1.75 300 400 500 600 700 800 900 40 60 80 100 120 140 160 Rear cell thickness (nm) 180 200 Voltage (V) Wavelength (nm)

Figure 4. a) Simulated J_{sc} generated in tandem OSC as a function of thickness of the front and back cells. b) Optimal current density-voltage (*J*-*V*) curve of the tandem OSC under the illumination of AM 1.5G (100 mW cm⁻²). c) EQE spectra of the front cell and rear cells.

(Figure S3c,d, Supporting Information), which are favorable for achieving high FF. As shown in Figure S4d in the Supporting Information, the rms roughness of PTB7-Th: NOBDT blend film is 1.92 nm. From the TEM images (Figure S4f, Supporting Information), a proper domain size could be observed.

The UV-vis absorption spectra of PBDB-T: F-M and PTB7-Th: NOBDT blend films are shown in Figure 1e. The front subcell PBDB-T: F-M film exhibited an absorption in the visible range of 300-750 nm, while rear sub-cell PTB7-Th: NOBDT showed an absorption extended to 900 nm and complemented PBDB-T: F-M nicely. EQE curves of the optimized single-junction devices with PBDB-T: F-M and PTB7-Th: NOBDT are shown in Figure 1g. The PBDB-T: F-M based device exhibited an efficient EQE response in the range of 300-738 nm and the PTB7-Th: NOBDT based device also showed a broad and high EQE response from 300 to 890 nm. Together with each other, they showed a response value over 70% from 470 to 810 nm, which indicated their potential in achieving high performance for TOSC. A conventional tandem structure was then employed in device fabrication, and the architecture of the TOSC and the corresponding energy diagram are presented in Figure 1d,f. After systematically optimizations, solution-processed ICL of ZnO/neutral pH PEDOT: PSS (n-PEDOT: PSS) was used to connect the top and bottom sub-cells, and perylene diimide functionalized with amino N-oxide (PDINO)^[49] was chosen as the cathode buffer layer because of its excellent electron extraction ability.

In series TOSCs, the overall J_{sc} relies on the sub- J_{sc} . In order to balance the current densities in the two sub-cells, the optical modeling based on the transfer matrix method was carried out to provide guidance for the optimal thicknesses of the sub-cells. The basis for this optimization is the wavelength dependent refractive index (n) and extinction coefficient (k) that measured by a spectroscopic ellipsometer. The simulation results are displayed in Figure 4a and I_{sc} reaches an optimum value of 12.15 mA cm⁻² when the thicknesses of the optimized PBDB-T: F-M and PTB7-Th: NOBDT layers are 105 and 100 nm, respectively. With the guidance from optical modeling above, the TOSC devices was optimized by keeping the ICL thickness constant and alter the thickness of the sub-cells. An evident compromise between the J_{sc} and FF of the tandem solar cell was generated when varying the thickness of the front cell, and the optimizing parameter comes out when the front sub-cell is as thick as 120 nm. Keeping the thickness of the front cell at the optimal value, the thickness of the rear cell was adjusted from 80 to 140 nm by changing the speed of spin coating, and when the thickness of rear cell was 100 nm, the TOSC reached a best PCE of 14.11 with a $J_{\rm sc}$ of 11.72 and an FF of 70% (Figure 4b). The detailed optimizing parameters are summarized in Table 3. To verify the results measured under AM 1.5G condition. EOE measurement was carried out. As shown in Figure 4c, the front sub-cell was excited by 800 nm light bias (high pass) and EQE value of the front cell reaches over 65% in the short range with integrated I_{sc} of 11.64 mA cm⁻². The back

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Active layer	V _{oc} [V]	$\int_{\rm sc}$ [mA cm ⁻²]	FF	PCE ^{a)} [%]	Film thickness of the front cell [nm]	Film thickness of the rear cell [nm]
PBDB-T: F-M (front cell) and PTB7-Th: NOBDT (rear cell)	1.69 ± 0.01	12.03 ± 0.11	$\textbf{0.66} \pm \textbf{0.01}$	12.88 (13.42)	80	100
	1.70 ± 0.01	11.84 ± 0.15	$\textbf{0.67}\pm\textbf{0.01}$	13.26 (13.65)	100	100
	1.71 ± 0.01	11.72 ± 0.15	$\textbf{0.70} \pm \textbf{0.01}$	13.92 (14.11)	120	100
	1.71 ± 0.01	11.33 ± 0.17	$\textbf{0.68} \pm \textbf{0.01}$	13.56 (13.67)	140	100
	1.71 ± 0.01	12.08 ± 0.12	$\textbf{0.66} \pm \textbf{0.01}$	13.44(13.63)	120	80
	1.71 ± 0.01	11.67 ± 0.12	$\textbf{0.67} \pm \textbf{0.01}$	13.72 (13.85)	120	120
	1.70 ± 0.01	11.45 ± 0.14	$\textbf{0.63} \pm \textbf{0.01}$	12.26(12.57)	120	140

^{a)}The average PCE was obtained from 20 devices and the best results are provided in parentheses.





cell that excited by 600 nm light bias (low pass) showed a broad EQE spectrum from 300 to 890 nm with a low response in the short wavelength region and high response over 68% at the long wavelength region, which corresponded to an integrated $J_{\rm sc}$ of 11.29 mA cm⁻². These results are very consistent with $J_{\rm sc}$ value obtained from the simulated solar light (AM 1.5G, 100 mW cm⁻²).

In conclusion, a double junction nonfullerene tandem organic solar cell with high efficiency has been designed and optimized. For the front sub-cell, a new NFA named F-M blended with wide bandgap polymer donor PBDB-T was used to achieve high V_{oc} of 0.98 V with efficient absorption in the visible region from 330 to 740 nm. Meanwhile, another NFA named NOBDT was designed to meet the demands of a rear sub-cell, by simultaneously tuning the HOMO and LUMO energy levels. NOBDT further broadens the absorption of NFBDT to the NIR region, when blended with narrow bandgap polymer donor PTB7-Th, NOBDT based devices gave a $V_{\rm oc}$ of 0.77 V with an absorption edge of 900 nm. By systematically optimizing the thickness of each layer in the TOSC, an outstanding PCE of 14.11%, with a $V_{\rm oc}$ of 1.71 V, a J_{sc} of 11.72 mA cm⁻² and a satisfactory FF of 0.70 was achieved. This performance is one of the best reported to date in the field of OSCs. These results demonstrate the potential of nonfullerene acceptor materials for TOSCs and might become the most vigorous competitor in the field of tandem solar cells.

Experimental Section

Materials: The detailed synthetic route of F-M and NOBDT (Schemes S1 and S2, Supporting Information) were demonstrated in the Supporting Information. Other photovoltaic materials were purchased from Solarmer Materials Inc. All chemicals and solvents were reagent grades and purchased from Sigma-Aldrich, Alfa Aesar, and TCI Chemical Co. respectively.

Single Cell Device Fabrication: All the single-junction cell was fabricated with the structure of ITO/PEDOT: PSS(4083)/active layers/PDINO/Al (see Figure 1c). First, A thin layer (20 nm) of PEDOT: PSS was spin cast on top of precleaned ITO substrates and annealed in air at 150 °C for 15 min. Then the PBDB-T and F-M (from a mixed solvent of chlorobenzene/1,8-diiodoctane (99.8:0.2, v/v) with a concentration of 16 mg mL⁻¹ and PBDB-T: F-M weight ratio of 1:1) or PTB7-Th: NOBDT (from a chloroform solution of 13 mg mL⁻¹ with PTB7 Th: NOBDT weight ratio of 1:1.6) was spin coated to form an active layer. For the PTB7-Th: NOBDT based cells, an extra 100 s solvent vapor annealing with chloroform was needed. After that, about 5 nm PDINO (dissolved in methanol with the concentration of 1 mg mL⁻¹) layer was spin coated on the top of the active layer. Finally, a layer of Al with thickness of 80 nm was deposited under high vacuum ($\approx 1 \times 10^{-4}$ Pa).

Tandem Cell Device Fabrication: The PBDB-T: F-M active layers were fabricated via the same process as single-junction cells. ZnO nanoparticles solution was spin coated on top of the active layer of the front cell, the ZnO nanoparticles were synthesized by the previously reported method.^[50] Then the n-PEDOT: PSS was spin coated with a thickness of 20 nm. The PTB7-Th: NOBDT active layer and PDINO electron extraction layer were fabricated via the same process as single-junction cells. The devices were completed after deposition of 80 nm Al as cathode. All the devices possess the work area of 0.04 cm².

Device Characterization: The J–V curves of photovoltaic devices were obtained using a Keithley 2400 source-measure unit. Photocurrent was measured under illumination with simulated 100 mW cm⁻² AM 1.5G irradiation using an SAN-EI XES-70S1 AAA class solar simulator,

calibrated with a reference Si solar cell. The EQEs of both sub-cells were measured using chopped monochromatic light in conjunction with the lock-in technique applying the determined bias light conditions. Light bias obtained by 600 nm low-pass and 800 nm high-pass optical filters was selected to excite (saturate) the front and rear cells to measure the rear and front cells, respectively.

Supporting Information

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

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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