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Efficient Tandem Organic Photovoltaics with Tunable

Rear Sub-cells

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SUMMARY

Tandem structure was invented to enhance photon utilization efficiency and reduce thermal loss. Considering the unique advantages of non-fullerene acceptors (NFAs), the combination of NFAs and the tandem concept shows great potential for organic photovoltaics (OPVs). Herein, a simple strategy to balance the voltage-current trade-off in tandem OPVs by employing mixed NFAs in rear sub-cells was reported. The V_{OC} and J_{SC} of rear sub-cells can be tuned by using the blend of donor/NFA/NFA. This strategy offers an easy approach to balance the V_{OC} and J_{SC} in tandem OPVs towards higher power conversion efficiency (PCE) without rational and careful synthesis of new materials. Tandem OPVs based on the mixed NFAs in rear sub-cell exhibited the best PCE of 13.3% in the lab. Importantly, the tandem devices were certified by National Renewable Energy Laboratory (NREL) under asymptotic scans, a PCE of 11.52% was achieved and recognized on the most recent NREL chart.

KEYWORDS: organic solar cells, tandem, non-fullerene, mixed acceptors, certified

INTRODUCTION

Photovoltaic (PV) technology is developed as a renewable clean energy alternative aimed to overcome the environmental and energy challenges of the human future. Especially, the solution-processable organic photovoltaics (OPVs) have attracted considerable attentions in the last decade due to some potential advantages, such as flexibility, light-weight, possible semi-transparence and fast large-area fabrication with low energy consumption.¹⁻⁶

In order to realize future commercialization, the power conversion efficiency (PCE) of OPV has to be further enhanced. To overcome the limitations of single-junction solar cells, tandem structure was invented by stacking two or more sub-cells together.^{7,8} Using this strategy, the photon utilization efficiency can be significantly improved due to the complementary absorptions of sub-cells. In addition, a major loss mechanism for single-junction solar cells is the photovoltage loss, which is induced by the thermalization of hot carriers when the energy of photons is greater than the bandgap.⁹ The tandem structure is a promising way to reduce the thermal loss which may finally overcome the Shockley-Queisser limit of single junction.¹⁰

So far, the most reported tandem OPVs were based on classical fullerene derivative acceptor (i.e. PCBM) with PCEs of 10-12%.¹¹⁻¹⁶ However, the progress of tandem OPVs was slow down in recent years due

to the limitations of the fullerene acceptor (i.e. weak absorption in the near-infrared (NIR) regions, insufficient thermal stability caused by easy aggregations, and large open-circuit voltage (V_{OC}) losses). Considering the unique advantages of non-fullerene acceptors (NFAs) over the fullerene acceptors,¹⁷⁻²⁰ the combination of NFAs and the tandem concept shows a great potential for very high performance OPVs: (1) the bandgap of NFAs can be tuned between 1.2 to 2.4 eV,²¹⁻²⁶ which can either broaden the absorption in the NIR region for the rear sub-cell or narrow the absorption to the blue region for the front sub-cell; (2) the V_{OC} loss of single-junction NFA-based solar cells can be minimized to 0.4-0.6 V,²⁷⁻³⁰ which guarantees small V_{OC} loss of tandem NFA-based solar cells; (3) the improved thermal stability of the NFA-based sub-cells^{31,32} is potentially robust towards the unavoidable thermal treatments of the interconnecting layer (ICL). Research into this promising area (tandem NFA-based solar cells) has started only in 2016 with a PCE of ca. 10%,³³⁻³⁵ and more recently, the PCEs reached >13%.³⁶⁻⁴³ However, the trade-off between the V_{OC} and the short-circuit current density (J_{SC}) in tandem OPVs is still challenging to balance, which limits further enhancement of efficiency. So far, to mitigate the trade-off, a rational and careful synthesis of new materials with only a slight difference in bandgaps is required to achieve higher efficiencies. However, due to the tedious and complex nature of organic synthesis, a

simple strategy to balance the trade-off between the V_{OC} and the J_{SC} in tandem OPVs would be highly desirable.

Herein, we report a simple strategy to balance the trade-off between the V_{OC} and the J_{SC} in tandem OPVs by employing mixed NFAs in rear sub-cells. The V_{OC} and J_{SC} of the rear sub-cells can be tuned in a wide range (V_{OC} of 0.67-0.75 V, J_{SC} of 22.7-20.5 mA cm⁻²) by using the blend^{44,45} of one donor (PTB7-Th⁴⁶) and two NFAs (FOIC⁴⁷ and F8IC⁴⁸). By this strategy, the V_{OC} and J_{SC} in tandem OPVs can be easily balanced towards higher PCE without a rational and careful synthesis of new NFAs (with a slight difference in bandgaps). As a result, the tandem NFA-based OPV with a PCE of 13.3% was achieved in our lab. More importantly, the encapsulated tandem devices were certified by National Renewable Energy Laboratory (NREL) under the new protocols (asymptotic scans, which are much tougher than regular fast scans), a PCE of 11.52% was achieved and recognized on the most recent NREL chart.⁴⁹

RESULTS AND DISCUSSION

Front and rear sub-cells

In this work, a wide bandgap polymer PBDB-T⁵⁰ ($E_g=1.85$ eV) and a medium bandgap polymer PTB7-Th ($E_g=1.63$ eV) were used as donors. A medium bandgap non-fullerene small molecule IT-M⁵¹ ($E_g=1.63$ eV) and two narrow bandgap non-fullerene small molecules FOIC ($E_g=1.33$ eV) and

F8IC ($E_g=1.29$ eV) were used as acceptors. The molecular structures and absorption spectra of these donors and acceptors are shown in Figure 1.

The J - V curves and external quantum efficiency (EQE) spectra of single-junction devices under the illumination of an AM 1.5 G solar simulator (100 mW cm^{-2}) are shown in Figure 2. The average (calculated from 15 individual devices) and the best device characteristics are summarized in Table 1. The geometry of single-junction device is inverted type: indium tin oxide (ITO)/zinc oxide (ZnO)/active layer/molybdenum trioxide (MoO_3)/silver (Ag). The front sub-cells were fabricated using PBDB-T as a donor and IT-M as an acceptor, resulting in an absorption edge at around 770 nm ($E_g=1.61$ eV, extracted by EQE spectrum). The average V_{oc} , J_{sc} , FF and PCE of PBDB-T/IT-M front sub-cells are 0.91 V, 16.3 mA cm^{-2} , 71.4% and 10.6%, respectively. The rear sub-cells were fabricated by using the blend of PTB7-Th, FOIC and F8IC. Compared to FOIC, the F8IC exhibit similar chemical structure but contains two more fluorine substituent groups, which can down-shift the lowest unoccupied molecular orbital (LUMO) energy level (0.08 eV) and highest occupied molecular orbital (HOMO) energy level (0.04 eV), and finally reduce the bandgap (0.04 eV). In Rear 1 sub-cell (FOIC/F8IC=0/100), the average V_{oc} and J_{sc} are 0.67 V and 22.7 mA cm^{-2} , respectively. After the increasing of the FOIC content in the mixed acceptors, the V_{oc} increases (0.70 V for Rear 2 (FOIC/F8IC=25/75), 0.72 V for Rear 3 (FOIC/F8IC=50/50), 0.73 V for Rear 4 (FOIC/

F8IC=75/25) and 0.75 V for Rear 5 (FOIC/F8IC=100/0)) and the J_{sc} decreases (22.2 mA cm⁻² for Rear 2, 21.9 mA cm⁻² for Rear 3, 21.3 mA cm⁻² for Rear 4 and 20.5 mA cm⁻² for Rear 5). As a result, Rear 1 to 5 exhibit different absorption edges (961 nm for Rear 1, 955 nm for Rear 2, 948 nm for Rear 3, 941 nm for Rear 4 and 932 nm for Rear 5, extracted by EQE spectra) but similar average FFs (ca. 70%) and PCEs (10.6-10.8%). In order to study the mechanism that affords the tunability of the bandgap and the V_{oc} of devices, LUMO and HOMO energy levels of FOIC/F8IC mixed acceptors are calculated by electrochemical cyclic voltammetry. The results are shown in Figure S1 (Supplemental Information). The LUMO and HOMO energy levels increased with the increasing of the FOIC contents. The tunability of the bandgap is attributed to the tunability of LUMO and HOMO energy levels of the mixed acceptors. In addition, the tunable LUMO energy level of the mixed acceptors is the reason for the tunable V_{oc} since the V_{oc} of devices is determined by the gap between the HOMO energy level of donor and LUMO energy level of acceptor.

From the integration of EQE spectra with AM 1.5G reference spectrum, the calculated J_{sc} was obtained, which was similar to the J - V measurement (the average error is 1.3%, Table 1). Thermal stress (continuously heating) was employed to investigate the stability of the front and rear sub-cells. As a result, the front and rear sub-cells exhibited good thermal stability,

preserving 95% and 91% of their original values after continuously heating at 100 °C for 60 min, respectively (Figure S2, Supplemental information).

Molecular packing behaviors

In order to study the molecular packing behaviors in the active layers of Rear 1 to 5, grazing-incidence wide-angle X-ray scattering (GIWAXS) measurements were carried out. GIWAXS can provide molecular-level structural information such as lattice constant and orientation of material packing. The 2D GIWAXS patterns of PTB7-Th/FOIC/F8IC blends in different rear sub-cells (Rear 1 to 5) and pure F8IC/pure FOIC films are shown in Figure 3 and Figure S3 (Supplemental information), respectively. The 1D GIWAXS profiles in both out-of-plane and in-plane directions were shown in Figure S4 (Supplemental information). The molecular packing in pure F8IC film is similar to that of pure FOIC film in terms of the orientation of material packing, as indicated by the similar ring-like lamellar peak at $q = 0.4 \text{ \AA}^{-1}$ and similar π - π stacking peak ($q = 1.7 \text{ \AA}^{-1}$) on out-of-plane direction. As shown in Figure 3, the packing behaviors of FOIC/F8IC are similar in all PTB7-Th/FOIC/F8IC active layers of Rear 1 to 5, which show similar peaks at $q = 0.4 \text{ \AA}^{-1}$ on in-plane direction (face-on) and at $q = 1.7 \text{ \AA}^{-1}$ on out-of-plane direction (face-on). The maintained film morphology of PTB7-Th/FOIC/F8IC active layer in a wide range of FOIC/F8IC ratios (0/100 to 100/0) is attributed to the similarity in chemical structures

between FOIC and F8IC (good compatibility), which leads to similar FFs (ca. 70%) of all Rear 1 to 5 devices.

Tandem devices

The geometry of tandem device is also inverted type: ITO/ZnO/PBDB-T: IT-M/ICL/PTB7-Th: FOIC: F8IC/MoO₃/Ag (Figure 4a). The ICL is composed of MoO₃, Mix-PEDOT:PSS (4083 and PH 500, 7:3, v/v) and ZnO. The energy alignments of all materials used in tandem devices are shown in Figure 4b. The energy levels of donors/acceptors were extracted from literature, and the work functions of materials in ICL were calculated using ultraviolet photoelectron spectroscopy (UPS) tests (Figure S5, Supplemental information). The average (calculated from 20 individual devices) and the best device characteristics of tandem devices based on different rear sub-cells are summarized in Table 2. By employing different rear sub-cells (Rear 1 to 5), the V_{OC} and J_{SC} of tandem devices can be easily tuned. The average V_{OC} of tandem devices can be tuned from 1.57 V to 1.66 V (from Rear 1 to Rear 5). The average J_{SC} of tandem devices can also be tuned from 11.1 mA cm⁻² to 9.9 mA cm⁻² (from Rear 1 to Rear 5), since the J_{SC} of front sub-cell can be tuned by thickness of PBDB-T/IT-M active layer to match the J_{SC} of rear sub-cell towards optimized PCE. By this strategy, the V_{OC} and J_{SC} in tandem OPVs can be easily balanced towards higher PCE without a rational and careful synthesis of new acceptors (with a slight

difference in bandgaps). As a result, tandem devices based on Rear 3 exhibit best performance, the histograms of the PCEs of tandem devices based on Rear 1, Rear 3 and Rear 5 are shown in Figure S6 (Supplemental information). The J - V curves and EQE spectra of tandem devices based on Rear 3 sub-cell under the illumination of an AM 1.5 G solar simulator (100 mW cm^{-2}) are shown in Figure 4c and 4d. The average (calculated from 20 individual devices) and the best device characteristics of tandem devices based on Rear 3 with different combinations of front/rear sub-cell thickness are also summarized in Table S1 (Supplemental information). The average V_{OC} , J_{SC} and FF of tandem devices based on Rear 3 are 1.62 V, 10.6 mA cm^{-2} and 73.9%, respectively. The best PCE of tandem devices based on Rear 3 (PTB7-Th/FOIC/F8IC, FOIC/F8IC=50/50) is as high as 13.3%, which is higher than the PCE measured in tandem devices based on PTB7-Th/F8IC binary blend (Rear 1, best PCE=12.7%) and tandem devices based on PTB7-Th/FOIC binary blend (Rear 5, best PCE=12.4%).

More importantly, the encapsulated tandem devices based on Rear 3 were certified by the NREL under the new protocols (asymptotic scans).^{52,53} The regular fast I - V scans ignore the hysteresis effects, depending on scan rates and directions and light bias exposure history etc. These fast scans may have resulted in some exaggerated efficiency reports. Asymptotic scans are measured by holding the cell at each voltage until the current reaches an asymptotic level, which is a tougher and accurate

measurement than the fast scans. The I - V measured results and EQE spectra of tandem devices based on Rear 3 certified by the NREL are shown in Figure 4e and Figure S7 (Supplemental information), respectively. The V_{oc} and FF measured by the NREL are lower than the results measured in our lab due to the possible slight degradations caused by encapsulation, shipment and the asymptotic scans. The certified devices were re-measured in our lab after the tests by the NREL, similar results were achieved in our lab as the certified results from NREL. Finally, a PCE of 11.52% was certified by the NREL under the new protocols.

Simulations

The light field simulations were carried out for studying the appropriate combination of the tandem design and shown in Figure 5. In the simulation, the front and Rear 3 sub-cells of tandem devices were set to thickness values ranging from 70 to 135 nm. After the optimization of thickness values, the integrated J_{sc} of the front sub-cell (125 nm) and rear sub-cell (80 nm) were able to be matched well (13.7 mA cm⁻² for front sub-cell and 13.7 mA cm⁻² for rear sub-cell), which is consistent with the trend observed in our J - V tests (Table S1, Supplemental information). The measured J_{sc} (10.6 mA cm⁻²) is much lower than the one in the simulation (13.7 mA cm⁻²) since the simulation assumes the internal quantum efficiency (IQE) to be 100% and no energy losses in ICL.

Conclusion

In summary, a simple strategy to balance the trade-off between the V_{oc} and the J_{sc} in tandem OPV by employing mixed NFAs in rear sub-cells was reported. The V_{oc} and J_{sc} of the rear sub-cells can be tuned in a wide range by using the blend of PTB7-Th/FOIC/F8IC: the V_{oc} can be tuned (0.67-0.75 V) due to the difference between the LUMO energy levels of two acceptors FOIC (-3.9 eV) and F8IC (-4.0 eV); the J_{sc} can be tuned (20.5-22.7 mA cm⁻²) due to the difference between the optical bandgaps of two acceptors FOIC (1.33 eV) and F8IC (1.29 eV). Thanks to the similarity in chemical structures between FOIC and F8IC (good compatibility), the film morphology of PTB7-Th/FOIC/F8IC active layer can be maintained in a wide range of FOIC/F8IC ratios (0/100 to 100/0), which leads to similar FFs (ca. 70%). By this strategy, the V_{oc} and J_{sc} in tandem OPV (PBDB-T/IT-M as the front sub-cells, $E_g=1.63$ eV) can be easily balanced towards higher PCE without a rational and careful synthesis of new acceptors (with a slight difference in bandgaps). As a result, tandem devices based on Rear 3 (PTB7-Th/FOIC/F8IC, FOIC/F8IC=50/50) with the best PCE of 13.3% was achieved in our lab. More importantly, the encapsulated tandem devices based on Rear 3 were tested by the NREL under the new protocols (asymptotic scans, which are much tougher than regular fast scans), a PCE of 11.52% was achieved and recognized on the most recent NREL chart.

EXPERIMENTAL PROCEDURES

Materials

Unless stated otherwise, solvents and chemicals were obtained commercially and used without further purification. PBDB-T⁵⁰, IT-M⁵¹ and PTB7-Th⁴⁶ were purchased from Solarmer Materials Inc. FOIC⁴⁷ and F8IC⁴⁸ were synthesized according to our previously reported procedures. 1,8-Diiodooctane (DIO), chlorobenzene (CB) and chloroform (CF) were obtained from Sigma-Aldrich Inc.

Solar cell fabrication and testing

Single-junction organic solar cells were fabricated using with the following structure: ITO/ ZnO/active layer/MoO₃/Ag. The ITO glass was pre-cleaned in an ultrasonic bath of acetone and isopropanol, and treated in ultraviolet-ozone chamber (Jelight Company, USA) for 15 min. A ZnO sol-gel solution (100mg zinc acetate dehydrate and 45 μ L ethanolamine were added into 1mL 2-methoxyethanol, followed by stirring at 60 °C for 3 hours.) was spin-coated (3000 rpm) onto the ITO glass to form a thin ZnO film (30 nm) and baked at 200 °C for 60 min. A mixture of PBDB-T/IT-M was dissolved in CB solvent (1:1, 20 mg/ml in total, with 0.75% DIO, v/v) and stirred overnight. A mixture of PTB7-Th/FOIC/F8IC was dissolved in CF solvent (8:x:12-x, 15 mg/ml in total, with 0.25% DIO, v/v) and stirred for one hour.

Afterwards, these solutions were spin-coated (1500-2500 rpm) on the ZnO layer to form photosensitive layers. A MoO₃ (ca. 10 nm) and Ag (ca. 100 nm) layers were then evaporated onto the surface of the photosensitive layer under vacuum (ca. 10⁻⁵ Pa) to form the back electrode. The active area of the device was 0.1 cm² (with mask).

For the tandem devices: the front sub-cells were prepared according to the single-junction procedure (ITO/ZnO/active layer), after which the samples were transferred into the evaporation chamber for MoO₃ buffer layer deposition. The thickness of MoO₃ was 6 nm. Mix-PEDOT:PSS solution was prepared by mixing PEDOT:PSS 4083 and PH500 with a ratio of 7:3 (v/v) and ultra-sonicating for 5 minutes. The Mix-PEDOT:PSS solution was then spin-casted (5000 rpm) onto MoO₃ layer and annealed at 100 °C for 2 min. 1.68 g zinc acetate was put into 84 mL methanol followed by adding 600 μL DI water. The solution was heated to 60 °C with stirring. 1g potassium hydroxide was dissolved into 42 mL methanol and then dropped into the zinc acetate/methanol solution within 15 min with stirring. After 2 h and 15 min, the reaction was stopped and the solution was cooled down overnight to precipitate the product. After that, the upper solution was removed and 80 mL methanol was added again to wash the precipitate product twice. Finally, the white precipitate was dispersed in the chloroform/butanol (3:7, v/v) to form a 10 mg/mL ZnO nanoparticle solution. After, ZnO nanoparticle solution was then spin-casted (2500 rpm)

and thermal-annealed at 100 °C for 2 min. The rear sub-cells were also prepared according to the single-junction procedure (active layer/MoO₃/Ag). The active area of the device was 0.1 cm² (with mask). Encapsulation was applied on the devices for certification, for which the active area of the device for certification was 0.057 cm² (with mask).

J-V characteristics of photovoltaic cells were taken using a Keithley 2400 source measure unit under a simulated AM 1.5G spectrum, with an Oriel 9600 solar simulator. The measurements were done in a glove box with nitrogen atmosphere. EQEs were measured using an integrated system (Enlitech, Taiwan). The light spectrum was calibrated using a monocrystalline photodetector of known spectral response. The EQE measurements of single junction devices were under short-circuit conditions. For tandem junction devices, light biases of 550 and 800 nm were selected to excite the front and rear sub-cells, respectively. The unexcited sub-cell was then measured using a Xe lamp passing through a monochromator with a typical intensity of 10mW.

UV-Vis absorption

Thin-film (on quartz substrate) absorption spectra were recorded on a 4100 Hitachi spectrofluorophotometer (steady absorption spectra with integrating sphere correction), for which the thickness of the films was ca. 100 nm.

GIWAXS characterization

Grazing incident wide-angle X-ray scattering (GIWAXS) measurement was performed at Advanced Light Source on the 7.3.3. beamline. All samples were deposited on the silicon wafer with 100 nm silicon oxide. Samples were irradiated by 10 KeV at a fixed X-ray incident angle of 0.10° - 0.14° with an exposure time of 3 s.

UPS characterization

Ultraviolet photoelectron spectroscopy (UPS) measurements carried out in this work used a helium discharge lamp emitting photons with energy at 21.2 eV to excite the samples. The onset of the secondary electron edge was used to determine the work function under a -7 V bias applied between samples and detectors. Clean gold was used as a reference.

Light field simulations

The light field simulations were carried out using a program based on the transfer matrix formalism. Light was simulated to be incident from glass substrate side, with optical field calculated in each location in the film stack. Absorption rate in the active layers was calculated every 5 nm together with AM 1.5G spectrum to obtain generation rate and thus short-circuit photocurrent density. Optical field intensity was simulated and

plotted at all wavelengths and locations in the film stack. The layers of tandem organic solar cells were regarded as homogeneous and isotropic with flat interfaces.

SUPPLEMENTAL INFORMATION

Supplemental Information accompanies this paper online.

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AUTHOR CONTRIBUTIONS

P.C., Y.L. and S.Y.C. contributed equally to this work. P.C. and Y.Y. designed the experiments. S.Y.C. and Y.L. designed the interconnecting layer. T.L. synthesized FOIC and F8IC. P.C., Y.L., S.Y.C., R.W., H.W.C., T.H., L.M. and S.N. performed device fabrication and data analysis. P.C., S.Y.C., P.S. and C.Z. contributed to characterization. P.C., Y.L., S.Y.C., K.W., B.S., X.Z. and Y.Y. co-

wrote the paper. All authors discussed the results and commented on the manuscript. Y.Y. directed the project.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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Figure 1. Molecular structures and film absorption

a Molecular (donor) structures of PBDB-T and PTB7-Th.

b Molecular (acceptor) structures of IT-M, FOIC and F8IC.

c Film absorptions spectra of PBDB-T, PTB7-Th, IT-M, FOIC and F8IC.

Figure 2. Photovoltaic characteristics of single-junction devices

a J - V curves of single-junction devices under illumination of an AM 1.5G solar simulator, 100 mW cm^{-2} .

b EQE spectra of single-junction devices.

Figure 3. Molecular packing behaviors

2D GIWAXS patterns of PTB7-Th/FOIC/F8IC blends in different rear sub-cells.

Figure 4. Device structure, energy alignments and photovoltaic characteristics of tandem devices

a Device structure.

b Energy levels of donor and acceptor materials, and work functions of inter layers.

c J - V curve of tandem device (based on Rear 3 sub-cell) under illumination of an AM 1.5G solar simulator, 100 mW cm^{-2} .

d EQE spectra of tandem device (based on Rear 3 sub-cell).

e Photovoltaic characteristics of tandem device (based on Rear 3 sub-cell)

with the NREL certification (asymptotic scans on encapsulated devices).

Figure 5. Light field simulations

a The light field distribution of tandem device based on Rear 3 (125 nm for front sub-cell and 80 nm for rear sub-cell).

b Generation rate of tandem device based on Rear 3 (125 nm for front sub-cell and 80 nm for rear sub-cell).

Table 1 Photovoltaic characteristics of single-junction devices.

Device	Donor	Acceptor (m/m)	V_{oc} (V)	J_{sc} (mA cm ⁻²)	Calculated		PCE (%)	
					J_{sc} (mA cm ⁻²)	FF (%)	average	best
Front	PBDB-T	IT-M	0.91±0.01	16.3±0.3	16.0	71.4±0.8	10.6±0.3	11.0
Rear 1	PTB7-Th	FOIC/F8IC (0/100)	0.67±0.01	22.7±0.4	22.4	69.5±0.8	10.6±0.2	10.9
Rear 2	PTB7-Th	FOIC/F8IC (25/75)	0.70±0.01	22.2±0.3	22.0	69.0±0.5	10.7±0.2	11.0
Rear 3	PTB7-Th	FOIC/F8IC (50/50)	0.72±0.01	21.9±0.5	21.7	69.1±0.6	10.8±0.2	11.0
Rear 4	PTB7-Th	FOIC/F8IC (75/25)	0.73±0.01	21.3±0.3	21.0	69.6±0.4	10.8±0.2	11.1
Rear 5	PTB7-Th	FOIC/F8IC (100/0)	0.75±0.01	20.5±0.4	20.2	69.5±0.5	10.7±0.2	11.0

Table 2 Photovoltaic characteristics of tandem devices.

Combination	V_{oc} (V)	Measured J_{sc}	Calculated J_{sc}	FF (%)	PCE (%)	
		(mA cm ⁻²)	(mA cm ⁻²) Front/Rear		average	best
Front/Rear 1	1.57±0.01	11.1±0.2	11.1/11.1	71.2±0.6	12.4±0.2	12.7

Front/Rear 2	1.60±0.01	10.8±0.2	10.9/10.8	72.3±0.7	12.5±0.2	12.9
Front/Rear 3	1.62±0.01	10.6±0.3	10.7/10.6	73.9±0.8	12.7±0.3	13.3
	1.5839	10.626	N/A	68.4	11.52 ¹	
Front/Rear 4	1.64±0.01	10.3±0.3	10.3/10.3	73.5±0.5	12.4±0.3	12.9
Front/Rear 5	1.66±0.01	9.9±0.2	10.1/9.9	72.9±0.7	12.0±0.2	12.4

¹Certified by the NREL