Electronic Supplementary Information

Vacuum-deposited organic solar cells utilizing a low-bandgap non-fullerene acceptor

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1. Experimental Section

Materials and General Methods:

All reactions involving air- or moisture-sensitive compounds were carried out in a dry reaction vessel under a positive pressure of nitrogen. Unless stated otherwise, starting materials were obtained from Adamas, Aldrich, or J&K and were used without further purification. Anhydrous THF and toluene were distilled over Na/benzophenone prior to use. Anhydrous DMF was distilled over CaH₂ prior to use. Compounds 1 and 2 were prepared according to published procedures. ¹H and ¹³C NMR spectra were measured with Bruker Fourier 300, Bruker Avance 400, or Bruker Avance 600 spectrometers. Chemical shifts for hydrogens are reported in parts per million (ppm, scale) downfield from tetramethylsilane and are referenced to the residual protons in the NMR solvent (CDCl₃: 7.26). ¹³C NMR spectra were recorded at 100 MHz. Chemical shifts for carbons are reported in parts per million (ppm, scale) downfield from tetramethylsilane and are referenced to the carbon resonance of the solvent (CDCl₃: 77.2). The data are presented as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, m = multiplet and/or multiple resonances, br = broad), coupling constant in hertz (Hz), and integration. MALDI measurements were performed with a MALDI-FT 9.4 T, Bruker solariX, or MALDI-TOF MS Bruker Autoflex III. Elemental analyses were performed with a Flash EA 1112 Series from ThermoQuest. UV-vis was recorded with Jasco V-570 spectrometers. Cyclic voltammetry (CV) was performed with a CHI620D potentiostat. All measurements were carried out in a one-compartment cell under a nitrogen atmosphere, equipped with a glassy-carbon electrode, a platinum counterelectrode, and an Ag/Ag⁺ reference electrode with a scan rate of 100 mV s⁻¹. The supporting electrolyte was a 0.1 mol/L diluted tetrabutylammonium perchlorate (TBAP) solution in acetonitrile (for acceptor) or methanol (for donor). All potentials were corrected against Fc/Fc⁺. Thermogravimetric analysis (TGA) was performed with a Shimadzu DTG 60 instrument at a heating rate of 10 °C min⁻¹ under a nitrogen atmosphere with runs recorded from room temperature to 600 °C. Differential scanning calorimetry (DSC) was performed with a DSC250 instrument at a heating/cooling rate of 10 °C min⁻¹ under a nitrogen atmosphere for two heating-cooling cycles.

Device Fabrication:

The device structure was: ITO/MoO_x (5 nm)/DTDCTB (x nm)/**CBD** (y nm)/BPhen (10 nm)/Al (100 nm). Organic solar cell devices were fabricated using ITO-coated glass substrates (15 Ω sq⁻¹), which were cleaned with de-ionized water, acetone, and isopropyl alcohol in successive 20 min sonication steps applying a final 20 min oxygen plasma treatment to eliminate any remaining organic component. Organic compounds including the purchased DTDCTB and BPhen, the synthesized **CBD** were purified at least once by temperature-gradient sublimation before vacuum deposition. All the metal oxide, organic films and metal electrodes were deposited layer by layer on the ITO coated glass substrates in a high vacuum chamber with base pressure ~ 1×10⁻⁴ Pa. The deposition was performed at a rate of 0.5–1 Å/s with the substrate held at room temperature. Thicknesses were monitored using a crystal oscillator during deposition and were verified later with spectroscopic ellipsometry. Shadow masks were used to define the OSC active area (0.09 cm²) of the devices.

Device Characterization:

The current density-voltage (J-V) characteristics of unencapsulated photovoltaic devices were measured under N_2 using a KEYSIGHT B2912A Precision Source/Measure Unit. An AAA grade solar simulator, with an AM 1.5 global filter operated at 100 mW cm⁻² was used to simulate the AM 1.5G solar irradiation. The illumination intensity was corrected by using a standard monocrystalline silicon reference cell (AK-200, KONICA MINOLTA, INC) calibrated by the National Institute of Advanced Industrial Science and Technology (AIST). The external quantum efficiency (EQE) was performed using certified incident photon to current conversion efficiency equipment from Enlitech (Taiwan).

Mobility Characterization:

Space charge-limited currents were tested in electron-only devices with a configuration of ITO/ZnO/Layer/Bphen/Al and in hole-only devices with a configuration $ITO/MoO_x/Layer/MoO_x/Al$ to determine the mobilities of the layers. The mobilities were determined by fitting the dark current to the model of a single carrier SCLC

current with field dependent mobility, which is described as

$$J = \frac{9\varepsilon_0 \varepsilon_r \mu_0 V^2}{8L^3} \tag{1}$$

Where *J* is the current, μ_0 is the zero-field mobility, ε_0 is the permittivity of free space, ε_r is the relative permittivity of the material, *V* is the effective voltage, and *L* is the thickness of the active layer. From the plots of $J^{0.5}$ vs. *V*, mobilities can be deduced.

AFM:

Atomic force microscopy (AFM) images of the thin films were obtained on a Nanoscope IIIa AFM (Digital Instruments) operating in tapping mode.

GIWAXS:

Grazing incidence wide-angle X-ray scattering (GIWAXS) is tested in CAS Key Laboratory of Nanosystem and Hierarchical Fabrication, CAS Center for Excellence in Nanoscience, National Center for Nanoscience and Technology, with a XEUSS SAXS/WAXS equipment.

2. Synthesis

CBD. Under protection of nitrogen Pd₂(dba)₃ (26 mg, 0.028 mmol), P(o-tol)₃ (34 mg, 0.11 mmol) was added to a solution of compound **1** (300mg, 0.35mmol) and **2** (224 mg, 0.77 mmol) in 10 mL toluene. The mixture was heated at 110 °C to reflux overnight. The toluene was removed under reduced pressure and the residuary crude product was purified by column chromatography eluating with dichloromethane to obtain **CBD** (153mg, yield 61%) as a dark blue solid. ¹H NMR (300 MHz, CDCl3): δ 8.79-8.77 (m, 4H), 8.29 (s, 2H), 8.05 (d, 3J = 8.1 Hz, 2H), 2.06 (t, 3J = 8.7 Hz, 4H), 1.31-1.16 (m, 4H), 1.14-0.98 (m, 4H), 0.80 (t, 3J = 7.2 Hz, 6H). ¹³C NMR (100 MHz, CDCl3): δ 161.87 , 151.91 , 150.97, 142.84, 141.62, 133.76, 130.71, 124.97, 123.34, 121.26, 114.06, 113.32, 99.98, 81.68, 54.58, 37.70, 26.88, 23.01, 13.87. HRMS (MALDI-TOF) calcd for C₃₇H₂₆N₈S₄ [M]+: 710.11633, found 710.11536 [M]+.

3. Figures



Fig. S1 Statistical plots of (a) energy loss versus PCE of typical high-performance fullerene-based VD-SMSCs (PCEs of over 5%) and (b) optical bandgap_{min} versus energy loss of NFA-based VD-SMSCs (optical bandgap_{min} is the lowest optical bandgap of active layer materials used).



Fig. S2 Thermal gravimetric analysis (TGA) curve of CBD.



Fig. S3 Differential scanning calorimetry (DSC) curve of CBD for the second heatingcooling cycle.



Fig. S4 UV-vis absorption spectra of CBD in chloroform solution and in solid state.



Fig. S5 Cyclic voltammogram of DTDCTB and **CBD** films in diluted MeOH and CH₃CN solution containing tetrabutylammonium perchlorate (TBAP) as supporting electrolyte with a scan rate of 100 mV s⁻¹, respectively. The gray line represents the cyclic voltammetry of Fc/Fc⁺ in TBAP/CH₃CN solution.



Fig. S6 J-V characteristics for the VD-SMSCs based on DTDCTB (x nm)/CBD (y nm) under AM 1.5 G illumination (100 mW cm⁻²).



Fig. S7 Evolution of the photovoltaic parameters over stored time of the optimized device based on DTDCTB/CBD without encapsulation stored in glove box. The results were obtained from 4 independent devices.



Fig. S8 $J_{\rm ph}$ versus $V_{\rm eff}$ characteristic for the optimal device based on DTDCTB/CBD.



Fig. S9 (a) V_{oc} and (b) J_{sc} dependences on light intensity for the optimal device based on DTDCTB/CBD.



Fig. S10 $J^{0.5}$ versus $V_{app}-V_{bi}-V_r$ plots of (a) the electron-only device with a structure of ITO/ZnO/CBD/Bphen/Al; (b) the hole-only device with a structure of ITO/MoO_x/DTDCTB/CBD/MoO_x/Al and (c) the electron-only device with a structure of ITO/ZnO/DTDCTB/CBD/Bphen/Al.



Fig. S11 (a) 2D GIWAXS pattern and (b) out-of-plane and in-plane scattering profiles of the pristine CBD film.

4. Tables

Table S1. Statistical sheet of energy loss versus PCE of typical high-performance fullerene-based VD-SMSCs (PCEs of over 5%).

| Denen | A = = = = = = = = | PCE | $V_{\rm oc}$ | $E_{\rm loss}$ | Ref. | |
|--------------------------------|--------------------------|------|--------------|----------------|------|--|
| Donor | Acceptor | [%] | [V] | [eV] | | |
| DBP | C ₇₀ | 7.9 | 0.92 | 0.85 | [1] | |
| DBP | C ₇₀ | 5.19 | 0.86 | 0.91 | [2] | |
| TPA-SO ₂ -Sprio-TPA | C ₇₀ | 5.4 | 0.94 | 0.83 | [3] | |
| HB194 | C ₆₀ | 6.1 | 0.96 | 0.81 | [4] | |
| DTTh | C_{70} | 5.41 | 0.87 | 0.90 | [5] | |
| DTTz | C ₇₀ | 6.2 | 0.95 | 0.82 | [5] | |
| Dye 8 | C ₆₀ | 6.2 | 0.93 | 0.82 | [6] | |
| DTDCTB | C ₇₀ | 5.81 | 0.79 | 0.67 | [7] | |
| DTDCTB | C ₇₀ | 8.0 | 0.8 | 0.66 | [1] | |
| DTDCPB | C_{70} | 6.8 | 0.93 | 0.73 | [8] | |
| DTDCPB | C_{70} | 9.6 | 0.92 | 0.74 | [1] | |
| DPDCPB | C ₇₀ | 5.6 | 1.0 | 0.73 | [8] | |
| DPDCTB | C ₇₀ | 5.8 | 0.88 | 0.61 | [8] | |
| iBuBTDC | C ₇₀ | 9.3 | 0.94 | 0.61 | [9] | |
| nBuBTDC | C ₇₀ | 7.5 | 0.92 | 0.63 | [9] | |
| antiBuBTDC | C ₇₀ | 7.5 | 0.93 | 0.62 | [9] | |
| DCPNT | C ₇₀ | 8.3 | 0.91 | 0.60 | [10] | |
| DTCPB | C ₇₀ | 6.55 | 0.9 | 0.87 | [11] | |
| DTCPBO | C ₇₀ | 5.96 | 0.95 | 0.82 | [11] | |
| DCV5T-Me3 | C ₆₀ | 6.9 | 0.95 | 0.74 | [12] | |
| DCV-SN5-Et | C ₆₀ | 5.96 | 0.89 | 0.83 | [13] | |
| DCV-S,N-heterohexacenes 1 | C ₆₀ | 5.9 | 0.90 | 0.82 | [14] | |
| DCV-S,N-heterohexacenes 2 | C ₆₀ | 5.9 | 0.95 | 0.75 | [14] | |
| DCV-S,N-heterohexacenes 3 | C ₆₀ | 7.1 | 0.96 | 0.74 | [14] | |
| DCV-S,N-heterohexacenes 4 | C ₆₀ | 5.9 | 0.96 | 0.72 | [14] | |
| DCV-S,N-heterohexacenes 5 | C ₆₀ | 6.6 | 0.97 | 0.71 | [14] | |
| DTPT | C_{70} | 5.64 | 0.98 | 0.79 | [15] | |
| BDP-1 | C ₆₀ | 6 | 0.72 | 0.66 | [16] | |
| BDP-2 | C ₆₀ | 6.4 | 0.76 | 0.65 | [16] | |
| BDP-3 | C ₆₀ | 6.1 | 0.75 | 0.67 | [16] | |
| CuPc | C ₆₀ | 5 | 0.54 | 1.06 | [17] | |
| DIBSQ | C_{70} | 6.32 | 0.87 | 0.78 | [18] | |
| synBTDC | C_{70} | 6.1 | 1.01 | 0.65 | [19] | |
| PYDC | C ₇₀ | 5.1 | 1.06 | 0.99 | [19] | |
| DCV-SN5-1 | C ₆₀ | 6.5 | 0.92 | 0.77 | [20] | |
| TDPM | C ₇₀ | 5.5 | 0.94 | 0.83 | [21] | |
| TAPC | C ₇₀ | 5.23 | 0.91 | 0.86 | [22] | |

| Donor | Acceptor | $E_{\rm g}{}^{\rm opt}{}_{\rm min}$ | $V_{\rm oc}$ | $E_{\rm loss}$ | Dof |
|-----------|---------------------------------|-------------------------------------|--------------|----------------|------|
| Donoi | | [eV] | [V] | [eV] | Kel. |
| tetracene | SubPc | 2.02 | 1.24 | 0.78 | [23] |
| rubrene | SubPc | 2.02 | 1.40 | 0.62 | [24] |
| SubPc | F ₃ SubPc | 2.02 | 1.10 | 0.92 | [25] |
| SubPc | F ₆ SubPc | 2.02 | 1.22 | 0.80 | [25] |
| SubPc | Cl ₆ SubPc | 2.02 | 1.31 | 0.71 | [25] |
| CuPc | F ₁₂ SubPc | 1.60 | 0.16 | 1.44 | [26] |
| SubPc | F ₁₂ SubPc | 2.02 | 0.71 | 1.31 | [26] |
| CuPc | F ₁₃ SubPc | 1.60 | 0.27 | 1.33 | [26] |
| SubNc | F ₁₃ SubPc | 1.67 | 0.70 | 0.97 | [26] |
| SubPc | F ₁₃ SubPc | 2.02 | 0.94 | 1.08 | [26] |
| tetracene | Cl-SubPc | 1.96 | 1.18 | 0.78 | [27] |
| tetracene | Cl-Cl ₆ SubPc | 1.99 | 0.89 | 1.10 | [27] |
| pentacene | Cl-SubPc | 1.73 | 0.87 | 0.86 | [27] |
| pentacene | Cl-Cl ₆ SubPc | 1.73 | 0.50 | 1.23 | [27] |
| pentacene | Cl-Cl ₁₂ SubPc | 1.73 | 0.41 | 1.32 | [28] |
| α-6Τ | Cl-Cl ₁₂ SubPc | 1.95 | 0.35 | 1.60 | [28] |
| POTbc | Cl-SubPc | 1.61 | 0.95 | 0.66 | [29] |
| POTbc | Cl-Cl ₆ SubPc | 1.61 | 0.80 | 0.81 | [29] |
| POTbc | Cl-Cl ₁₂ SubPc | 1.61 | 0.60 | 1.01 | [29] |
| DIP | SubNc/Cl ₆ SubPc | 1.67 | 1.03 | 0.64 | [30] |
| α-6Τ | Cl-SubPc | 1.96 | 1.10 | 0.86 | [31] |
| α-6Τ | PhO-SubPc | 2.01 | 1.17 | 0.84 | [31] |
| α-6Τ | Ph-SubPc | 1.98 | 1.21 | 0.77 | [31] |
| SubPc | FSuBPcDimer | 1.66 | 0.89 | 0.77 | [32] |
| α-6Τ | F ₅ SubPc | 2.02 | 1.16 | 0.86 | [33] |
| α-6Τ | 35F ₂ PhO-SubP | 2.02 | 1.13 | 0.89 | [33] |
| α-6Τ | 246F ₃ PhO-SubPc | 2.02 | 1.20 | 0.82 | [33] |
| α-6Τ | PhO-SubPc | 2.01 | 1.21 | 0.80 | [33] |
| α-6Τ | SubPc | 2.02 | 1.09 | 0.93 | [34] |
| α-6Τ | SubNc | 1.67 | 0.94 | 0.73 | [34] |
| α-6Τ | SubNc/SubPc | 1.67 | 0.96 | 0.71 | [34] |
| α-6Τ | μ -oxo-(SubPc) ₂ | 1.94 | 0.96 | 0.98 | [35] |
| MD376 | CPTQ-Pr | 1.89 | 0.74 | 1.15 | [36] |
| MD376 | CPTQ-Ph | 1.89 | 0.48 | 1.41 | [36] |
| MD376 | CPTQ-EH | 1.89 | 0.88 | 1.01 | [36] |
| MD376 | CPTQ-Oc | 1.89 | 0.86 | 1.03 | [36] |
| CuPc | PTCBI | 1.60 | 0.53 | 1.07 | [37] |
| ZnPc | PTCBI | 1.55 | 0.58 | 0.97 | [37] |
| PdPc | PTCBI | 1.71 | 0.52 | 1.19 | [37] |

Table S2. Statistical sheet of optical $bandgap_{min}$ versus energy loss of NFA-based VD-SMSCs (optical $bandgap_{min}$ is the lowest optical bandgap of active layer materials used, which has been colored in the Table).

| PtPc | PTCBI | 1.76 | 0.49 | 1.27 | [37] |
|--------|-------|------|------|------|-----------|
| DTDCTB | CBD | 1.41 | 0.78 | 0.63 | This Work |

Table S3. Optical and electrochemical properties of CBD.

| Table 55: Optical and electrochemical properties of CDD. | | | | | | | |
|--|----------------------|------------------------|-------------------------|-------|-------|--|--------------------------------|
| | $\lambda_{max, sol}$ | $\lambda_{onset, sol}$ | $\lambda_{onset, film}$ | HOMO | LUMO | $\mathrm{E}_{\mathrm{g}}^{\mathrm{opt}}$ | $\mathrm{E_g}^{\mathrm{elec}}$ |
| | [nm] | [nm] | [nm] | [eV] | [eV] | [eV] | [eV] |
| CBD | 680 | 751 | 878 | -5.42 | -3.84 | 1.41 | 1.58 |
| | | | | | | | |

Table S4. The device performance parameters for the VD-SMSCs based on DTDCTB(5, 10, 20, 30 nm)/CBD (20 nm) under the irradiation of AM 1.5G, 100 mW cm⁻².

| DTDCTB | V | I | FF | DCE |
|-----------|------|-----------------------|---------------|-------------|
| Thickness | | $J_{\rm sc}$ | 1,1, L0/ 1 | FCE [0/] |
| [nm] | [v] | [mA cm ²] | [70] | [70] |
| 5 | 0.73 | 1.84 | 34.88 | 0.47 |
| 10 | 0.78 | 2.93 | 37.58 | 0.86 |
| 20 | 0.76 | 2.52 | 39.40 | 0.76 |
| 30 | 0.75 | 2.25 | 39.09 | 0.66 |

5. NMR Charts



References

- O. L. Griffith, X. Liu, J. A. Amonoo, P. I. Djurovich, M. E. Thompson, P. F. Green and S. R. Forrest, *Phys. Rev. B*, 2015, **92**, 085404.
- [2] Z. Wang, D. Yokoyama, X.-F. Wang, Z. Hong, Y. Yang and J. Kido, *Energy Environ. Sci.*, 2013, 6, 249–255.
- [3] C.-Y. Chan, Y.-C. Wong, M.-Y. Chan, S.-H. Cheung, S.-K. So and V. W.-W. Yam, *Chem. Mater.*, 2014, 26, 6585–6594.
- [4] V. Steinmann, N. M. Kronenberg, M. R. Lenze, S. M. Graf, D. Hertel, K. Meerholz, H. Bürckstümmer, E. V. Tulyakova and F. Würthner, Adv. Energy Mater., 2011, 1, 888–893.
- [5] J. Kim, H.-S. Shim, H. Lee, M.-S. Choi, J.-J. Kim and Y. Seo, J. Phys. Chem. C, 2014, 118, 11559–11565.
- [6] A. Arjona-Esteban, J. Krumrain, A. Liess, M. Stolte, L. Huang, D. Schmidt, V. Stepanenko, M. Gsanger, D. Hertel, K. Meerholz and F. Würthner, *J. Am. Chem. Soc.*, 2015, 137, 13524–13534.
- [7] L-Y. Lin, Y.-H. Chen, Z.-Y. Huang, H.-W. Lin, S.-H. Chou, F. Lin, C.-W. Chen, Y.-H. Liu and K.-T. Wong, J. Am. Chem. Soc., 2011, 133, 15822–15825.
- [8] Y.- H. Chen, L.-Y. Lin, C.-W. Lu, F. Lin, Z.-Y. Huang, H.-W. Lin, P.-H. Wang, Y.-H. Liu, K.-T. Wong, J. Wen, D. J. Miller and S. B. Darling, *J. Am. Chem. Soc.*, 2012, **134**, 13616–13623.
- [9] X. Che, C.-L. Chung, C.-C. Hsu, F. Liu, K.-T. Wong and S. R. Forrest, Adv. Energy Mater., 2018, 8, 1703603.
- [10] C. -K. Wang, X. Che, Y.-C. Lo, Y.-Z. Li, Y.-H. Wang, S. R. Forrest, S.-W. Liu and K.-T. Wong, *Chem-Asian J*, 2020, 15, 2520–2531.
- [11] C.-H. Chen, H.-C. Ting, Y.-Z. Li, Y.-C. Lo, P.-H. Sher, J.-K. Wang, T.-L. Chiu, C.-F. Lin, I.-S. Hsu, J.-H. Lee, S.-W. Liu and K.-T. Wong, ACS Appl. Mater. Interfaces, 2019, 11, 8337–8349.
- [12] R. Fitzner, E. Mena-Osteritz, A. Mishra, G. Schulz, E. Reinold, M. Weil, C. Körner, H. Ziehlke, C. Elschner, K. Leo, M. Riede, M. Pfeiffer, C. Uhrich and P. Bäuerle, J. Am. Chem. Soc., 2012, 134, 11064–11067.
- [13] T. D. Leitner, A. Vogt, D. Popović, E. Mena-Osteritz, K. Walzer, M. Pfeiffer and P. Bäuerle, *Mater. Chem. Front.*, 2018, 2, 959–968.
- [14] C. Wetzel, A. Mishra, E. Mena-Osteritz, K. Walzer, M. Pfeiffer and P. Bäuerle, J. Mater. Chem. C, 2016, 4, 3715-3725.
- [15] C.-L. Chung, C.-Y. Chen, H.-W. Kang, H.-W. Lin, W.-L. Tsai, C.-C. Hsu and K.-T. Wong, Org. Electron., 2016, 28, 229–238.
- [16] T.-y. Li, J. Benduhn, Y. Li, F. Jaiser, D. Spoltore, O. Zeika, Z. Ma, D. Neher, K. Vandewal and K. Leo, *J. Mater. Chem. A*, 2018, 6, 18583–18591.
- [17] J. Xue, B. P. Rand, S. Uchida and S. R. Forrest, Adv. Mater., 2005, 17, 66-71.
- [18] G. Chen, Z. Ling, B. Wei, J. Zhang, Z. Hong, H. Sasabe and J. Kido, Front. Chem., 2018, 6, 412.
- [19] X. Che, C. L. Chung, X. Liu, S. H. Chou, Y. H. Liu, K.-T. Wong and S. R. Forrest, *Adv. Mater.*, 2016, 28, 8248–8255.

- [20] A. Mishra, D. Popovic, A. Vogt, H. Kast, T. Leitner, K. Walzer, M. Pfeiffer, E. Mena-Osteritz and P. Bäuerle, *Adv. Mater.*, 2014, 26, 7217–7223.
- [21] H.-I. Lu, C.-W. Lu, Y.-C. Lee, H.-W. Lin, L.-Y. Lin, F. Lin, J.-H. Chang, C.-I. Wu and K.-T. Wong, *Chem. Mater.*, 2014, 26, 4361–4367.
- [22] M. Zhang, H. Wang, H. Tian, Y. Geng and C. W. Tang, Adv. Mater., 2011, 23, 4960–4964.
- [23] N. Beaumont, S. W. Cho, P. Sullivan, D. Newby, K. E. Smith and T. S. Jones, *Adv. Funct. Mater.*, 2012, 22, 561–566.
- [24] Y. Lin, J. Zhong, X. Yan and L. Li, J. Mater. Sci. Mater. Electron., 2017, 28, 9167–9173.
- [25] P. Sullivan, A. Duraud, I. Hancox, N. Beaumont, G. Mirri, J. H. R. Tucker, R. A. Hatton, M. Shipman and T. S. Jones, *Adv. Energy Mater.*, 2011, 1, 352–355.
- [26] H. Gommans, T. Aernouts, B. Verreet, P. Heremans, A. Medina, C. G. Claessens and T. Torres, *Adv. Funct. Mater.*, 2009, 19, 3435–3439.
- [27] N. Beaumont, J. S. Castrucci, P. Sullivan, G. E. Morse, A. S. Paton, Z.-H. Lu, T. P. Bender and T. S. Jones, *J. Phys. Chem. C*, 2014, **118**, 14813–14823.
- [28] J. S. Castrucci, D. S. Josey, E. Thibau, Z.-H. Lu and T. P. Bender, J. Phys. Chem. Lett., 2015, 6, 3121–3125.
- [29] H. Raboui, D. S. Josey, Y. Jin and T. P. Bender, ACS Omega, 2020, 5, 25264– 25272.
- [30] B. Verreet, K. Cnops, D. Cheyns, P. Heremans, A. Stesmans, G. Zango, C. G. Claessens, T. Torres and B. P. Rand, *Adv. Energy Mater.*, 2014, 4, 1301413.
- [31] D. S. Josey, S. R. Nyikos, R. K. Garner, A. Dovijarski, J. S. Castrucci, J. M. Wang, G. J. Evans and T. P. Bender, ACS Energy Lett., 2017, 2, 726–732.
- [32] B. Verreet, B. P. Rand, D. Cheyns, A. Hadipour, T. Aernouts, P. Heremans, A. Medina, C. G. Claessens and T. Torres, *Adv. Energy Mater.*, 2011, 1, 565–568.
- [33] K. L. Sampson, D. S. Josey, Y. Li, J. D. Virdo, Z.-H. Lu and T. P. Bender, J. Phys. Chem. C, 2018, 122, 1091–1102.
- [34] K. Cnops, B. P. Rand, D. Cheyns, B. Verreet, M. A. Empl and P. Heremans, *Nat. Commun.*, 2014, 5, 3406.
- [35] J. S. Castrucci, R. K. Garner, J. D. Dang, E. Thibau, Z.-H. Lu and T. P. Bender, ACS Appl. Mater. Interfaces, 2016, 8, 24712–24721.
- [36] K. Menekse, P. Chen, B. Mahlmeister, O. Anhalt, A. Kudzus, M. Stolte and F. Würthner, J. Mater. Chem. C, 2020, 8, 15303–15311.
- [37] I. Kim, H. M. Haverinen, Z. Wang, S. Madakuni, Y. Kim, J. Li and G. E. Jabbour, *Chem. Mater.*, 2009, **21**, 4256–4260.