Following in Operando the Structure Evolution-Induced Degradation in Printed Organic Solar Cells with Nonfullerene Small Molecule Acceptor

Kerstin S. Wienhold, Wei Chen, Shanshan Yin, Renjun Guo, Matthias Schwartzkopf, Stephan V. Roth, and Peter Müller-Buschbaum*

Understanding the degradation mechanisms of printed bulk-heterojunction (BHJ) organic solar cells during operation is essential to achieve long-term stability and realize real-world applications of organic photovoltaics. Herein, the degradation of printed organic solar cells based on the conjugated benzodithiophene polymer PBDB-T-SF and the nonfullerene small molecule acceptor IT-4F with 0.25 vol% 1,8-diiodooctane (DIO) solvent additive is studied in operando for two different donor:acceptor ratios. The inner nano-morphology is analyzed with grazing incidence small angle X-ray scattering (GISAXS), and current–voltage (I–V) characteristics are probed simultaneously. Irrespective of the mixing ratio, degradation occurs by the same degradation mechanism. A decrease in the short-circuit current density (JSC) is identified to be the determining factor for the decline of the power conversion efficiency. The decrease in JSC is induced by a reduction of the relative interface area between the conjugated polymer and the small molecule acceptor in the BHJ structure, resembling the morphological degradation of the active layer.

1. Introduction

Organic solar cells show great potential as a renewable energy source, and power conversion efficiencies (PCEs) above 16% were demonstrated for lab-scale devices.[1,2] However, on the way to marketability, the long-term stability of these devices has to be improved, and a large-scale fabrication process has to be developed. To overcome the challenge of upscaling the thin-film deposition, promising techniques, such as spraying, inkjet printing, and meniscus-guided slot-die coating, are introduced in the field of organic photovoltaics.[3–12] Even though the stability of organic solar cells could be improved successfully by the synthesis of new materials,[13–15] end-group and side-chain modification,[16] or the development of an inverted device structure,[17–21] the poor long-term stability of most high-efficiency materials has to be further improved for a commercial breakthrough.[22–26] Therefore, understanding the degradation mechanism of printed bulk-heterojunction (BHJ) photovoltaics is essential to realize the production of large-area organic solar cells with outstanding PCE and excellent long-term stability. The chemical degradation of organic solar cells in the presence of water or oxygen has been studied for many materials and can be avoided by proper encapsulation of the devices.[19,27] However, physical degradation with morphological changes in the active layer occurs even in the absence of reactive molecules as shown for several materials.[22–24] So far, two major pathways of the morphological degradation were identified: Starting from an optimized morphology of the BHJ, either a demixing-induced coarsening of the domains or mixing-induced shrinkage of the domains was identified.[22–24] Domain coarsening in combination with an increase in distances between neighboring domains resulted in a decrease in the short-circuit current density (JSC) during device degradation as first identified for the model system poly(3-hexylthiophene) (P3HT) and phenyl-C61-butyric acid methyl ester (PCBM).[22] Domain shrinkage caused a loss in connectivity, thereby inducing dead ends for charge carriers, and resulted in a fill factor (FF)-driven device degradation as found in the case of poly[2,1,3-benzothiadiazole-4,7-diyl [4,4-bis[2-ethylhexyl]-4H-cyclopenta[2,1-b:3,4-b′] dithiophene-2,6-diyl]], (PCPDTBT) and phenyl-C71-butyric acid methyl ester.
As proved in earlier studies,[22–24] morphology degradation is well studied in operando with a simultaneous measurement of GIXAS and J–V characteristics. To obtain statistical information, four organic solar cells are connected in parallel to measure average J–V characteristics. In addition, in the GIXAS experiment, the X-ray beam is aligned to impinge the sample as a small line, which gives morphological information about the four organic solar cells simultaneously. For GIXAS, we select an incidence angle (of 0.4°) well above the critical angles of the involved materials, such as PBDB-T-SF and IT-4F, to probe information from the full thickness and analyze the inner nano-structure of the active layer.[31,44] The grazing incidence geometry allows analyzing a larger sample area with high statistical significance and to measure thin films with a layer thickness on the order of 100 nm, which is assumed to be the ideal thickness regime for organic solar cells.[28]

2.1. Degradation of Organic Solar Cells with 1:1 and 1:2 Donor:Acceptor Ratio

The 2D GIXAS data of printed organic solar cells with a 1:1 and 1:2 donor:acceptor ratio show the significant change of morphology during operation (Figure S2 and S3, Supporting Information). Within the first 30 min, a fast and distinct structure evolution is observed. At longer illumination times, the change of the morphology decelerates and almost stabilizes but does not fully stop within the time span of the in operando experiment. For 2D GIXAS data analysis, horizontal line cuts (Figure 1a,e) are carried out at the strongest scattering contributions, the critical angle (Yoneda region) of PBDB-T-SF, which is calculated to be 0.12° for the used X-ray energy of 11.65 keV. To obtain the average polymer domain sizes in the active layer, these horizontal line cuts are modeled. The used model is based on the effective interface approximation (EIA) of the distorted wave Born approximation (DWBA).[45,46] To consider the local monodisperse approximation (LMA), the overall scattering intensity is defined as an incoherent superposition of scattering intensities originating from individual polymer domains in the thin film. The GIXAS data are modeled with three cylindrical substructures, which is a well-established approach to characterize the morphology of thin polymer films.[47–49] The respective cylinders are assumed to be pure polymer domains.[22] In Figure 1a,e, horizontal line cuts of the 2D GIXAS data (black dots) for printed organic solar cells based on a 1:1 and 1:2 donor:acceptor ratio and the corresponding modeling results (red lines) are shown for different operation times (from bottom to top). For organic solar cells based on a 1:1 donor:acceptor ratio, the average structure sizes of polymer domains increase under operation (Figure 1b–d). The largest structure (Figure 1b) grows from (80 ± 2) nm to (98 ± 2) nm, whereas the medium structure (Figure 1c) grows from (30 ± 1) nm to (39 ± 1) nm and the smallest structure (Figure 1d) from (10.0 ± 0.5) nm to (17.0 ± 0.5) nm. The corresponding distances are (200 ± 10) nm, (130 ± 10) nm, and (50 ± 5) nm and do not change significantly within the time span of the experiment. For organic solar cells based on a 1:2 donor:acceptor ratio, the largest domain structure (Figure 1f) grows from (90 ± 2) nm to (117 ± 2) nm. The medium structure size (Figure 1g) is about (29 ± 1) nm at the start of the operation and grows to (36 ± 1) nm during operation, which is similar to
the findings obtained for the device based on a 1:1 donor:acceptor ratio. In contrast, the size of the smallest polymer domains (Figure 1h) is reduced from $(12.5 \pm 1.0) \text{nm}$ to $(6.5 \pm 1.0) \text{nm}$, which is a trend opposite to what is found in the 1:1 donor:acceptor ratio device. The corresponding distances are $(200 \pm 10) \text{nm}$, $(100 \pm 10) \text{nm}$, and $(40 \pm 5) \text{nm}$ and do not alter during the operation.

The observed structural growth under operation of a printed organic solar cell based on a 1:1 ratio of PBDB-T-SF:IT-4F shares a limited similarity to findings from previous studies performed on spin-coated P3HT:PCBM devices with a 1:1 donor:acceptor ratio.\(^{[22]}\) However, for such fullerene-based organic solar cells, the increase in domain sizes and also the average distance between medium-sized domains increased significantly under illumination. In active layers prepared with solvent additive, so far, a domain shrinkage was reported as a morphology degradation mechanism instead of a domain coarsening.\(^{[23]}\) Therefore, for the PBDB-T-SF:IT-4F solar cells of this study being manufactured with 0.25 vol% 1,8-diiodooctane (DIO) as solvent additive,\(^{[50]}\) the observed domain coarsening is unexpected.

The observed morphological degradation in PBDB-T-SF:IT-4F solar cells based on a 1:2 ratio shares no similarity with previous studies performed on organic solar cells with an excess of acceptor. Schaffer et al. observed a decrease in the medium and smallest domain sizes under illumination of a spin-coated PCPDTBT:PCBM-based organic solar cell with a 1:2.7 donor:acceptor ratio prepared with solvent additive.\(^{[24]}\) For a spin-coated PTB7-Th:PCBM-based device with a donor:acceptor of 1:1.5, Yang et al. observed decreasing average structure sizes for devices processed with solvent additive.\(^{[23]}\) In both systems, the FF and not the $J_{SC}$ were detrimental to the device failure. The amount of residual solvent additive was determined by the relative scattering intensity at the critical angle of the respective compound.\(^{[23,24]}\)

A loss in solvent additive was found responsible for the domain shrinkage in previous works, which is not observed in this study (Figure S5, Supporting Information). This is favorable, as DIO was found to enhance the device performance of printed PBDB-T-SF:IT-4F-based organic solar cells by provoking the formation of small polymer domains in the BHJ layer.\(^{[50]}\)

In contrast to previous studies, structure coarsening without altering the average distances between polymer domains is found to be the crucial factor for device failure in our work. We assume this is due to different chemical structures of the active materials, which provoke different interactions of the donor and acceptor molecules with surrounding molecules. During device degradation, rearrangement of the polymer can occur provoking microstructure evolution and charge trapping. However, the aggregation of the nonfullerene small molecule acceptor is diffusion-limited and, therefore, has a stabilizing effect on the BHJ morphology.\(^{[21]}\) In addition, in this study, the correlated roughness determined by vertical line cuts of the 2D GISAXS data is only poorly developed and changes only slightly or even decreases under illumination (Figure S4, Supporting Information), which differs from previous studies, which observed a significant increase in correlated roughness for solar organic solar cells.

**Figure 1.** Temporal evolution of the morphology of printed organic solar cells based on a a–d) 1:1 PBDB-T-SF:IT-4F ratio and e–h) 1:2 ratio. a,e) Horizontal line cuts of the 2D GISAXS data (black dots) and modeling results (red lines) by applying a model based on the DWBA and the LMA are shown for different time steps of operation (0, 2, 5, 15, 30, 60, 90, 140, 190, and 240 min, from bottom to top). Parameters determined from the GISAXS modeling are the average domain sizes for the b,f) largest, c,g) medium, and d,h) smallest polymer domains. The error bars give a range in which the fit still describes the scattering data. The solid black lines (in (b–d) and (f–h)) are guides to the eye.
cells processed with DIO. Thus, the different degradation mechanism found for PBDB-T-SF:IT-4F solar cells as compared with other systems is attributed to the different mobility and interactions of the involved donor and acceptor materials.

2.2. Modeling the Degradation of the Short-Circuit Current Density

From the three different characteristic structure sizes determined in the GISAXS data analysis, the size of the medium substructure, which is about some tens of nanometer, is expected to be the crucial factor, as it is close to the scale of typical exciton diffusion lengths determined for several organic solar cell materials. For slot-die-coated active layers based on PBDB-T-SF:IT-4F, the size of the medium substructure is about 30 nm. The morphology observed with atomic force microscopy (AFM) for spin-coated active layers is similar to the morphology observed for slot-die-coated PBDB-T-SF:IT-4F films even though the largest structure was not reported in the previous study.

To correlate the morphological changes obtained from the scattering experiment with the solar cell performance, I–V curves are measured simultaneously, and the characteristic device parameters are extracted. The initial parameters are given in Table S1, Supporting Information. Figure 2a,c shows the temporal evolution of the normalized device parameters, namely, the PCE, $J_{SC}$, $V_{OC}$, and FF of printed organic solar cells based on a 1:1 and a 1:2 donor:acceptor ratio within the first 4 h of illumination. The degradation of $J_{SC}$ is identified to be the determining factor for the decay of the solar cell performance, as the device parameters $V_{OC}$ and FF stabilize after 30 min and the relative values do not drop below 0.91 for the $V_{OC}$ and 0.86 for the FF within the timescale of the experiment. Based on the knowledge from earlier studies of P3HT:PCBM solar cells, the significant reduction of the normalized $J_{SC}$ to 0.76 for a 1:1 and 0.80 for a 1:2 donor:acceptor ratio is expected to result from a structure coarsening and a related reduction of the interface-to-volume ratio between donor and acceptor. As exciton splitting takes place at the interface, the probability of exciton dissociation into free charge carriers depends critically on the interface between donor and acceptor. Figure 3 shows the structure coarsening and reduction of interface-to-volume ratio in the BHJ during operation. In our model approach, in agreement with the model described by Schaffer et al., it is assumed that only the medium-sized domains significantly contribute to the solar cell performance, as typical exciton diffusion lengths are in a similar range. In accordance with the model applied to describe the scattering data, polymer domains are described as cylinders (Figure 3a,c). In the model, a photon is absorbed by a polymer molecule within a cylindrical shaped domain, and an exciton is generated, which moves to the donor:acceptor interface where dissociation into free charge carriers occurs. The probability for this process depends on the relative interface area between the polymer and the acceptor.

Figure 2. Degradation of normalized device parameters during operation for a printed organic solar cell based on a,b) 1:1 and c,d) 1:2 donor:acceptor ratio of PBDB-T-SF:IT-4F in terms of a,c) PCE (green), $J_{SC}$ (blue), $V_{OC}$ (red), and FF (black). b,d) Comparison of the measured (blue) and theoretically predicted $J_{SC}$ (black dots) using a model as explained in the text. The error bars arise from the GISAXS modeling error.
which is defined as the interface-to-volume ratio of the polymer cylinder. Excitons that move along the length of the cylinder will undergo recombination before reaching the interface and do not contribute to the $J_{SC}$. Therefore, the photocurrent is independent of the length of the cylinder, and a consideration of the cylinder cross section is sufficient to explain the evolution of the relative $J_{SC}$. The probability of exciton dissociation and generation of photocurrent depends on the relative interface area and, respectively, on the circumference of the cylinder (Figure 3b,d). Equation (1) is based on a model developed by Schaffer et al. to predict the degradation of the normalized $J_{SC}$ in a P3HT:PCBM-based spin-coated organic solar cell during operation. Equation (1) is the theoretically predicted value applying the model from Equation (1) (black dots). The error bars are estimated by calculating the theoretically predicted $J_{SC}$ (Equation (1)) for the upper and lower domain size limit as determined in the GISAXS data modeling. Model and experiment are in excellent agreement. Therefore, the decrease in the interface-to-volume ratio is identified as the determining factor for the significant degradation of the $J_{SC}$ during operation. The reduction of the relative $J_{SC}$ to 0.76 for a 1:1 or 0.80 for a 1:2 donor:acceptor ratio provokes a decline of the normalized PCE to 0.63.

3. Conclusion

In the in operando study, we compared printed organic solar cells with two different donor:acceptor ratios of 1:1 and 1:2. Irrespective of the mixing ratio, degradation occurs by the same degradation mechanism, and a decrease in the $J_{SC}$ is identified to be the determining factor for the decline of the PCE. With GISAXS, the growth of polymer domains is observed, whereas the domain distances remain unchanged, which causes a reduction of the interface-to-volume ratio in the BHJ. Thereby the probability of exciton dissociation is lowered. The observed decline of the $J_{SC}$ correlates very well with the calculated current based on the changed nanoscale BHJ structure. Thus, the morphology degradation is leading to the device failure.

The degradation mechanism observed for printed PBDB-T:IT4F-based devices differs from previous studies on spin-coated fullerene-based organic solar cells. Therefore, new materials should be studied in operando, as knowledge gained from one material system might not simply be transferred to other materials or processing conditions. The presented results give insight into the degradation of meniscus-guided slot-die-coated organic solar cells and are a first step toward the development of long-term stable organic photovoltaics.

4. Experimental Section

Device Fabrication: In this work, organic solar cells with an inverted geometry (glass/indium tin oxide (ITO)/BHJ/MoO3/Al) were fabricated. The conjugated polymer poly[(2,6-(4,8-bis(5-(2-ethylhexylthio)-4-fluorothiophen-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)], denoted

Figure 3. Schematic of the morphology evolution in the active layer during operation as assumed in the model with only a small fraction of acceptor molecules shown for clarity of the presentation. a) At the start of the operation, a BHJ structure with small polymer domains (blue cylinders) and small molecule acceptor domains (red cuboids) is observed. b) A cross section of a polymer cylinder with a small radius is shown. A high interfaceto-volume ratio facilitates exciton dissociation into free charge carriers at the donor–acceptor interface. The electron (orange) and the electron hole (green) move toward the electrodes and a high $J_{SC}$ is measured experimentally. The relative interface area is given by the circumference (purple) of the cylinder per cross-sectional area. c) Under illumination, a growth of polymer domains occurs. d) In the cross section, a reduction of interface (purple) between donor and acceptor is observed provoking a reduction of exciton dissociation probability. In a polymer cylinder with large radius, the interface-to-volume ratio is reduced provoking a reduction of exciton dissociation probability and $J_{SC}$. The probability of exciton dissociation and generation of photocurrent depends on the relative interface area and, respectively, on the circumference of the cylinder (Figure 3b,d). Equation (1) is based on a model developed by Schaffer et al. to predict the degradation of the normalized $J_{SC}$ in a P3HT:PCBM-based spin-coated organic solar cell during operation. Equation (1) is the theoretically predicted value applying the model from Equation (1) (black dots). The error bars are estimated by calculating the theoretically predicted $J_{SC}$ (Equation (1)) for the upper and lower domain size limit as determined in the GISAXS data modeling. Model and experiment are in excellent agreement. Therefore, the decrease in the interface-to-volume ratio is identified as the determining factor for the significant degradation of the $J_{SC}$ during operation. The reduction of the relative $J_{SC}$ to 0.76 for a 1:1 or 0.80 for a 1:2 donor:acceptor ratio provokes a decline of the normalized PCE to 0.63.

3. Conclusion

In the in operando study, we compare printed organic solar cells with two different donor:acceptor ratios of 1:1 and 1:2. Irrespective of the mixing ratio, degradation occurs by the same degradation mechanism, and a decrease in the $J_{SC}$ is identified to be the determining factor for the decline of the PCE. With GISAXS, a growth of polymer domains is observed, whereas the domain distances remain unchanged, which causes a reduction of the interface-to-volume ratio in the BHJ. Thereby the probability of exciton dissociation is lowered. The observed decline of the $J_{SC}$ correlates very well with the calculated current based on the changed nanoscale BHJ structure. Thus, the morphology degradation is leading to the device failure.

The degradation mechanism observed for printed PBDB-T:IT4F-based devices differs from previous studies on spin-coated fullerene-based organic solar cells. Therefore, new materials should be studied in operando, as knowledge gained from one material system might not simply be transferred to other materials or processing conditions. The presented results give insight into the degradation of meniscus-guided slot-die-coated organic solar cells and are a first step toward the development of long-term stable organic photovoltaics.
PBDB-T:SF and the small molecule acceptor 3-(3-bis(2-methylene)-(33-(1,1-dicyanomethylene)-6,7-difluoro-indanone))-5,5,11,11-tetrakis(4-hexyloxyphenyl)-dithiieno[2,3-d:2′,3′-d′]-s-indaceno[1,2-b:5,6-b′]dithiophene, denoted IT-4F, were purchased from Solarmer Energy Inc. Appropriate donor:acceptor ratios were dissolved in chlorobenzene (Merck KGaA) with 0.25 vol% 1,8-DIO (Carl Roth GmbH) as solvent additive. The 7 mg mL⁻¹ solution was stirred at 100 °C for 24 h before slot-die coating the active layer. ITO-coated substrates (SOLEMS S.A., 12 Ω sq⁻¹ sheet resistance, 7.5 cm × 2.5 cm) were sequentially ultrasonically cleaned for 20 min with Alconox (Merck KGaA), deionized water, acetone (Merck KGaA), and isopropanol (Merck KGaA) and plasma treated for 10 min (Plasma-System-Nano, Diener Electronic GmbH, 0.4 mbar, O₂, 83% power). Zink acetate dehydrate (1 g) (Merck KGaA) was dissolved in 10 mL 2-methoxyethanol (Merck KGaA) and 284 μL ethanolamine (Merck KGaA) and stirred for 8 h at room temperature. This precursor solution was spin-coated (5000 rpm, 60 s) on the ITO-coated glass substrates. After annealing at 200 °C for 60 min in air, the substrates were cooled down to room temperature before thin-film deposition. Meniscus-guided slot-die coating was performed at ambient conditions and room temperature with a flow rate of 10 μL s⁻¹, a printing velocity of 10 mm s⁻¹, and a height (distance between printer head and substrate) of 1 mm to achieve a dry film thickness of (100 ± 15) nm. After printing, the samples were cut into slices (2.5 × 2.5 cm²) and transferred into a N₂-filled glove box. Thin layers of MoO₃ (10 nm, Carl Roth GmbH) and Al (10 nm, chemPUR) were thermally evaporated under vacuum conditions (10⁻⁵ mbar). The solar cells were transported to the synchrotron source in sealed, non-transparent containers filled with N₂ to avoid degradation by oxygen, air humidity, or ambient light.

**Set up and Measurement Conditions:** Printed organic photovoltaics based on PBDB-T:SF:IT-4F with a device area of 2.5 cm × 2.5 cm and a pixel size of 0.12 cm² were used without encapsulation. The devices were inserted into a vacuum chamber (10⁻⁷ mbar) to exclude degradation by oxygen and air humidity. The chamber walls were cooled with water (15 °C) to avoid a temperature-induced decrease in the solar cell performance.

**Grazing Incidence Small Angle X-Ray Scattering (GISAXS):** GISAXS was performed at the MiNaXS beamline P03 at the PETRA III synchrotron source at DESY, Hamburg.⁵¹ Measurements were carried out with a wavelength of 0.10642 nm and a sample-detector distance of 5262 mm. The incidence angle was aligned to 0.4° before the scattering experiment. A Pilatus 1 M detector (Dectris Ltd.) with a pixel size of 172 × 172 μm² was used for detecting the GISAXS signal. Oversaturation of the detector was avoided by a beamstop applied at the specular beam position. In operando, GISAXS was performed at one fixed position on the active layer close to the electrodes to avoid scattering contributions from the metal contacts. Measurements of 0.1 s were performed after 0, 2, 5, 15, 30, 60, 90, 140, 190, and 240 min of operation. Tests on radiation damage were done for each solar cell to rule out this problem for all systems studied (Figure S6, Supporting Information). Scattering data were analyzed and calibrated (sample-detector distance, beam center) using an open source Python program named Directly Programmable Data Analysis Kit (DPDAK).⁵² Horizontal line cuts were carried out at the critical angle of PBDB-T:SF, which was calculated to be 0.12° for the applied X-ray energy of 11.65 keV. The current–voltage characteristics were recorded every 20 s with a SourceMeter Keithley 2400 under AM1.5 illumination (100 mW cm⁻²). To record average J–V characteristics with high statistical significance, four solar cell pixels close to the GISAXS measurement position were connected in parallel. For the organic solar cell based on a 1:1 donor:acceptor ratio, the initial PCE was 2.3%. The device based on a donor:acceptor ratio of 1:2 achieved a PCE of 4.5% at the start of the device operation.

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

**Acknowledgements**

The authors acknowledge funding from Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) via International Research Training Group 2022 Alberta/Technical University of Munich International Graduate School for Environmentally Responsible Functional Materials (ATUMS) and under Germany’s Excellence Strategy—EXC 2089/1—390776260 (e-conversion) and as well as from TUM.solar in the context of the Bavarian Collaborative Research Project Solar Technologies Go Hybrid (SoTech) and the Center for NanoScience (CeNS). K.S.W. acknowledges funding by the Hans Böckler Stiftung and W.C., S.Y., and R.G. by the China Scholarship Council (CSC). In operando, GISAXS experiments were carried out at the light source PETRA III at DESY, a member of the Helmholtz Association (HGF).

**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

degradation mechanisms, meniscus-guided slot-die coatings, organic solar cells, short-circuit currents

[Received: May 16, 2020  
Published online: June 8, 2020]

---

[1] Q. An, X. Ma, J. Gao, F. Zhang, Sci. Bull. 2019, 64, 504.
[2] B. Fan, D. Zhang, M. Li, W. Zhong, Z. Zeng, L. Ying, F. Huang, Y. Cao, Sci. China Chem. 2019, 62, 746.
[3] C. N. Hoth, P. Schilinsky, S. A. Choulis, C. J. Brabec, Nano Lett. 2008, 8, 2806.
[4] C. N. Hoth, S. A. Choulis, P. Schilinsky, C. J. Brabec, Adv. Mater. 2007, 19, 3973.
[5] F. C. Krebs, Sol. Energy Mater. Sol. Cells 2009, 93, 394.
[6] T. M. Eggenhuisen, Y. Galagan, A. F. K. V. Biezemans, T. M. W. L. Slaats, W. P. Voorhuisijzen, S. Kommeren, S. Shanmu, J. P. Teunissen, A. Hadipour, W. J. H. Verhees, S. C. Veenstra, M. J. J. Coer, J. Gilot, R. Andriessen, W. A. Groen, J. Mater. Chem. A 2015, 3, 7255.
[7] J. Chang, C. Chi, J. Zhang, J. Wu, Adv. Mater. 2013, 25, 6442.
[8] F. Liu, S. Ferdous, E. Schäibli, A. Hexemer, M. Church, X. Ding, C. Wang, T. P. Russell, Adv. Mater. 2015, 27, 886.
[9] S. Prollér, F. Liu, C. Zhu, C. Wang, T. P. Russell, A. Hexemer, P. Müller-Buschbaum, E. M. Herzig, Adv. Energy Mater. 2016, 6, 1501580.
[10] X. Gu, L. Shaw, K. Gu, M. F. Toney, Z. Bao, Nat. Commun. 2018, 9, 534.
[11] C. Grotto, D. Moia, B. P. Rand, P. Heremans, Adv. Funct. Mater. 2011, 21, 64.
[12] D. Vak, S.-S. Kim, J. Q., S.-H. Oh, S.-I. Na, J. Kim, D.-Y. Kim, Appl. Phys. Lett. 2007, 91, 81102.
[13] S. M. McAffee, S. V. Dayneko, P. Josse, P. Blanchard, C. Cabanetos, G. C. Welch, Chem. Mater. 2017, 29, 1309.
[14] S. Holliday, R. S. Ashraf, A. Wadsworth, D. Baran, S. A. Yousaf, C. B. Nielsen, C. H. Tan, S. D. Dimitrov, Z. Shang, N. Gasparini, M. Alamoudi, F. Laquai, C. J. Brabec, T. P. Russell, S. Shanmugam, J. P. Teunissen, W. J. H. Verhees, T. M. W. L. Slaats, W. P. Voorhuisijzen, S. Kommeren, S. Shanmu, J. P. Teunissen, A. Hadipour, W. J. H. Verhees, S. C. Veenstra, M. J. J. Coer, J. Gilot, R. Andriessen, W. A. Groen, J. Mater. Chem. A 2015, 3, 7255.
