In Situ Graded Passivation via Porphyrin Derivative with Enhanced Photovoltage and Fill Factor in Perovskite Solar Cells

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While perovskite solar cells (PSCs) have recently experienced a rapid rise in power conversion efficiency (PCE), the prevailing PSCs still contain nondesirable defects in the interior and interface of the perovskite layer, which limits further enhancement in PCE and device stability. Herein, a new D–π–A-type zinc pyridine porphyrin derivative (ZnPP) is synthesized and used as a passivation molecular via the antisolvent process for modifying the typical perovskite bulk thin film, leading to a new type of PSC with a graded passivation of the perovskite layer. Impressively, it is found that ZnPP treatment significantly improves the quality of perovskite films and reduces charge transport losses through passivating the uncoordinated Pb2+ cations, yielding devices with a high efficiency of 21.08% with fill factor (FF) of 82.91% and demonstrating the promise of integration of perovskite bulk thin films with tailor molecular via graded modification.

1. Introduction

Although organic–inorganic perovskites are known from the 19th century, unprecedented advances have been made in the past decade with the certified power conversion efficiency (PCE) now reaching 25.5%. High photocurrents, simple and low-cost fabrication processes, and the intrinsic advantages of perovskite materials promise to make perovskite solar cells (PSCs) one of the most competitive candidates for the future development of photovoltaic market. However, the formation of defects on the surface and grain boundaries of the perovskite films is inevitable when conventional solution-processed processes are used. These defects provide sites for nonradiative recombination and play a role in the perovskite degradation which compromises both device performance and stability. Theoretical studies have indicated that the defects mainly consist of I vacancy defects (VI) and I vacancies replaced by Pb antisite defects (PbI) because of their low formation energy.

In other words, most of the defects in or on the perovskite films are related to uncoordinated Pb2+ ions. And, in high-quality perovskite polycrystalline thin films that have monolayered grains, interior defects of perovskite are microscale compared with the surface defects. In previous studies, it has been proven to be gradient passivation and mainly concentrated on the surface of perovskite by in situ depositing the passivation molecular in the antisolvent. Therefore, this method has natural advantages to fully optimize the perovskite device under the smallest change in film composition and the simplest operating procedures. Basically, by using this in situ method, the passivation molecular is required to be effective and the antisolvent soluble.

To date, numerous functional groups, such as pyridine, amine groups, sulfonate, carbonyl groups, which can react with uncoordinated Pb2+ have been investigated to passivate defects and thus inhibit nonradiative recombination in perovskite films. Porphyrins are heterocyclic macromolecular compounds with highly conjugated structures; the π–π stacking between molecules is conducive to charge transfer; and the structure can be easily modified by specific functional groups because there are multiple reaction sites at the meso- and β-positions. Moreover, due to the unique structures, porphyrins present outstanding thermal stability and excellent photophysical and electrochemical properties, for example, excellent near-UV light harvest and charge transport abilities. Therefore, porphyrins are considered as promising candidate materials for use in PSCs.

Recently, porphyrin used as additives for PSCs has gained outstanding achievement. Lin and co-workers had found porphyrin
YD2-o-C8 was a valuable passivator for three cationic perovskite solar cells and it can efficiently suppress defects and adjust energy-level alignment of perovskite film, which helped the PSCs to get a high PCE with 20.5%. Gao et al. also used a series of D–π–A porphyrins with cyanoacrylic acid as acceptor to passivate the perovskite surface and obtained a best efficiency of 22.37%. Cao and co-workers demonstrated that monoammonium porphyrin assisted PSCs to achieve a high PCE by controlling the crystallization, passivating defects, and/or promoting hole transport when embedded into the perovskite film. Cao’s group also found that porphyrin with thiol could coordinate with Pb defects and help PSCs to get a better efficiency by treating the surface of perovskite film. Porphyrin with other functional groups also shown great potential in improving PSCs or OPV/PSCs efficiency. The above case shows that porphyrin molecules have great potential in passivation of PSCs.

Herein, a new D–π–A-type zinc pyridine porphyrin derivative 5,15-dipyridyl-10,20-bis(4-(N,N-bis(4-methoxyphenyl)amino)benzyl) porphyrin zinc (coded as ZnPP, Figure 1a) was designed and synthesized for use as a passivation molecular which was incorporated in the film during the antisolvent treatment to improve the performance of PSCs. Pyridine is introduced into porphyrin molecular as a functional group to interact with uncoordinated Pb\(^{2+}\). Triarylamine at 10,20-positions is used as a donor group to tailor the electron density distribution in the pyridine group through porphyrin as a π bridge, and increase the pyridine’s coordination with exposed Pb\(^{2+}\) cations. The large steric hindrance of triarylamine will also decrease the aggregation of the porphyrin molecular. After treatment with a small amount of ZnPP, the perovskite films showed higher crystallinity, more uniform morphology, and lower trap density compared to the primary film. These improvements lead to a higher champion PCE of 21.08% for the ZnPP-treated devices, in contrast to the 20.18% of the best control device. Moreover, the stability of unencapsulated PSC devices with ZnPP treatment showed an improvement compared to the control cells. This work provides new insights for the use of porphyrin derivatives to improve the performance of PSCs.

![Figure 1. a) Chemical structure and b) ESP of ZnPP; c–e) FTIR spectra of powder samples of ZnPP and mixture of ZnPP and PbI2; XPS spectra of f) Pb 4f and g) Zn 2p for the control and ZnPP-treated perovskite films.](image-url)
2. Results and Discussion

A new D-π-A-type zinc porphyrin complex derivative ZnPP, with triphenylamine as donor, pyridine as acceptor, and porphyrin as π bridge, was designed and synthesized for use as a passivation molecular in PSCs. ZnPP was obtained through MacDonald 2 + 2 cyclization and the detailed synthetic procedures are presented in Scheme S1, Supporting Information. An electrostatic potential (ESP) map of ZnPP was calculated by using Gaussview software with self-consistent field (SCF) density matrix and is presented in Figure 1b. It is clearly shown that the negative charges are mainly located on the N atom of the pyridine, which is expected to coordinate with Pb2⁺ cations and the triphenylamine group is the electron-rich group conjugating with the electron-withdrawing group through the large delocalized π system supplied by the porphyrin. The UV–vis spectra and fluorescence emission spectra of ZnPP in chlorobenzene (CB) are shown in Figure S1a, Supporting Information. ZnPP exhibited a strong Soret absorption peak at 419 nm with two weak Q bands at 557 and 602 nm. When the ZnPP solution was irradiated with a xenon lamp at 419 nm, the maximum fluorescence emission peak appeared at 629 nm. With longer storage time, the originally clarified chlorobenzene solution will begin to precipitate, and an obvious redshift (about 38 nm) in the UV–vis spectra was observed before and after the addition of PbI₂ (Figure S3, Supporting Information). These results indicated the interaction between ZnPP and PbI₂. X-ray photoelectron spectroscopy (XPS) measurements were carried out to further investigate such interactions between ZnPP and the perovskite. For the pure perovskite film without ZnPP treatment, there are two main Pb 4f peaks located at 138.48 and 143.39 eV, corresponding to the Pb 4f7/2 and Pb 4f5/2, respectively, and two small peaks at lower binding energy being related to the metallic Pb0 which is generally believed to be strongly tied to the defects (Figure 1f). After embedding ZnPP into the perovskite films, the Pb 4f signals shifted to lower binding energies (BEs) of 138.34 and 143.24 eV, respectively, and the relative content ratio of Pb0 to the total Pb content (Pb0/(Pb0 + Pb2⁺)) decreased from 6.5% in the control film to 3.8%, indicating the passivating interaction between the ZnPP and the undercoordinated Pb2⁺ ions in the perovskite film. As shown in Figure 1g, the binding energy of Zn 2p3/2 at 1021.81 eV was observed in the ZnPPTreated perovskite film, suggesting the presence of porphyrin in the perovskite films.

The amount of ZnPP plays a vital role in fabricating perovskite thin films. To examine the influence of it on the surface morphology of perovskite films, the scanning electron microscope (SEM) analysis was carried out (Figure 2a–d). The grain sizes of the perovskite films were measured, and the statistics are summarized in Figure 2e. The compact film without ZnPP was formed with an average grain size of about 680 nm. After incorporation of ZnPP, the average perovskite

![Figure 2. Top-view SEM of perovskite film a) without, with b) 0.02 mg mL⁻¹, c) 0.05 mg mL⁻¹, and d) 0.08 mg mL⁻¹ of ZnPP in CB, e) statistics grain size of perovskite with different concentration of ZnPP treatment, f,g) indexed XRD patterns of perovskite films with different concentration of ZnPP treatment, and h) UV–vis absorption spectra of perovskite thin films with (0.05 mg mL⁻¹) and without ZnPP treatment.](image-url)
grain sizes (799.8, 829.4, 754.6 nm for 0.02, 0.05, 0.08 mg mL\(^{-1}\), respectively) become larger and get maximum at a concentration of 0.05 mg mL\(^{-1}\), suggesting the ZnPP treatment could effectively improve the growth of perovskite grains. XRD patterns were also measured to investigate the influence of the ZnPP treatment on the structure of the perovskite. As presented in Figure 2f,g, the peaks at 14.11°, 24.45°, and 28.28° were indexed to the (100), (111), and (200) lattice planes of the typical perovskite, respectively.\(^{136}\) Compared to the control film, there are no additional peaks, and no peak shifts for the films treated by ZnPP treatment, manifesting that the ZnPP molecular was only attached to the interface and surface of perovskite film and did not change the crystal structure of the perovskite.\(^{37}\) However, the target samples exhibited stronger diffraction intensities and narrower full widths at half maximum (FWHM) at 2\(\theta = 14.11^\circ\), especially for the 0.05 mg mL\(^{-1}\) ZnPP-treated film, in which the FWHM decreased from 0.090° (control film) to 0.073° (Figure 2g). As is known, the higher intensities suggest better crystallinity and the narrower FWHM is indicative of larger average crystal sizes.\(^{38}\) The XRD results further confirm that the ZnPP treatment could contribute to higher quality perovskite films, but above an optimal concentration, negative effects can be observed, in agreement with the SEM results discussed above. UV–vis absorption spectra of perovskite thin films without and with (0.05 mg mL\(^{-1}\)) ZnPP are shown in Figure 2h. For both perovskite films, the absorption edge onset at about 800 nm and the spectra show no shift. And the treated film displayed a slight absorption enhancement, which could be related to the improvement of film quality.\(^{39}\) Based on the results of the SEM, XRD, and UV–vis absorption analysis, we note that neither the incorporation of ZnPP change the cubic perovskite nor the ZnPP participate in the lattice formation of the 3D perovskite. Briefly, the ZnPP dripped in perovskite layer just acted as heterogeneous nucleation sites for the crystallization of 3D perovskite to improve crystal formation and growth. Moreover, as time of flight secondary ion mass spectrometry (TOF-SIMS) shown in Figure S4, Supporting Information, the perovskite thin film with rich ZnPP at the top surface and its concentration gradually decreased at the bottom after spin coating.\(^{16,17}\)

The surface properties of with (0.05 mg mL\(^{-1}\)) and without ZnPP-treated perovskite films were further analyzed by atomic force microscopy (AFM). As observed in Figure 3a,b, the incorporation of ZnPP yields a smoother film surface. The root mean square (RMS) roughness of the perovskite film treated with the 0.05 mg mL\(^{-1}\) solution of ZnPP was decreased from 24.8 nm for the control perovskite film to 23.8 nm, suggesting a smoother surface for the ZnPP-treated film. Some recent studies have shown that the interfacial defects between the perovskite film and the HTM (i.e., Spiro-OMeTAD) layer have a stronger negative influence on the PCE when compared to that of the grain

![AFM images](attachment:afm_images.png)

**Figure 3.** The AFM images of perovskite thin film a) without and b) with 0.5 mg mL\(^{-1}\) ZnPP treatment, c) normalized CWPL spectra excited at 470 nm, and d) TRPL decay of these films on a glass substrate.
boundaries.\cite{40,41} It is therefore conceivable that the smoother surface of the perovskite film leads to less interfacial defects at the perovskite/HTM interface, thus an improved PCE. Moreover, as shown in the continuous-wave photoluminescence (CWPL) spectroscopy (Figure 3c), the PL peaks also show no shift, which agrees with the observed UV–vis absorption edge. Furthermore, the ZnPP-treated perovskite film deposited on glass substrate gives an enhanced PL intensity compared with the control perovskite film when the films were excited at 470 nm, indicating that ZnPP effectively suppressed the nonradiative recombination defects.\cite{41} However, when we deposited the perovskite films on FTO/SnO2 layer, the faster PL quenching for modified perovskite mostly be assigned to the faster charge transfer (Figure S5a, Supporting Information). PL for the perovskite/Spiro-OMeTAD films was also conducted as shown in Figure S5b, Supporting Information; the films with ZnPP treated also appeared an increase PL quenching than the control films. Time-resolved PL (TRPL) measurements of the films were performed, and the results fitting with a biexponential decay formula: 

\[
f(t) = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)
\]

are shown in Figure 3d and Table S1, Supporting Information. The ZnPP-treated perovskite film exhibits photocarrier lifetimes that were more than three times those of the control film, indicating a reduced trap density and a slower photocarrier recombination rate. The extended lifetime also suggests that the ZnPP incorporation improves the quality of the perovskite film, where defect concentrations are minimized and thus the recombination of photocarriers is suppressed. However, the ZnPP-treated samples that with ETL or with HTM both showed the shorter average carrier lifetime constant \(\tau_{ave}\) than the control one, illustrating that the charge transfer between the perovskite and charge transport layers was improved (Figure S6, Supporting Information).

![Figure 4.](image)

**Figure 4.** a) The structure of device we used in this work, b) cross-sectional SEM of the full device with 0.05 mg mL\(^{-1}\) ZnPP treatment, c) current density–voltage (\(J–V\)) curves and d) \(J–V\) curve hysteresis and (e) IPCE spectra (left) with the integrated JSC (right) based on the IPCE data of the optimized devices with or without ZnPP-treated under reverse scan, f) the photovoltaic statistic parameters of PSCs based on CF and CF NS2, which were measured in reverse scan under 1 sun illumination, g) long-term stability of the control and ZnPP-treated unencapsulated devices being stored in a nitrogen glove box.
In this work, devices with n–i–p planar structure of glass/FTO/SnO₂/Perovskite/Spiro-OMeTAD/Ag (Figure 4a), where the ZnPP was introduced into the perovskite layer as a passivating molecular during the antisolvent treatment, were fabricated to study the effect of ZnPP on device performance. Figure 4b shows a representative cross-sectional SEM image of a ZnPP-treated PSC. The perovskite crystals are observed to be continuous through the film thickness, which will be beneficial for high performance. On the contrary, stacked grains were observed for the perovskite layer without the ZnPP treatment (Figure S7, Supporting Information). ZnPP concentrations of 0.01, 0.03, 0.05, and 0.07 mg mL⁻¹ in the antisolvent were used to determine the optimal concentration, and the corresponding results are shown in Figure S8, and Table S2, S3, Supporting Information. The PCE of the devices was significantly enhanced with increasing ZnPP concentration up to an optimal concentration of 0.05 mg mL⁻¹. The open-circuit voltage (V_OC) and the fill factor (FF) showed the same increasing trend as the PCE. The J_SC remained essentially unchanged by the addition of the ZnPP. It is clearly shown that the improvement of the PCE is mainly due to the increase of V_OC with an increase also in the FF. The concentration of 0.05 mg mL⁻¹ for ZnPP in CB was found to be optimal to achieve the high-efficiency devices, in agreement with the SEM and XRD results presented above.

The champion devices’ J–V curves under reverse scan are shown in Figure 4c. The PSC with ZnPP treatment exhibited a high efficiency of 21.08%, with a V_OC of 1.126 V, a J_SC of 22.37 mA cm⁻², and a FF of 82.91%. In contrast, the control device had a PCE of 13.07%, with a V_OC of 1.057 V, a J_SC of 16.71 mA cm⁻², and a FF of 72.52%. The unencapsulated devices being stored in a nitrogen glove box finally, a steady-state PCE output of 19.34% and 20.06% was obtained separately for the control and ZnPP-treated cells in a period of 280 s. As shown in the external quantum efficiency (EQE) spectra (Figure 4e), the devices modified with ZnPP show a slightly higher EQE value, indicating a better charge extraction efficiency in the PSC, which is mainly associated to the reduction of non-radiative recombination and improvement of the interface contact. The integrated current densities of the devices with and without ZnPP treatment were calculated to be 22.65 and 22.41 mA cm⁻², respectively, which closely matched the J_SC values from the J–V measurement. To gain more insight into the effect of ZnPP on the optical properties of the device, statistical data of 32 devices with and without ZnPP treatment were evaluated. As illustrated in Figure 4f and Table S5, Supporting Information, the treated devices had a higher average PCE of 20.35 ± 0.38%, V_OC of 1.109 ± 0.013, and FF of 82.46 ± 0.74 compared with the control devices exhibiting an average PCE of 19.45 ± 0.47%, V_OC of 1.064 ± 0.020, and FF of 82.12 ± 0.63. The above results show that ZnPP can significantly improve the cells efficiency, especially in terms of open-circuit voltage, indicating that ZnPP can effectively passivate defects and reduce nonradiative recombination. The narrower distribution indicates that the treatment of ZnPP improves the reproducibility of high-performance perovskite.

We then examined the long-term stabilities of those devices. The unencapsulated devices being stored in a nitrogen glove box while tested in the atmospheric (≈50 RH%) were assessed. As shown in Figure 4g, the long-term device stability is tested every 24 h. While the control device shows a decrease of more than 10% in PCE after 1000 h, less than 2% PCE loss is observed for the ZnPP-treated PSC, demonstrating the enhanced device stability. And, in Figure S10, Supporting Information, the water contact angle of pure perovskite film enlarged from 57.3° to 59.2° of the ZnPP-treated films. The enhancement of moisture stability is mostly owing to the better crystallization and lower defect of perovskite film after ZnPP treatment. In addition, the ZnPP-treated device presented a better thermal stability than the control device at 85 °C in a nitrogen environment (Figure S11, Supporting Information).

In consideration of the excellent performance of the cells, we further characterized the films and corresponding devices to acquire a better understanding of the mechanisms for the

Figure 5. a) EIS of with or without ZnPP-treated PSCs under an applied bias of 0.6 V in darkness, b) dark-state J–V curves of full with or without ZnPP-treated devices, c) SCLC measurement based on electron-only devices of FTO/SnO₂/perovskite (with or without ZnPP treatment)/PCBM/Ag under dark conditions.
improvement of efficiency. Electrochemical impedance spectroscopy (EIS) was used to study the charge transfer and recombination of the devices at an applied voltage of 0.6 V in darkness. The Nyquist plots are shown in Figure 5a and fitted with the equivalent circuit diagram in the inset. The charge recombination resistance ($R_{\text{rec}}$) was determined to be 39821 $\Omega \cdot \text{cm}^{-2}$ for the ZnPPTreated device bigger than the results based on control devices (25 301 $\Omega \cdot \text{cm}^{-2}$), indicating that the ZnPPTreated device suppressed the charge recombination and resulted an enhanced $V_{\text{OC}}$ in the corresponding device. The dark-state $J-V$ curves of those devices are shown in Figure 5b, and a lower leakage current of ZnPPTreated device was observed which will lead to less charge recombination and lead to a higher $V_{\text{OC}}$ in PSCs.

We further evaluated the trap density ($n_{\text{trap}}$) through a space charge limited current (SCLC) measurement based on electronically-only devices of FTO/SnO$_2$/perovskite (with or without ZnPPTreatment)/PCBM/Ag under dark conditions and the dark current–voltage curves are shown in Figure 5c. According to the slope, the curve can be divided into three regions along with the bias increasing: the ohmic region, the trap-filled limited (TFL) region, and the trap-free SCLC region. The trap-filled limit voltage ($V_{\text{TFL}}$) is the turning point between the ohmic region and the TFL region, representing the state that the traps of the device are filled at a certain bias voltage. The $n_{\text{trap}}$ can be obtained from $V_{\text{TFL}}$ by using the formula: $n_{\text{trap}} = 2e\varepsilon_0 V_{\text{TFL}}/\varepsilon L^2$, where $\varepsilon_0$ is the vacuum permittivity (8.854 $\times 10^{-12}$ F m$^{-1}$), $\varepsilon$ is the relative dielectric constant of the perovskite, $L$ is the thickness of the perovskite film, and $V_{\text{TFL}}$ of ZnPPTreated and control device was 0.139 and 0.210 V, and the corresponding $n_{\text{trap}}$ was determined to be 1.51 $\times 10^{15}$ and 2.29 $\times 10^{15}$ cm$^{-3}$, respectively. These results suggested that passivation with ZnPPTreat can significantly reduce the trap density in perovskite film. The reduction of defects and the improvement of the film quality are the main reasons for the enhanced performance of the ZnPPTreated PSCs.

3. Conclusion

In summary, we synthesized a new D–π–A-type zinc pyridine porphyrin derivative (ZnPPT) and demonstrated the feasibility for ZnPPTreated as a passivation molecular in antisolvent process to enhance PSCs performance. When embedded ZnPPTreated into perovskite layer, the quality of perovskite film was significantly improved such as pinhole-free, large and uniform grains, and smooth morphology. The pyridine functional group in ZnPPTreated could passivate the undercoordinated Pb$^{2+}$ cations, leading to a lower trap density and reduction of the defect-assisted recombination in the perovskite film. Based on these promotions, the PSCs fabricated with ZnPPTreated achieved a higher champion PCE of 21.08% compared to the 20.18% of control device. Our treatment strategy enriched the selection of passivator for high-performance PSCs.

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.

Data Availability Statement

The data that support the findings of this study are available in the supplementary material of this article.

Keywords

graded passivation, high efficiency, high stability, perovskite solar cells, porphyrin derivative

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[1] A. Kojima, K. Teshima, Y. Shirai, T. Miyasaka, J. Am. Chem. Soc. 2009, 131, 6050.
[2] NREL, Best Research-Cell Efficiencies, https://www.nrel.gov/pv/cell-efficiency.html (accessed: December 2021).
[3] J. J. Yoo, G. Seo, M. R. Chua, T. G. Park, Y. Lu, F. Rotermund, Y. K. Kim, C. S. Moon, N. J. Jeon, J. P. Correa-Baena, V. Bulovic, S. S. Shin, M. G. Bawendi, J. Seo, Nature 2021, 590, 587.
[4] J. Jeong, M. Kim, J.seo, H. Lu, P. Ahlawat, A. Mishra, Y. Yang, M. A. Hope, F. T. Eckemeyer, M. Kim, Y. J. Yoon, I. W. Choi, B. P. Darwich, S. J. Choi, Y. Jo, J. H. Lee, B. Walker, S. M. Zakeeruddin, L. Emsley, U. Rothlisberger, A. Hagfeldt, D. S. Kim, M. Gratzel, J. Y. Kim, Nature 2021, 592, 381.
[5] H. Yang, Y. Feng, Z. Tu, K. Su, X. Fan, B. Liu, Z. Shi, Y. Zhang, C. Zhao, B. Zhang, Nano Res. 2019, 12, 3129.
[6] R. Xia, X. X. Gao, Y. Zhang, N. Drigo, V. I. E. Queloz, F. F. Tirani, R. Scopellitti, Z. Huang, X. Fang, S. Kinge, Z. Fei, C. Roldan-Carmona, M. K. Nazeeruddin, P. J. Dyson, Adv. Mater. 2020, 32, 2003801.
[7] Y. Zhang, M. Chen, Y. Zhou, W. Li, Y. Lee, H. Kanda, X.-X. Gao, R. Hu, K. G. Brooks, R. Zia, S. Kinge, N. P. Padture, M. K. Nazeeruddin, Adv. Energy Mater. 2020, 10, 2001300.
[8] Q. D. Yang, J. Li, Y. Cheng, H. W. Li, Z. Guan, B. Yu, S. W. Tsang, J. Mater. Chem. A 2017, 5, 9852.
[9] Y. Zhang, Z. Zhou, F. Ji, Z. Li, G. Cui, P. Gao, E. Oveisi, M. K. Nazeeruddin, S. Pang, Adv. Mater. 2018, 30, 1707143.
[10] B. Yang, J. Suo, F. Di Giacomo, S. Othof, D. Bogachuk, Y. Kim, X. Sun, L. Wagner, F. Fu, S. M. Zakeeruddin, A. Hinsch, M. Gratzel, A. Di Carlo, A. Hagfeldt, ACS Energy Lett. 2021, 6, 3916.
[11] R. J. E. Westbrook, T. J. Macdonald, W. Xu, L. Lanzetta, J. M. Marin-Beloqui, T. M. Clarke, S. A. Haque, J. Am. Chem. Soc. 2021, 143, 12230.
[12] L. Gao, H. Su, Z. Xu, Y. Hu, J. Zhang, S. Liu, Sol. RRL 2021, 5, 2100416.
