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Regulating Surface Termination for Efficient Inverted Perovskite Solar Cells with Greater Than 23% Efficiency

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ABSTRACT: Passivating surface and bulk defects of perovskite films has been proven to be an effective way to minimize nonradiative recombination losses in perovskite solar cells (PVSCs). The lattice interference and perturbation of atomic periodicity at the perovskite surfaces often significantly affect the material properties and device efficiencies. By tailoring the terminal groups on the perovskite surface and modifying the surface chemical environment, the defects can be reduced to enhance the photovoltaic performance and stability of derived PVSCs. Here, we report a rationally designed bifunctional molecule, piperazinium iodide (PI), containing both R₂NH and R₂NH₂⁺ groups on the same six-membered ring, behaving both as an electron donor and an electron acceptor to react with



different surface-terminating ends on perovskite films. The resulting perovskite films after defect passivation show released surface residual stress, suppressed nonradiative recombination loss, and more *n*-type characteristics for sufficient energy transfer. Consequently, charge recombination is significantly suppressed to result in a high open-circuit voltage (V_{OC}) of 1.17 V and a reduced V_{OC} loss of 0.33 V. A very high power conversion efficiency (PCE) of 23.37% (with 22.75% certified) could be achieved, which is the highest value reported for inverted PVSCs. Our work reveals a very effective way of using rationally designed bifunctional molecules to simultaneously enhance the device performance and stability.

■ INTRODUCTION

Organic-inorganic metal halide perovskite solar cells (PVSCs) have gained enormous attention during the past few years owing to their superb semiconducting properties, relatively simple and easy processing, low cost, and rapidly ascending power conversion efficiencies (PCEs) reaching as high as 25.5%.¹⁻¹⁰ However, the champion PCE of PVSC is still below that predicted from the theoretical Shockley–Queisser (S-Q) limit, mainly due to the loss from nonradiative recombination. Unlike the robust perovskite oxides, the frail Coulombic interaction and weak ionic bonding of organic-inorganic halide perovskites (OIHPs) cause more vulnerable atomic reorganization and deviations on the derived film surface.¹¹ The crystal lattice interference and atomic periodicity perturbation at the surface of OIHPs alter the electronic behavior and band structure, generating a considerable number of nonradiative recombination centers. Such behaviors are more prominent at the surface than in the bulk of OIHP films, which will significantly affect the perovskite material properties and device performance.^{12,13}

However, originating from the various surface terminations and undercoordinated sites, surface defects are notably different from those formed in the bulk of OIHPs. The undercoordinated Pb^{2+} and halide sites are the predominant trap sources on surfaces that cause nonradiative recombination losses. In terms of the surface energy, vacant terminations are more stable than those from PbI₂ flat and methylammonium iodide/formamidinium iodide (MAI/FAI) terminations, which can induce many vacancy defects (such as V_I and V_{MA}/V_{FA}) on the surface.¹⁴ The larger FA⁺ with a smaller dipole moment has a weaker interaction with the [PbI₆]²⁻ octahedral than does MA⁺. Thereby, the antisite Pb_I defects are formed more easily in FA⁺-dominant OIHPs with lower formation energies on the surface than in bulk, which may cause deep-level defects such as Pb clusters (i.e., Pb²⁺ dimers).¹⁵

Recently, an enormous amount of effort has been devoted to suppressing the nonradiative recombination loss in order to further enhance the open-circuit voltage ($V_{\rm OC}$) and PCE by passivating positive Pb²⁺ traps and negative halide traps.^{16–20} Various molecules have been developed either as electron donors or as electron acceptors for passivating positively and negatively charged traps.^{21–30} Among them, Lewis acids such as

Received: September 14, 2020

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Figure 1. Simulated PXRD of (a) $(PI)_2PbI_2$ ·2DMSO and (b) $(PDI)_2PbI_2$. Insets are the optical microscopy images. Crystal structures of (c) $(PI)_2PbI_2$ ·2DMSO and (d) $(PDI)_2PbI_2$.¹H NMR spectra in d_6 -DMSO of (e) PI and PI + PbI₂ and (f) PDI and PDI + PbI₂.

carboxylic acid and phosphoric acid, sulfonic groups, and ammonium groups can neutralize undercoordinated halides through coordinate bonding to form Lewis adducts. On the other hand, Lewis bases, such as carboxylate and amine groups, and electron-rich aromatic structures have been reported to reduce undercoordinated lead ions and/or lead clusters by donating a lone pair of electrons.

Although numerous molecules have been developed to tailor the surface chemical environments and surface defects, most of them can only passivate either the positively or negatively charged defects. There are very few molecules that can passivate both Pb²⁺ and halide ion traps on the perovskite surface.^{21,28} To achieve enhanced passivation effects, the ability to introduce stronger binding action between the passivator and perovskite to form an ionic bond and a stable chemical interaction is critical. Therefore, it is essential to develop multifunctional molecules that can passivate both positively and negatively charged defects with simple solution treatments to further enhance the device performance.

Here, we report the development of a novel bifunctional molecule, piperazinium iodide (PI), containing both an R_2NH and an $R_2NH_2^+$ group on the same six-membered ring with an in-plane dipole that is capable of functioning as an electron donor and an electron acceptor to react with different surface terminating groups. It was found that PI could form a Pb–N bond in the single crystal of (PI)₂PbI₂·2DMSO, which was grown as a model compound to investigate the chemical interactions between PI and PbI₂. After introducing PI for surface treatment, the residual stress of the film surface could also be released. The tuning of surface termination with PI treatment also helps to achieve a more n-type characteristic film to facilitate charge transfer. The combined effects resulted in

suppressed nonradiative recombination loss and a significantly reduced $V_{\rm OC}$ loss of 0.33 V with a very low ΔV_3 of 60.13 mV. The PCE of inverted (p-i-n) devices achieved 23.37% (with 22.75% certified) with a $V_{\rm OC}$ of 1.17 V, which is the highest value for inverted PVSCs to date.

RESULTS AND DISCUSSION

To demonstrate the specific interaction of different functional groups (neutral R_2NH and the $R_2NH_2^+$ cation) in **PI**, we have also synthesized piperazinium diiodide (PDI) with two $R_2NH_2^+$ cations for comparison. The detailed synthesis is summarized in the Supporting Information (SI). The (PI)₂PbI₂·2DMSO (CCDC 1935315) and (PDI)₂PbI₂ (CCDC 2009125) single crystals were grown using the reported antisolvent vaporassisted crystallization method.³¹ Detailed crystal data and the refinement of (PI)₂PbI₂·2DMSO and (PDI)₂PbI₂ are listed in Table S1, and the corresponding structures are shown in Figure 1. The rod-like translucent (PI)₂PbI₂·2DMSO single crystals are millimeter-sized and have a 1D chain organic-inorganic hybrid structure (Figure 1a). The lone-pair electrons of the R_2NH on PI replace a halide to bond with Pb to form a Pb-N bond with a bond length of 2.80 Å, indicating a strong chemical interaction between Pb²⁺ and the lone pair of the neutral R₂NH group (Figure 1c). Surprisingly, different from the 3D structure of MAPbI₃ or FAPbI₃, (PDI)₂PbI₂ single crystals possess a 0D organic-inorganic hybrid structure in which the metal halide ions (PbI₆⁴⁻) are completely isolated from each other and surrounded by the piperazinium organic cations (Figure 1d). The interactions of PI and PDI with PbI₂ in the two model compounds are further explored with ¹H NMR spectrometry. As shown in Figure 1e, the fast proton exchanges among NH, HDO, and DMSO induce the weak signal of H from NH or



Figure 2. High-resolution XPS spectra of corresponding perovskite films: (a) C 1s spectra, (b) N 1s spectra, and (c) Pb 4f spectra.



Figure 3. (a–c) Two-dimensional GIWAXS patterns and (d) the grazing incidence X-ray diffraction (GIXRD) spectrum of the corresponding perovskite films with an incident angle of 0.2° . * denotes PbI₂. (e–g) GIXRD spectrum at different tilt angles for the reference film and **PI**- and **PDI**-treated films, respectively. (h) Residual strain of the corresponding perovskite films' diffraction strain data as a function of $\sin^2 \varphi$. All of the perovskite films are deposited on an ITO substrate.

 $\rm NH_2^+$ in the **PI** sample. However, after mixing PbI₂ and **PI** in solvent, the strong interaction between R₂NH and Pb²⁺ surpasses proton exchange to give a more well-defined signal.^{32,33} On the other hand, the ¹H NMR spectrum of **PDI** shows less difference upon addition of PbI₂ (Figure 1f). These results help to confirm the distinctive interaction induced by the neutral R₂NH on **PI**, which has not been reported before.

To investigate the potential interactions of **PI** and **PDI** with the perovskite film surface, the materials were deposited via spin coating (1 mg/mL in dry isopropanol) on the perovskite film with a composition of $Cs_{0.05}(FA_{0.95}MA_{0.05})_{0.95}Pb(I_{0.95}Br_{0.05})_3$. High-resolution X-ray photoelectron spectroscopy (XPS) was performed as shown in Figure 2. In the C 1s XPS spectrum, the binding energies (BEs) at 284.8, 286.5, and 288.4 eV are assigned to C-C, C=NH²⁺, and C=O, respectively (Figure 2a). Oxidized carbon species may originate from the decay of the perovskite film when exposed to the ambient environment during testing.³⁴ The peak area of C=O shows a visible decrease after PI and PDI treatments, which indicates the suppressed oxidation process and improved film stability.³⁵ In the N 1s XPS spectrum, the featured bonds of C–N (400.7 eV) and C= NH^{2+} (402.4 eV) from FA⁺/MA⁺ in the reference film slightly shift to lower binding energies (400.5 and 402.2 eV, respectively) after PI treatment (Figure 2b). This shift may originate from the formation of hydrogen bonds N-H…N between the FA⁺/MA⁺ and the R₂NH from PI.³⁶ However, there is no peak shift in the N 1s spectrum after PDI treatment, which helps to differentiate the unique function of PI with the R₂NH group. The new peaks appearing at 285.4 eV in the C 1s spectrum and at 399.8 eV in the N 1s spectrum are attributed to the C bonds to neutral N (C-NH-C) and neutral N in PI, respectively.³⁷ These peaks further verify the existence of PI. In the Pb 4f spectrum, the binding energies at 143.3 and 138.4 eV are assigned to $4f_{5/2}$ and $4f_{7/2}$ of divalent Pb²⁺, respectively. And the two shoulder peaks

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Figure 4. (a) Steady-state PL spectra and (b) time-resolved photoluminescence plots of perovskite films. Confocal photoluminescence (PL) intensity maps of (c) reference perovskite film and perovskite films with (d) **PI** and (e) **PDI** treatments. The contour in the pictures represents the auto level of PL intensity, with the sequence of blue, purple, magenta, red, green, and cyan.

at 141.6 and 136.6 eV at lower BE are associated with metallic Pb⁰ (Figure 2c). These peaks move to higher binding energy by more than 400 meV only after PI treatment (centered at 143.8 and 138.9 eV) in terms of bond formation with the R₂NH in PI, which is in line with the single-crystal studies.^{32,38} In addition, the peak area of Pb⁰ decreased significantly after both PI and PDI treatments. Pb⁰ is an indication of the existence of iodide and cation vacancies on the perovskite film, which can be inhibited by the surface treatments of both PI and PDI.³⁹ Besides, electron donor R₂NH in PI interacts strongly with undercoordinated Pb²⁺ as implied by the single-crystal results, contributing to the greatly decreased Pb⁰ peak after PI treatment.

Grazing-incidence wide-angle X-ray scattering (GIWAXS) characterization at an incident angle of 0.2° was also carried out to explore the surface crystallite structure of perovskite films after **PI** and **PDI** treatments. As shown in Figure 3a–c, the GIWAXS patterns of films treated with **PI** and **PDI** show higher intensities along the (101) ring ($|q| = 0.95-1.08 \text{ Å}^{-1}$), which indicates better crystallinity compared to that of the reference film. There are no new peaks that emerge after either **PI** or **PDI** treatment. However, excessive PbI₂ in the position at $|q| = 0.88-0.94 \text{ Å}^{-1}$ disappeared only after **PI** treatment (Figures S5 and S6). This result is consistent with the measurements from grazing incidence X-ray diffraction (GIXRD) at an incident angle of 0.2° (Figure 3d). The PbI₂ signal that decreased only after **PI** treatment indicates a strong interaction, which is in line with the single-crystal structure and XPS results.

To investigate the effects of **PI** and **PDI** treatments on the surface crystal structure, we employed the GIXRD technique with the $2\theta - \sin^2 \varphi$ method to analyze the residual stress on the film surface.^{40,41} The (012) plane at 31.6° was chosen as the target because of its diversity in providing more grain information and a dilute orientation effect on the linear relationship of $2\theta - \sin^2 \varphi$ in the GIXRD measurements. Figure 3e–g shows that the scattering peaks gradually shift to the left by varying φ from 10 to 60° at different levels. The film stress can be calculated by fitting 2θ as a function of $\sin^2 \varphi$, in which the

negative slope of the fitting line indicates tensile stress that exists at the perovskite film. As shown in Figure 3h, the residual tensile strain gradually decreases from 61.57 ± 6.92 MPa for the reference film to 27.54 ± 2.16 and 40.15 ± 3.89 MPa after PI and PDI treatments, respectively. This shows that the defect passivation in the A-site vacancy and in undercoordinated Pb²⁺ with R₂NH₂⁺ and R₂NH groups results in lower surface residual stress. After surface treatment with PI, the R₂NH₂⁺ group can insert the A-site vacancy and the R₂NH group can react with the undercoordinated Pb²⁺, thus regulating the surface termination and releasing the surface residual stress, which can play an important role in carrier dynamics and device performance.^{41,42}

To understand more about the passivation effect of PI, the recombination occurring in the perovskite films was investigated by steady-state PL and time-resolved photoluminescence (TRPL) analysis. As shown in Figure 4a, the PL intensities of perovskite films after PI and PDI treatments are about 5 and 3 times higher than those of the reference films, suggesting that their nonradiative recombination loss is alleviated considerably after surface passivation. The TRPL decay curves (Figure 4b) were fitted with biexponential function $I(t) = A_1 \exp(-t/\tau_1) +$ $A_2 \exp(-t/\tau_2)$, where τ_1 and τ_2 are the fast and slow decay components, respectively (Tables S2 and S3). The average lifetime (τ_{avg}) can be calculated with $\tau_{avg} = \frac{\sum_{i=1}^{n} A_i \tau_i^2}{\sum_{i=1}^{n} A_i \tau_i}$. We found that the perovskite films after PI and PDI surface treatments possessed a longer carrier lifetime compared to that of the reference film. The τ_{avg} values of the reference perovskite film and PI- and PDI-treated films are 305, 1948, and 1461 ns, respectively. The significantly prolonged lifetimes of perovskite films after PI and PDI treatments are attributed to the suppressed defects such as lead clusters, undercoordinated halides, and Pb-I antisite which usually cause nonradiative recombination.⁴³ The combined effects of R₂NH and R₂NH₂⁺ groups on PI for defect passivation are superior to those obtained from PDI with only the R₂NH₂⁺ group, which demonstrates the benefit of having multifunctional passivators. The trap density $(N_{\rm trap})$ was calculated with space-charge-



Figure 5. (a) Device structure of the inverted PVSCs. (b) Current density-voltage (J-V) characteristics of devices with and without surface treatments. (c) Statistics of PCE distribution for PVSCs with and without **PI** treatment. (d) J-V curves of the **PI**-treated device with different scan directions (forward, 1.2 to -0.1 V; reverse, -0.1 to 1.2 V). (e) External quantum efficiency (EQE) spectra of the champion device with **PI** treatment. (f) Stabilized power output of a **PI**-treated device tracked at the maximum power point (MPP) under AM 1.5G illumination.

limited-current (SCLC) method (Figure S8). The $N_{\rm trap}$ of the reference film based on the hole-only device is about 2.54 × 10¹⁶ cm⁻³. After the passivation with PI and PDI, the $N_{\rm trap}$ was reduced to 8.4 × 10¹⁵ and 1.64 × 10¹⁶ cm⁻³, respectively. The lower $N_{\rm trap}$ after PI treatment demonstrates the effectiveness of defect passivation by PI compared to that by PDI, which is consistent with the PL and TRPL results.

Confocal photoluminescence (PL) mappings were also conducted to explore the optoelectronic properties of perovskite films as displayed in Figure 4c-e. The PL intensity in the central area of a single grain is much higher than those from the grain boundaries, which indicates better charge transfer with minimized recombination. After PI treatment, the overall PL intensity is significantly improved and the intensity distribution is more homogeneous compared to those obtained from the reference and PDI-treated films. The PL peak position distribution of the films was counted, and the PL peak histogram of the films was demonstrated in Figures S9 and S10. The distribution of PL peaks on the perovskite film is considerably narrowed after PI treatment, suggesting that the surface phase segregation is suppressed. A more homogeneous film is favorable for charge transfer because the energy loss during the transfer between domains can be significantly reduced.^{44,4}

Ultraviolet photoelectron spectroscopy (UPS) was employed to analyze the electronic structures of perovskite films after **PI** treatment. The valence band maximum (E_V) shifts by 180 meV toward the vacuum level (E_{VAC}), while the E_F shifts by 350 meV toward the conduction band minimum (E_C) after treatment (Figure S11). This E_F shift indicates that the **PI**-treated films demonstrate more n-type characteristics, which is probably due to the changed surface termination.^{46,47} The PbI₂ termination has been reported to have deeper energy levels than those of the MA⁺/FA⁺ terminations.⁴⁸ After introducing **PI** onto the film surface, the dipole in **PI** orients away from the surface, exposing electropositive ammonium terminal groups and enabling band bending between the perovskite and the electron-transporting layer, which can facilitate more efficient charge transfer.

To verify the passivation effect of PI on photovoltaic performance, the devices were fabricated with a configuration of ITO glass/PTAA/perovskite/C₆₀/bathocuproine (BCP)/Ag as shown in Figure 5a. The reference device without passivation showed a PCE of 20.76% (average PCE: 19.67%) with an opencircuit voltage (V_{OC}) of 1.06 V, a short-circuit current density (J_{SC}) of 24.93 mA cm⁻², and a fill factor (FF) of 78.57% under 1 sun illumination (AM 1.5G, 100 mW cm⁻²) (Figure S12 and Table S4). The PCE of the devices after PDI treatment was improved to 21.98% (average PCE: 21.31%), benefiting from the enhanced $V_{\rm OC}$ (1.13 V) due to the passivated A-site vacancy defects by the $R_2NH_2^+$ group (Figure 5b). However, J_{SC} decreased, perhaps due to the possible formation of lowerdimensional perovskites, which inhibited charge transport. On the contrary, the devices after being treated with PI achieved a significantly enhanced PCE of 23.37% ($V_{\rm OC}$ of 1.17 V, FF of 80.17%, J_{SC} of 24.92 mA cm⁻²) (average PCE: 22.26%) with negligible hysteresis as shown in Figure 5c,d. The device performance was validated by an independent certification laboratory to show a high PCE of 22.75% with a J_{SC} of 24.68 mA cm^{-2} , a V_{OC} of 1.16 V, and an FF of 79.16% (Figure S13). This is the highest certified PCE for inverted PVSCs to date. The external quantum efficiency (EQE) was measured as shown in Figure 5e. The integrated photocurrent of the champion device with 24.18 mA cm⁻² matched well with the values obtained from the I-V curves.

Figure 5f exhibits the stabilized power output at the maximum power point (MPP) for the **PI**-treated champion device under continuous AM 1.5G illumination. The stabilized PCE is 22.88%, which is in good agreement with the PCE obtained from the *J*-*V* curves. The greatly improved PCE is mainly attributed to the highly enhanced $V_{\rm OC}$ from 1.06 to 1.17 V due to **PI** passivation. The $V_{\rm OC}$ loss is significantly reduced to 0.33 V,



Figure 6. (a) Highly sensitive external quantum efficiency (EQE) spectra of the corresponding devices. (b) EQE of EL and the EL spectra of the champion device with PI treatment. (c) V_{OC} loss analysis of the corresponding devices.

which is among the lowest values in PVSCs reported so far (Figure S14). Moreover, the PI passivation not only enhanced the device performance but also improved its stability. The encapsulated device could maintain 93% of its initial efficiency under humid air (RH 55 \pm 5%, 25 °C), while the efficiencies of the reference device degraded to 40% of its original values. Also, the PI-treated device can maintain over 98% of its initial efficiency while that of the reference device decreased to 87% of its initial efficiency under continuous illumination at 200 h.

In order to quantitatively analyze the impact of PI and PDI treatments on $V_{\rm OC}$ loss, we employed the detailed balance theory to calculate the $V_{\rm OC}$ loss:^{49–51}

$$\begin{split} q\Delta V &= \mathrm{Eg} - qV_{\mathrm{OC}} \\ &= (\mathrm{Eg} - qV_{\mathrm{OC}}^{\mathrm{SQ}} + qV_{\mathrm{OC}}^{\mathrm{SQ}}) + \Delta qV_{\mathrm{OC}}^{\mathrm{rad}} + \Delta qV_{\mathrm{OC}}^{\mathrm{nonrad}} \\ &= (\mathrm{Eg} - qV_{\mathrm{OC}}^{\mathrm{SQ}}) + (qV_{\mathrm{OC}}^{\mathrm{SQ}} - qV_{\mathrm{OC}}^{\mathrm{rad}}) + (qV_{\mathrm{OC}}^{\mathrm{rad}} - qV_{\mathrm{OC}}) \\ &= q(\Delta V_1 + \Delta V_2 + \Delta V_3) \end{split}$$

Here, *q* is the elementary charge, ΔV is the overall voltage loss, Eg is the perovskite band gap, V_{OC}^{SQ} is the Shockley–Queisser limit of V_{OC} , V_{OC}^{rad} refers to the V_{OC} in which only radiative recombination occurred in PVSCs, ΔV_{OC}^{SQ} is the V_{OC} loss caused by the nonideal EQE above the band gap, ΔV_{OC}^{rad} is the V_{OC} loss of the sub-band-gap radiative recombination, and ΔV_{OC}^{nonrad} is the V_{OC} loss of nonradiative recombination. According to the theory, V_{OC} loss consists of three parts, ΔV_1 , ΔV_2 , and ΔV_3 . ΔV_1 comes from the radiative recombination above Eg. The reference and **PI**- and **PDI**-treated PVSCs have similar ΔV_1 values of 265.15, 264.61, and 265.11 mV, respectively.

 ΔV_2 results from the energy loss from blackbody radiation, where the EQE of PVSCs extend into the region below Eg. It can be computed through the highly sensitive EQE (Figure 6a).^{52,53} The calculated ΔV_2 values are 27.37, 2.73, and 12.46 mV for the reference and the PI- and PDI-treated devices, respectively. The peaks appearing in the region of 1.25–1.35 eV in the highly sensitive EQE spectra demonstrate that the photocurrent contributed to shallow trap states as reported before.^{20,22} ΔV_3 is the voltage loss mainly owing to the nonradiative recombination, being expressed by the following equation where $k_{\rm B}$ is the Boltzmann constant and EQE_{EL} is the EQE of electroluminescence (EL). The EQE_{EL} values were collected by using the PVSCs as light-emitting diodes (LEDs) (Figure 6b and Figure S17). The EQE_{EL} of the reference device is 0.55%, which can be converted to a ΔV_3 value of 134.35 mV. The ΔV_3 value of the **PI**-treated device was reduced significantly to 60.13 mV with an EQE_{EL} of as high as 9.77%. Such a low value is among the smallest energy losses of photovoltaic devices, further proving the excellent passivating effect of **PI** on reducing the nonradiative recombination loss.⁵⁴ The $V_{\rm OC}$ loss analysis of ΔV_1 , ΔV_2 , and ΔV_3 is shown in Figure 6c and Table S5. Thus, a considerably reduced $V_{\rm OC}$ deficit of 0.33 V could be achieved, which is among the lowest values reported so far.

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CONCLUSIONS

We have demonstrated a very effective way to passivate the surface defects of perovskites using a bifunctional molecule containing both $R_2NH_2^+$ and R_2NH groups on a six-membered ring to improve both the efficiency and stability of inverted PVSCs. The $(PI)_2PbI_2\cdot 2DMSO$ single crystal was grown as a model compound to mimic the interactions between PI and perovskite surface defects. The PI molecule with an R_2NH electron donor and an $R_2NH_2^+$ electron acceptor forms a dipole to reduce residual stress and suppress nonradiative recombination loss in perovskites to boost the efficiency of inverted PVSCs to a very high value of 23.37% (with 22.75% certified) and a reduced V_{OC} deficit of 0.33 V. This work paves a new way for using rationally designed molecular passivators to reduce the surface defects of perovskite films and further improve the efficiency and stability of derived PVSCs.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/jacs.0c09845.

Details concerning synthesis, device production, and characterization methods (PDF)

Single-crystal structure of $(PI)_2PbI_2$ ·2DMSO (1935315) (CIF)

Single-crystal structure of (PDI)₂PbI₂ (2009125) (CIF)

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Journal of the American Chemical Society

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by APRC Grants of the City University of Hong Kong (9380086 and 9610421), Innovation and Technology Bureau supported programs (ITS/497/18FP and GHP/021/18SZ), the Guangdong-Hong Kong-Macao joint laboratory of optoelectronic and magnetic 6bal materials (no. 2019B121205002), an ECS grant (CityU 21301319), a Collaborative Research Fund grant (C5037-18G) from the Research Grants Council of Hong Kong, the Natural Science Foundation of Guangdong Province (2019A1515010761), the Guangdong Major Project of Basic and Applied Basic Research (no. 2019B030302007), the Air Force Office of Scientific Research (FA9550-18-1-0046), and a Teaching Start-Up Grant of the City University of Hong Kong (6000672). Z.Z. and A.J. are grateful for the technical support provided by Mr. Shekman Yiu for single-crystal analysis.

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