Improved Air Stability of Tin Halide Perovskite Solar Cells by an N-Type Active Moisture Barrier

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Tin halide perovskite solar cells are promising for the next generation of highly efficient photovoltaics. Their commercialization can be accelerated by increasing their stability in moisture and oxygen. Herein, an n-type organic molecule (IO-4Cl) is applied as an interlayer between the perovskite films and electron transport layers in p-i-n structured devices. The electron-rich indacenodithieno-[3,2-b]thiophene enhances electron transport, while the hydrocarbon side chains and rigid conjugated backbone isolate air. It is also shown that the C=O in IO-4Cl can coordinate with Sn²⁺ on perovskite films' surface and grain boundaries to enhance perovskite crystal stability. In addition, IO-4Cl slows down crystallization dynamics, resulting in lower non-radiation recombination. The moisture ingress in the perovskite films is tracked under high relative humidity (RH) and it is found that IO-4Cl can mitigate moisture infiltration. Finally, the devices with IO-4Cl maintain 95% of the initial power conversion efficiency after 1200 h of storage in a nitrogen-filled glovebox, and their stability in ambient air (60-80% RH) is significantly improved against pristine devices, thus demonstrating the beneficial effects of IO-4Cl interlayer on device stability.

1. Introduction

Over the past decade, single-junction organic–inorganic hybrid perovskite solar cells (PSCs) were developed rapidly, with lead halide PSCs achieving power conversion efficiencies (PCEs) over 26%.^[1] The PCE of module, monolithic perovskite/silicon tandem, all-perovskite tandem devices are also more than 22%,^[2]

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32.5%,^[3,4] and 28%,^[5] respectively. In addition, many researches have been explored to inhibit lead leakage.[6-8] However, lead toxicity and bioavailability to the environment and human health have not been solved. To solve this issue, researchers tried substituting lead with an environmentally friendly metal, leading to the development of lead-free perovskites, such as bismuthbased, germanium-based, antimony-based, and tin-based perovskites.[9-12] Among them, tin halide perovskites (THPs) have demonstrated excellent potential as a non-toxic light absorber for replacing lead-based perovskite materials in PSC applications, owing to their optimal bandgap (1.2-1.4 eV) that carries the possibility of achieving the maximum efficiency according to Shockley-Queisser theoretical limit.^[13–15] Additionally, THPs exhibit high absorption coefficients, carrier mobility, and a small exciton binding energy.^[16]

Moisture penetrates quickly into perov skite films through the surface and grain boundaries, leading to device performance degradation due to the perovskite materials' decomposition.^[17,18] Therefore, improving the stability of THPs against moisture is paramount to protect the surface and grain boundaries against moisture ingress. Tin halide perovskite solar cells (THPSCs) with a p-i-n structure show negligible hysteresis,^[19,20] low cost, and more straightforward

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Figure 1. a) Schematic illustration of IO-4Cl acting on THP film. b) FTIR spectra of pure IO-4Cl and perovskite-IO-4Cl. c) XPS spectra of Sn element of the pristine and target THP films.

fabrication than the n-i-p structure.^[21] In the p-i-n structure, fullerene and its derivates are often used as ETLs with high electron mobility and conductivity.^[12,22,23] However, they also show some drawbacks, such as a lack of coordination with Sn²⁺, poor energy alignment with the THPs films,^[24] an energetic disorder in contact with the perovskite films,^[25] and ion-induced deep traps.^[26] Significantly, they do not protect the perovskite films due to low resistance against moisture penetration.^[27]

At present, lots of additives have been developed to stabilize perovskite films, such as antioxidants,^[28–32] Lewis bases,^[33] amine-based additives,^[34] and organic macromolecules.^[35–37] Among these, using organic macromolecules in precursor solutions to form low-dimension structures is a popular method for improving the efficiency and stability of THPSCs.^[35] However, the modest moisture stability of THPs remains unsolved due to the organic macromolecules acting as spacer layers inside the crystal structure. N-type organic small molecules used as interlayers are promising in improving the efficiency and stability of lead halide PSCs. Such molecules can reduce trap densities, inhibit nonradiative recombination, and enhance resistance against moisture, especially at the surface of the perovskite films.^[17,38,39]

This work introduced an n-type organic molecule, IO-4Cl, as the interlayer between the THPs films and ETL to mitigate moisture penetration. IO-4Cl was chosen due to the effective electron transport with an electron-rich indacenodithieno-[3,2-b]thiophene and hydrophobicity with side chains and rigid conjugated backbone. In addition, the C=O group can coordinate with Sn^{2+} at the surface and grain boundaries of THP films to stabilize the crystal structure. The crystal crystallization of the THP films was analyzed using in situ synchrotron radiation. We also track the infiltration process of water and oxygen under high relative humidity (RH), showing the changes in crystallization, surface morphology, and content of Sn^{2+} . Finally, devices incorporat

ing IO-4Cl exhibited excellent stability in the N_2 atmosphere for 1200 h. They also maintained 72% of their initial PCE under high RH conditions, while pristine devices only remained at 22% of their initial PCE.

2. Result and Discussion

2.1. Mechanism of Passivator

To verify the effect of IO-4Cl on THP films, we dissolved it in chlorobenzene and used the solution as an anti-solvent during the film's preparation process. As shown in Figure 1a, IO-4Cl can cover crystal grain boundaries and surfaces of THP films, creating a physical barrier against the infiltration of water and oxygen molecules from the atmosphere. Energy-dispersive X-ray (EDS) mapping of Cl element on perovskite film with IO-4Cl can ensure the distributions of IO-4Cl (Figure S1, Supporting Information). Besides, the crystal growth process was regulated to stabilize the perovskite phase due to the coordination of C=O and Sn²⁺. According to recent reports, a higher defect density can help IO-4Cl locate on grain boundaries and surfaces, resulting in effective passivation.^[40,41] To understand how IO-4Cl interacts with the THPs, Fourier transform infrared (FTIR) and X-ray photoelectron spectroscopy (XPS) spectra were measured. As shown in Figure 1b, the C=O bond stretching vibration in pure IO-4Cl powder is located at 1725 cm⁻¹.^[42] However, for the THP-IO-4Cl powder, the vibration peak of C=O is shifted to a lower value of 1718 cm⁻¹, indicating the coordination between C=O and Sn.^{2+[43]} Furthermore, the XPS spectra in Figure 1c revealed that the binding energies of $Sn^{2+} 3d_{3/2}$ and $Sn^{2+} 3d_{5/2}$ shifted to 494.33 and 485.90 eV (the target THP film) from 494.84 and 486.40 eV, respectively (the pristine THP film). Besides, the O 1s shifted from 531.32 (pristine film, Figure S2, Supporting Information) to 531.86 eV (target film, Figure S2, Supporting







Figure 2. 2D GIWAXS patterns of the pristine THP film at a) $\theta = 0.025^{\circ}$ b) $\theta = 0.05^{\circ}$ c) $\theta = 0.075^{\circ}$ d) $\theta = 0.3^{\circ}$. 2D GIWAXS patterns of the target THP film at e) $\theta = 0.025^{\circ}$ f) $\theta = 0.05^{\circ}$ g) $\theta = 0.075^{\circ}$ h) $\theta = 0.3^{\circ}$. Azimuthally integrated 1D plots along the out-of-plane direction (azimuth at 90°) at different incident angles for i) the pristine and j) target film. Radially integrated intensity plots along the ring at $q = 10 \text{ nm}^{-1}$ at different incident angles for k) the pristine and J target THP film.

Information). This shift in binding energies confirms the coordination between Sn^{2+} and C=O in the presence of IO-4Cl.^[42]

2.2. Crystalline Properties of THP

To investigate the crystal structure of THP films, we performed grazing-incidence wide-angle X-ray scattering (GIWAXS) and obtained 2D diffraction patterns at various scattering angles (θ = 0.025°, 0.05°, 0.075° and 0.3°). Figure 2a-d, displays the patterns for the pristine THP film, while Figure 2e-h shows those for the film with IO-4Cl (referred to as the target THP film). Although the Debye-Scherrer-like ring (D-S ring) about the (100) crystal plane at $q = 10 \text{ nm}^{-1}$ appeared similar in intensity for both films, a closer examination of the line profiles (Figure 2i,j) revealed some differences. Specifically, the intensity of (100) crystal plane in pristine THP film at $q = 10 \text{ nm}^{-1}$ was stronger than that of the target film before $\theta = 0.075^{\circ}$. However, at $\theta = 0.3^{\circ}$, the intensity of the target film was stronger than that of the pristine film, suggesting that the presence of IO-4Cl molecules in the crystal boundary and surface of the target films enhanced its crystallization and obscured some of its crystal information at low incidence angles. Furthermore, we conducted a radial integration analysis of the intensity along the ring at $q = 10 \text{ nm}^{-1}$ (Figure 2k,l), which confirms the trend observed in the line profiles (Figure 2i,j).

Additionally, in situ GIWAXS was used to explore the crystal information of THP films over time. The intensity of *q* integrated during the time interval of 0 to 400 s is shown in **Figure 3**a,b,

while Figure 3c displays the peak area from Figure 3a,b. The peak area of the target film was larger than that of the pristine film, indicating that IO-4Cl promotes the crystallization of the THP films. Moreover, the crystallization time increased from 109 to 119 s, confirming enhanced crystallization of the target films.^[12,44]

To quantitatively analyze the crystal orientation distribution, the orientational order parameter *S* is calculated as follows:^[12,45,46]

$$S = \frac{1}{2} \left(3f_{\perp} - 1 \right) \tag{1}$$

here f_{\perp} represents the orientation of $[SnX_6]^{4-}$ octagon along the axis that is normal to the substrate surface, related to Figure 3d,e. The increased *S* value means a better orientation in the out-of-plane direction. Specifically, the *f* value, is given by the following function:

$$f_{\perp} = \int_{0}^{\frac{\pi}{2}} (\cos x)^{2} f(x) \, dx \tag{2}$$

where f(x) is the geometrically corrected scattering intensity.

To further investigate the crystal orientation distribution of the different halide perovskite films, we analyzed the changes in radially integrated intensity along the ring at $q = 10 \text{ nm}^{-1}$ over time, as presented in Figure 3d,e. We then extracted the value of the orientational order parameter *S* from Figure 3d,e for the different halide perovskite films. As shown in Figure 3f, the *S* value







Figure 3. Crystal kineties of THP films through suitable GIWAXS. Intensity of *q* integrating with times changes in a) the pristine film and b) target film. c) Peak area changes with time along with $q = 10 \text{ nm}^{-1}$ from (a) and (b). Radially integrated intensity patterns with times changes along $q = 10 \text{ nm}^{-1}$ in d) the pristine film and e) target film. f) Orientation order parameter from (d) and (e) changes with times at $q = 10 \text{ nm}^{-1}$.

of the target film is increased to ≈ 0.9 , which was higher than that of the pristine film (0.72). Additionally, the time required for crystal orientation variations in the target film was delayed by 36 s compared to the pristine film. This observation suggests that the presence of IO-4Cl in the crystal boundary and surface of the target film leads to the enhancement of the preferential crystal orientation and effectively facilitates charge transport and extraction in the vertical direction. The results demonstrate that IO-4Cl can effectively promote the crystallization of THP.

2.3. Performance and Characterization of THPSCs

As shown in Figure 4a, the configuration of the PSCs was indium tin oxide (ITO)/PEDOT:PSS/THP/C60/bathocuproine (BCP)/Ag. Current density-voltage (J-V) plots were recorded to evaluate the effect of IO-4Cl in THPSCs under AM 1.5G illumination (100 mW cm⁻²). As shown in Figure 4b, the pristine devices possess a maximum PCE of 10.1%, an open-circuit voltage (V_{OC}) of 0.68 V, a fill factor (FF) of 67.7%, and a short-circuit current density (J_{SC}) of 21.88 mA cm⁻². In contrast, the target devices exhibited a higher PCE of 11.3%, a $V_{\rm OC}$ of 0.70 V, an FF of 72.4%, and a I_{SC} of 22.31 mA cm⁻² (Figure 4c). The corresponding integrated J_{SC} values from incident photon-to-current conversion efficiency (IPCE) were 21.94 and 21.29 mA cm⁻² for the target and pristine devices, respectively (see Figure 4d). The steady-state photo-current density of the pristine device was 17.96 mA cm⁻² and a stable output PCE of 9.70% at a maximum power point (MPP) voltage of 0.54 V. The target device showed an increased steady-state output with a photo-current density of 19.82 mA cm⁻² and a stable output PCE of 11.10% at an MPP voltage of 0.56 V (Figure 4e). The improvement of PCE for target devices

was attributed to enhanced $V_{\rm OC}$ and FF resulting from the wellmatched energy band alignment between the target THP film and ETL. The dark *J*–V curves demonstrated that the target device had a smaller leakage current and higher carrier injection current than the pristine device, indicating reduced shunting paths and increased charge extraction by adding IO-4Cl into the THP films^[47] (Figure S3, Supporting Information).

Kelvin probe force microscopy (KPFM) and conductive atomic force microscope (C-AFM) were conducted to explore the interface properties between the perovskite film and ETL. The KPFM images of the pristine and target perovskite films were presented in Figure S4a and b, Supporting Information, respectively. A comparison of the contact potential difference (CPD) values in Figure S4c, Supporting Information showed that the pristine THP film exhibited an average CPD value of \approx 34.39 mV. In contrast, the target perovskite film exhibited an average CPD value of \approx 165.30 mV. This result indicates that adding IO-4Cl decreased the THP film's work function (WF), thereby facilitating chargecarrier extraction and transportation at the interface between the THP film and ETL.^[48,49] The increase in average CPD value was attributed to the reduction of defect states from uncoordinated Sn²⁺ on the surface of the THP films through coordination between C=O in IO-4Cl and Sn²⁺, which prevented nonradiative recombination.^[50] The average current values obtained from the C-AFM measurements of the pristine and target THP films were 7.80 and 13.75 pA, respectively, as shown in Figure S4df, Supporting Information. The enhanced current confirms that charge-carrier transport is improved in the target device.^[51–53] To further investigate the charge-carrier transport, the conductivity of the THP film was calculated from the current-voltage (I-V)characteristic curves, as shown in Figure S5, Supporting Information. The target film exhibited an increased conductivity of www.advancedsciencenews.com

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Figure 4. a) Schematic illustration of THPSCs. J-V plots of b) the pristine and c) target devices. d) IPCE spectra and integrate J_{SC} of the pristine and target devices. Stabilized J_{SC} and PCE under maximum power point of e) the pristine and f) target devices. g) V_{OC} and h) J_{SC} response under different light intensities. i) J-V plots of 1 cm² for the pristine and target devices.

 \approx 1.61 × 10⁻⁵ S cm⁻², compared to the pristine film's conductivity of 1.37 × 10⁻⁵ S cm⁻², indicating more efficient charge-carrier transport, which is consistent with the results obtained from KPFM and C-AFM.^[42,54]

The effective transport of charges in THP films can be identified using ultraviolet photoelectron spectroscopy (UPS). As shown in Figure S6a–d, Supporting Information, the valance band maximumenergies (E_{VB}) of the pristine and target THP were calculated to be -4.90 and -4.98 eV, respectively, using the formula $E_{VB} = 21.2$ -($E_{cutoff} - E_i$), where E_{cutoff} and E_i were ionization energy and cut-off energy, respectively.^[55] The UV– visible (UV–vis) absorption spectrum shows that the bandgap (E_g) of pristine and target perovskite films were 1.38 eV, respectively (Figure S6e, Supporting Information). The conduction band minimum energies (E_{CBM}) were -3.54 eV for the pristine halide perovskite film and -3.60 eV for the target film using the formula $E_{CBM} = E_{VBM} + E_g$, respectively. As shown in Figure S6f, Supporting Information, the target perovskite film represented optimal energy alignment compared to pristine film.

The light intensity-dependent current–voltage measurements were conducted to reveal the mechanism of charge carrier recombination. As shown in Figure 4g, the slope values were determined to be 1.61 $K_{\rm B}T/q$ in the target device and 1.87 $K_{\rm B}T/q$

in the pristine device. Compared to the pristine device, the reduced slope value in the target device indicates that trap-assisted recombination was constrained.[35] It is worth noting that the power law dependence between current density and light intensity can also facilitate trap-assisted recombination.^[56] As shown in Figure 4h, the target device exhibited a higher slope of 0.95 than that of the pristine device (0.92), which is consistent with the result of reduced nonradiative recombination. Steady-state photoluminescence (PL) also displayed that IO-4Cl can inhibit nonradiative recombination due to less defect density^[57] (Figure S7, Supporting Information). Furthermore, the density of trap states (N_t) was extracted from the space charge limited current (SCLC) measurement based on an electron-only device with an ITO/SnO₂/THP/C60/Ag (Figure S8, Supporting Information). The pristine electron-only device's trap-filled limit voltage (V_{TEI}) was found to have a higher value of 0.23 V than that of the target device at 0.13 V. The values of the pristine and target electrononly devices were $\approx 3.73 \times 10^{15}$ and 1.94×10^{15} cm⁻³, respectively. Such results confirm the reduction of trap state density upon introducing IO-4Cl.^[47] Finally, we prepared THPSCs with a larger active area of 1 cm². A PCE of 8.9%, V_{OC} of 0.68 V, J_{SC} of 19.80 mA cm^{-2,} and FF of 66.2% were obtained from the target device (see Figure 4i).

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Figure 5. Statistical box charts of a) V_{OC} b) J_{SC} c) FF d) PCE. e) Stability of the 12 pristine and 12 target devices stored in an N₂-filled glovebox for 1200 h. f) Stability of the 12 pristine and 12 target devices under air atmosphere with RH = $\approx 60-80\%$ for 200 min.

2.4. Stability of THPSCs

We analyzed the performance of 16 individual devices by quantifying their $V_{\rm OC}$, $J_{\rm SC}$, FF, and PCE. As shown in **Figure 5**a–d, the target devices with 0.5 mg mL⁻¹ IO-4Cl presented superior photoelectronic performance and reproducibility compared to the pristine and other IO-4Cl concentrations devices. Figure 5e exhibits the stability of 12 devices stored in a nitrogen glove box for 1200 h, wherein the average PCE of pristine devices decreased to 76% of their initial value, while that of the target devices was only reduced by 5%. The stability of 12 devices exposed in the air with RH of \approx 60–80% for 200 min was presented in **Figure 6**f, where the PCE of pristine devices was decreased to only 22% of their initial value, while the target devices still maintained 72% of their initial PCE.

We conducted water contact angle measurements to explore the hydrophobicity of the THP films. As shown in Figure 6a-c and Figure S9, Supporting Information, the pristine THP film showed progress of 46°, 29°, and 10° at 0, 5, and 10 min, respectively. The target film presented 83°, 74°, and 62° at the corresponding time. This suggests that the target film possessed stronger resistance to water than the pristine film. To evaluate the films' stability, we exposed them to air with an RH of \approx 60– 80% for 60 min (see Figure 6d,e). The pristine THP film appeared off-white after the exposure, whereas the target film showed only a few off-white areas, indicating improved stability due to the presence IO-4Cl. The extent of degradation is depicted in Figure S10, Supporting Information. The scanning electron microscope (SEM) and X-ray diffraction (XRD) measurements were performed to verify the surface morphology and crystal structure. Figure 6f,g, and Figure S11, Supporting Information exhibit the morphology of pristine and target perovskite films exposed to ambient air with RH of \approx 60–80% at 0, 15, and 60 min. At 15 min, the pristine film shows heavy erosion on the surface and crystal boundaries, while the film with IO-4Cl exhibits mild boundary degradation. The pristine THP film was destroyed after 60 min, especially at the boundaries, whereas the target film still shows the perovskite morphology. The excellent stability of the target film can be ascribed to IO-4Cl covering on surface and crystal boundaries.^[58–60] The XRD results also confirm that the THP film with IO-4Cl possesses superior stability (see Figure 6h,i). Additionally, we investigated the rate of Sn²⁺ oxidation through XPS. As shown in Figure 6j,k, and Figure S12, Supporting Information, the proportion of Sn²⁺ in pristine THP film was reduced to 63.94% from 84.66% after exposing to the air with RH = \approx 60– 80% for 15 min, and that of THP film with IO-4Cl was decreased by only 8.50% from 88.45% to 79.95%. Besides, we also compared films in pure oxygen, after 60 min, the Sn²⁺ content of pristine perovskite film decreased 35.04%, while target film only reduced 22.7%, indicating that IO-4Cl is retarding the oxidation of Sn²⁺ due to coordination action (Figure S13, Supporting Information).

3. Conclusion

In summary, we showed an n-type organic molecule interface to improve the interface stability and electron transport. The IO-4Cl was used as the modification layer on the surface and at the grain boundaries of THP films to provide a barrier against moisture and oxygen. The large size and rigid conjugated backbone of IO-4Cl make it an effective barrier. The coordination of C=O in IO-4Cl with Sn²⁺ on the surface and in the crystal boundaries of THP films can stabilize the crystal structure. Interestingly, the electron-rich indacenodithieno-[3,2-b]thiophene of IO-4Cl enhanced electron transport. Perovskite's crystallization kinetics and water as well as oxygen infiltration behavior were also systematically investigated. The THP film with IO-4Cl showed slow crystallization compared with pristine film. The devices fabricated with IO-4Cl-protected THP films demonstrated superior stability to those without IO-4Cl protection. Specifically, the unencapsulated target devices maintained an initial PCE of 95% after being stored in a nitrogen-filled glovebox for 1200 h. The pristine devices maintained only 76% of their initial PCE under the same conditions. Moreover, the target devices showed excellent air stability, maintaining 72% of their initial PCE under a relative

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Figure 6. Contact angles of water for a) the pristine and b) target THP films. c) Contact angles' plots of THP films under different times. Images of d) the pristine and e) target THP films in the air with RH \approx 60–80% for 60 min. SEM images of f) the pristine and g) target THP films putting in the air with RH \approx 60–80% for 60 min. XRD patterns of h) the pristine and i) target THP films tested in the air with RH \approx 60–80% for 0, 15, and 60 min. XPS spectra of Sn 3d for j) the pristine and k) target THP films putting on air with RH \approx 60–80% for 15 min.

humidity (RH) of \approx 60–80% for 200 min. The pristine devices experienced a 78% decrease in initial PCE under the same conditions.

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.

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Data Availability Statement

Research data are not shared.

Keywords

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- NREL, Best Research-Cell Efficiency Chart, https://www.nrel.gov/pv/ assets/pdfs/best-research-cell-efficiencies.pdf, Augest 2023.
- [2] Y. Ding, B. Ding, H. Kanda, O. J. Usiobo, T. Gallet, Z. Yang, Y. Liu, H. Huang, J. Sheng, C. Liu, Y. Yang, V. I. E. Queloz, X. Zhang, J.-N. Audinot, A. Redinger, W. Dang, E. Mosconic, W. Luo, F. De Angelis, M. Wang, P. Dörflinger, M. Armer, V. Schmid, R. Wang, K. G. Brooks, J. Wu, V. Dyakonov, G. Yang, S. Dai, P. J. Dyson, et al., *Nat. Nanotechnol.* 2022, *17*, 598.

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- [3] N. Ren, P. Wang, J. Jiang, R. Li, W. Han, J. Liu, Z. Zhu, B. Chen, Q. Xu, T. Li, B. Shi, Q. Huang, D. Zhang, S. Apergi, G. Brocks, C. Zhu, S. Tao, Y. Zhao, X. Zhang, *Adv. Mater.* **2023**, *35*, 2211806.
- [4] S. Mariotti, E. Köhnen, F. Scheler, K. Sveinbjörnsson, L. Zimmermann, M. Piot, F. Yang, B. Li, J. Warby, A. Musiienko, D. Menzel, F. Lang, S. Keßler, I. Levine, D. Mantione, A. Al-Ashouri, M. S. Härtel, K. Xu, A. Cruz, J. Kurpiers, P. Wagner, H. Köbler, J. Li, A. Magomedov, D. Mecerreyes, E. Unger, A. Abate, M. Stolterfoht, B. Stannowski, R. Schlatmann, et al., *Science* **2023**, *381*, 63.
- [5] R. Lin, Y. Wang, Q. Lu, B. Tang, H. G. Jiayi Li, Y. Gao, H. Li, C. Ding, J. Wen, P. Wu, C. Liu, S. Zhao, K. Xiao, Z. Liu, C. Ma, Y. Deng, L. Li, F. Fan, H. Tan, *Nature* **2023**, *620*, 994.
- [6] X. Meng, X. Hu, Y. Zhang, Z. Huang, Z. Xing, C. Gong, L. Rao, H. Wang, F. Wang, T. Hu, L. Tan, Y. Song, Y. Chen, *Adv. Funct. Mater.* **2021**, *31*, 2106460.
- [7] T. Wang, J. Yang, Q. Cao, X. Pu, Y. Li, H. Chen, J. Zhao, Y. Zhang, X. Chen, X. Li, *Nat. Commun.* **2023**, *14*, 1342.
- [8] Y. Zhang, L. Xu, Y. Wu, H. Zhang, F. Zeng, J. Xing, B. Liu, Y. Qi, B. Dong, X. Bai, H. Song, Adv. Funct. Mater. 2023, 33, 2214102.
- M. Lyu, J.-H. Yun, M. Cai, Y. Jiao, P. V. Bernhardt, M. Zhang, Q. Wang, A. Du, H. Wang, G. Liu, L. Wang, *Nano Res.* **2016**, *9*, 692.
- [10] T. Krishnamoorthy, H. Ding, C. Yan, W. L. Leong, T. Baikie, Z. Zhang, M. Sherburne, S. Li, M. Asta, N. Mathews, S. G. Mhaisalkar, J. Mater. Chem. A 2015, 3, 23829.
- [11] F. Jiang, D. Yang, Y. Jiang, T. Liu, X. Zhao, Y. Ming, B. Luo, F. Qin, J. Fan, H. Han, L. Zhang, Y. Zhou, J. Am. Chem. Soc. 2018, 140, 1019.
- [12] G. Li, Z. Su, M. Li, F. Yang, M. H. Aldamasy, J. Pascual, F. Yang, H. Liu, W. Zuo, D. Di Girolamo, Z. Iqbal, G. Nasti, A. Dallmann, X. Gao, Z. Wang, M. Saliba, A. Abate, *Adv. Energy Mater.* **2021**, *11*, 2101539.
- [13] F. Hao, C. C. Stoumpos, D. H. Cao, R. P. H. Chang, M. G. Kanatzidis, *Nat. Photonics* 2014, 8, 489.
- [14] M. H. Kumar, S. Dharani, W. L. Leong, P. P. Boix, R. R. Prabhakar, T. Baikie, C. Shi, H. Ding, R. Ramesh, M. Asta, M. Graetzel, S. G. Mhaisalkar, N. Mathews, *Adv. Mater.* **2014**, *26*, 7122.
- [15] A. Filippetti, S. Kahmann, C. Caddeo, A. Mattoni, M. Saba, A. Bosin, M. A. Loi, J. Mater. Chem. A 2021, 9, 11812.
- [16] W.-F. Yang, F. Igbari, Y.-H. Lou, Z.-K. Wang, L.-S. Liao, Adv. Energy Mater. 2020, 10, 1902584.
- [17] D. Koo, Y. Cho, U. Kim, G. Jeong, J. Lee, J. Seo, C. Yang, H. Park, Adv. Energy Mater. 2020, 10, 2001920.
- [18] J. Yang, C. Liu, C. Cai, X. Hu, Z. Huang, X. Duan, X. Meng, Z. Yuan, L. Tan, Y. Chen, Adv. Energy Mater. 2019, 9, 1900198.
- [19] J. H. Heo, H. J. Han, D. Kim, T. K. Ahn, S. H. Im, Energy Environ. Sci. 2015, 8, 1602.
- [20] Y. Bai, X. Meng, S. Yang, Adv. Energy Mater. 2018, 8, 1701883.
- [21] L. Xu, X. Feng, W. Jia, W. Lv, A. Mei, Y. Zhou, Q. Zhang, R. Chen, W. Huang, *Energy Environ. Sci.* 2021, 14, 4292.
- [22] C.-H. Kuan, J.-M. Chih, Y.-C. Chen, B.-H. Liu, C.-H. Wang, C.-H. Hou, J.-J. Shyue, E. W.-G. Diau, ACS Energy Lett. 2022, 7, 4436.
- [23] P.-W. Liang, C.-C. Chueh, S. T. Williams, A. K.-Y. Jen, Adv. Energy Mater. 2015, 5, 1402321.
- [24] X. Jiang, F. Wang, Q. Wei, H. Li, Y. Shang, W. Zhou, C. Wang, P. Cheng, Q. Chen, L. Chen, Z. Ning, *Nat. Commun.* **2020**, *11*, 1245.
- [25] J. Warby, F. Zu, S. Zeiske, E. Gutierrez-Partida, L. Frohloff, S. Kahmann, K. Frohna, E. Mosconi, E. Radicchi, F. Lang, S. Shah, F. Peña-Camargo, H. Hempel, T. Unold, N. Koch, A. Armin, F. De Angelis, S. D. Stranks, D. Neher, M. Stolterfoht, *Adv. Energy Mater.* **2022**, *12*, 2103567.
- [26] Y. Shao, Z. Xiao, C. Bi, Y. Yuan, J. Huang, Nat. Commun. 2014, 5, 5784.
- [27] J. Lian, B. Lu, F. Niu, P. Zeng, X. Zhan, Small Methods 2018, 2, 1800082.
- [28] Z. Lin, C. Liu, G. Liu, J. Yang, X. Duan, L. Tan, Y. Chen, Chem. Commun. 2020, 56, 4007.

- [29] R. Lin, K. Xiao, Z. Qin, Q. Han, C. Zhang, M. Wei, M. I. Saidaminov, Y. Gao, J. Xu, M. Xiao, A. Li, J. Zhu, E. H. Sargent, H. Tan, *Nat. Energy* **2019**, *4*, 864.
- [30] H. Liu, L. Wang, R. Li, B. Shi, P. Wang, Y. Zhao, X. Zhang, ACS Energy Lett. 2021, 6, 2907.
- [31] K. Zhang, A. Späth, O. Almora, V. M. Le Corre, J. Wortmann, J. Zhang, Z. Xie, A. Barabash, M. S. Hammer, T. Heumüller, J. Min, R. Fink, L. Lüer, N. Li, C. J. Brabec, ACS Energy Lett. 2022, 7, 3235.
- [32] X. Dai, S. Chen, H. Jiao, L. Zhao, K. Wang, Z. Ni, Z. Yu, B. Chen, Y. Gao, J. Huang, *Nat. Energy* **2022**, *7*, 923.
- [33] T. Wu, X. Liu, X. He, Y. Wang, X. Meng, T. Noda, X. Yang, L. Han, Sci. China: Chem. 2020, 63, 107.
- [34] M. E. Kayesh, K. Matsuishi, R. Kaneko, S. Kazaoui, J.-J. Lee, T. Noda, A. Islam, ACS Energy Lett. 2018, 4, 278.
- [35] B.-B. Yu, Z. Chen, Y. Zhu, Y. Wang, B. Han, G. Chen, X. Zhang, Z. Du, Z. He, *Adv. Mater.* **2021**, *33*, 2102055.
- [36] W. Ke, C. C. Stoumpos, M. Zhu, L. Mao, I. Spanopoulos, J. Liu, O. Y. Kontsevoi, M. Chen, D. Sarma, Y. Zhang, M. R. Wasielewski, M. G. Kanatzidis, *Sci. Adv.* **2017**, *3*, e1701293.
- [37] H. Xu, Y. Jiang, T. He, S. Li, H. Wang, Y. Chen, M. Yuan, J. Chen, Adv. Funct. Mater. 2019, 29, 1807696.
- [38] Q. Cao, Y. Li, Y. Zhang, J. Zhao, T. Wang, B. Yang, X. Pu, J. Yang, H. Chen, X. Chen, X. Li, S. Ghasemi, H. Salari, A. Hagfeldt, X. Li, *Adv. Energy Mater.* 2022, 12, 2201435.
- [39] J. A. Hong, M. Jeong, S. Park, A.-Y. Lee, H. S. Kim, S. Jeong, D. W. Kim, S. Cho, C. Yang, M. H. Song, *Adv. Sci.* **2023**, *10*, 2205127.
- [40] M. Abdi-Jalebi, Z. Andaji-Garmaroudi, S. Cacovich, C. Stavrakas, B. Philippe, J. M. Richter, M. Alsari, E. P. Booker, E. M. Hutter, A. J. Pearson, S. Lilliu, T. J. Savenije, H. Rensmo, G. Divitini, C. Ducati, R. H. Friend, S. D. Stranks, *Nature* **2018**, *555*, 497.
- [41] T. Niu, J. Lu, R. Munir, J. Li, D. Barrit, X. Zhang, H. Hu, Z. Yang, A. Amassian, K. Zhao, S. (F.). Liu, *Adv. Mater.* **2018**, *30*, 1706576.
- [42] X. Luo, Z. Shen, Y. Shen, Z. Su, X. Gao, Y. Wang, Q. Han, L. Han, Adv. Mater. 2022, 34, 2202100.
- [43] J. Yang, W. Tang, R. Yuan, Y. Chen, J. Wang, Y. Wu, W.-J. Yin, N. Yuan,
 J. Ding, W.-H. Zhang, *Chem. Sci.* 2021, *12*, 2050.
- [44] X. Meng, J. Lin, X. Liu, X. He, Y. Wang, T. Noda, T. Wu, X. Yang, L. Han, Adv. Mater. 2019, 31, 1903721.
- [45] J. Song, G. Zhou, W. Chen, Q. Zhang, J. Ali, Q. Hu, J. Wang, C. Wang, W. Feng, A. B. Djurisic, H. Zhu, Y. Zhang, T. Russell, F. Liu, *Adv. Mater.* 2020, *32*, 2002784.
- [46] J. T. Rogers, K. Schmidt, M. F. Toney, G. C. Bazan, E. J. Kramer, J. Am. Chem. Soc. 2012, 134, 2884.
- [47] G. Liu, Y. Zhong, W. Feng, M. Yang, G. Yang, J.-X. Zhong, T. Tian, J.-B. Luo, J. Tao, S. Yang, X.-D. Wang, L. Tan, Y. Chen, W.-Q. Wu, Angew. Chem., Int. Ed. 2022, 134, e202209464.
- [48] R. Wang, J. Xue, K.-L. Wang, Z.-K. Wang, Y. Luo, D. Fenning, G. Xu, S. Nuryyeva, T. Huang, Y. Zhao, J. L. Yang, J. Zhu, M. Wang, S. Tan, I. Yavuz, K. N. Houk, Y. Yang, *Science* **2019**, *366*, 1509.
- [49] W. Zhang, Y. Cai, H. Liu, Y. Xia, J. Cui, Y. Shi, R. Chen, T. Shi, H.-L. Wang, Adv. Energy Mater. 2022, 12, 2202491.
- [50] N. Li, X. Niu, L. Li, H. Wang, Z. Huang, Y. Zhang, Y. Chen, X. Zhang, C. Zhu, H. Zai, Y. Bai, S. Ma, H. Liu, X. Liu, Z. Guo, G. Liu, R. Fan, H. Chen, J. Wang, Y. Lun, X. Wang, J. Hong, H. Xie, D. S. Jakob, X. G. Xu, Q. Chen, H. Zhou, *Science* **2021**, *373*, 561.
- [51] Q. Wang, Q. Dong, T. Li, A. Gruverman, J. Huang, Adv. Mater. 2016, 28, 6734.
- [52] J.-W. Lee, Z. Dai, T.-H. Han, C. Choi, S.-Y. Chang, S.-J. Lee, N. De Marco, H. Zhao, P. Sun, Y. Huang, Y. Yang, *Nat. Commun.* **2018**, *9*, 3021.
- [53] J. Eichhorn, C. Kastl, J. K. Cooper, D. Ziegler, A. M. Schwartzberg, I. D. Sharp, F. M. Toma, *Nat. Commun.* 2018, *9*, 2597.
- [54] C. Wang, H. Hao, S. Chen, K. Cao, H. Yu, Q. Zhang, G. Wan, W. Shang, W. Huang, RSC Adv. 2017, 7, 29944.

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- [55] T. Mahmoudi, M. Kohan, W.-Y. Rho, Y. Wang, Y. H. Im, Y.-B. Hahn, *Adv. Energy Mater.* **2022**, *12*, 2201977.
- [56] A. Rajagopal, P.-W. Liang, C.-C. Chueh, Z. Yang, A. K.-Y. Jen, ACS Energy Lett. 2017, 2, 2531.
- [57] T. Ye, K. Wang, Y. Hou, D. Yang, N. Smith, B. Magill, J. Yoon, R. R. Mudiyanselage, G. A. Khodaparast, K. Wang, S. Priya, J. Am. Chem. Soc. 2021, 143, 4319.
- [58] Z. Liu, F. Cao, M. Wang, M. Wang, L. Li, Angew. Chem., Int. Ed. 2020, 59, 4161.
- [59] Y. Zhao, J. Wei, H. Li, Y. Yan, W. Zhou, D. Yu, Q. Zhao, Nat. Commun. 2016, 7, 10228.
- [60] L. Zuo, H. Guo, D. W. Dequilettes, S. Jariwala, N. De Marco, S. Dong, R. Deblock, D. S. Ginger, B. Dunn, M. Wang, Y. Yang, *Sci. Adv.* 2017, *3*, e1700106.