Supplementary Information for

Mitigating tin ion migration and reinforcing buried interface via synergistic polymer-modified tin oxide

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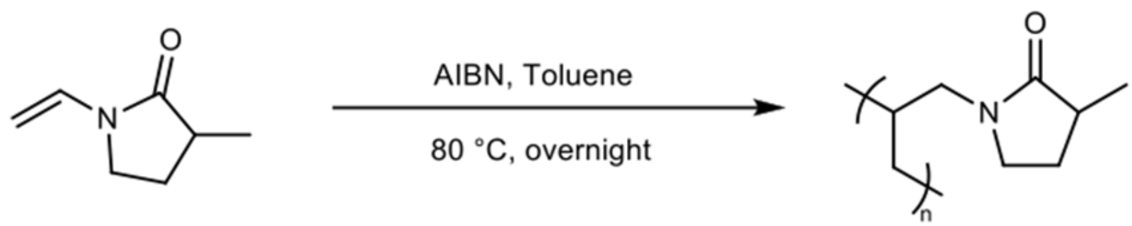
Supplementary Notes

Supplementary Note 1. Synthesis and characterization of PED, PEM

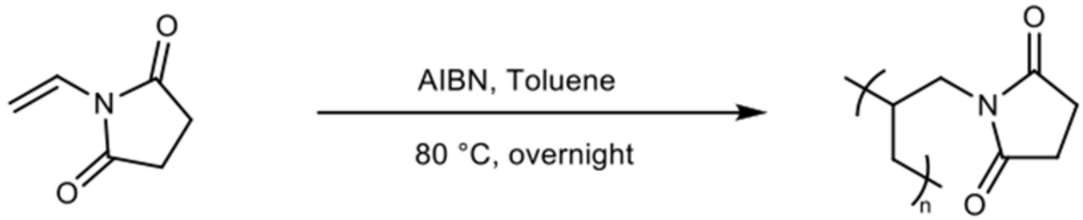
The detailed synthetic routes and characterizations of PED and PEM are shown in in Supplementary Scheme 1 and Supplementary Fig 1-4.

^{1}H NMR spectra were measured on Bruker AdvanceCore 400 MHz NMR spectrometers. Gel permeation chromatography (GPC) were measured on Shimadzu model LG-2030C 3D.



Supplementary Scheme. 1. Synthesis route of PED

Under a nitrogen atmosphere, 1-ethenylpyrrolidine-2,5-dione (ED) (0.2 mL) was dissolved in toluene (1 mL) together with 2,2′-azobis(2-methylpropionitrile) (AIBN, 0.002 mg). The solution was heated and stirred at 80 °C overnight to effect free-radical polymerization. To improve the solubility of the product, 1mL chloroform (CF) were added to the solution. The mixture was then poured into diethyl ether (DE) to precipitate the polymer. The resulting precipitated polymer was collected by filtration, purified by three cycles of reprecipitation (dissolution in CF followed by precipitation with DE, and dried under vacuum to constant mass. The PED sample was obtained as flake-like solids (Mn=5033, Mw=7465).



Supplementary Scheme 2. Synthesis route of PEM

Similarly, under a nitrogen atmosphere, 1-ethenyl-3-methylpyrrolidin-2-one (EM) (0.2 mL) was dissolved was dissolved in toluene (1 mL) together with AIBN (0.002 mg). The solution was heated and stirred at 80 °C overnight to effect free-radical polymerization. To improve the solubility of the product, 1mL chlorobenzene (CB) was added to the solution. The mixture was then poured into diethyl ether (DE) to precipitate the polymer. The resulting precipitated polymer was collected by filtration, purified by three cycles of reprecipitation (dissolution in CB followed by precipitation with DE, and dried under vacuum to constant mass. The PEM sample appeared as a free-flowing granular powder (Mw=1577, Mn=1600).

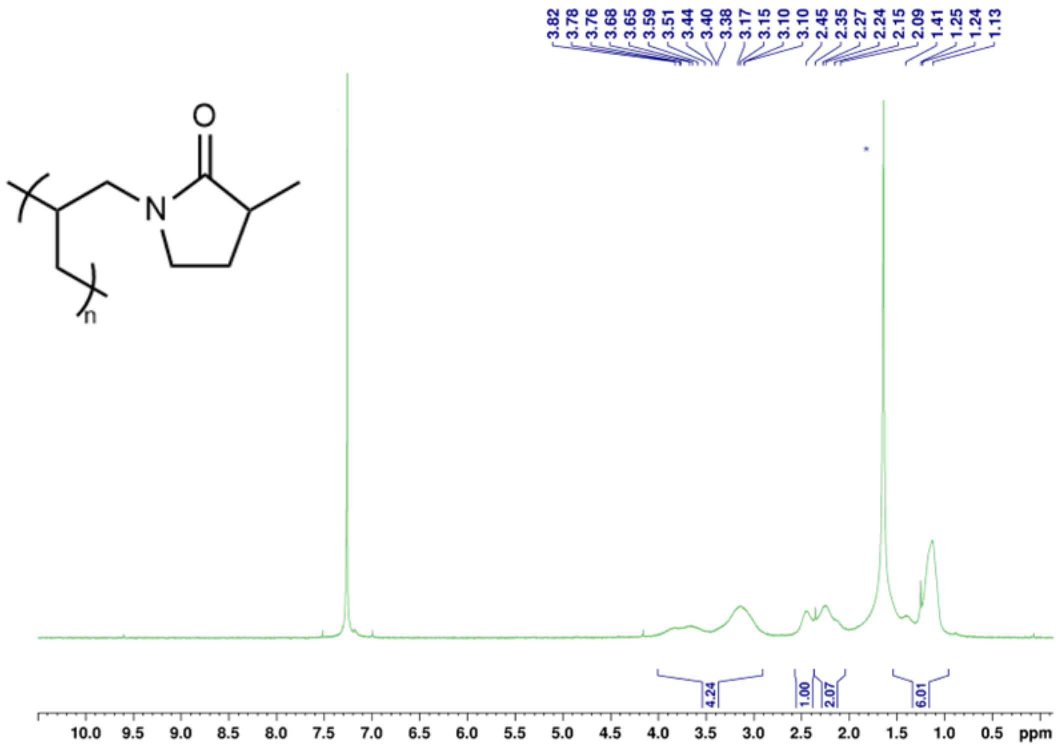
Supplementary Note 2. Perovskite thin-film peeling process

The perovskite thin-film peeling process was performed as follows (process provided in **Supplementary Figure 27**. A uniform layer of A–B epoxy was first applied onto a clean glass substrate (Glass/FTO). The perovskite film was then placed with its top surface in direct contact with the epoxy layer and gently flipped or pressed to ensure complete adhesion. The assembly was left to cure for >8 h under ambient conditions. After curing, the two substrates were carefully separated, leaving the perovskite film adhered to the epoxy-coated glass. This configuration exposes the bottom interface of the perovskite layer for subsequent characterization.

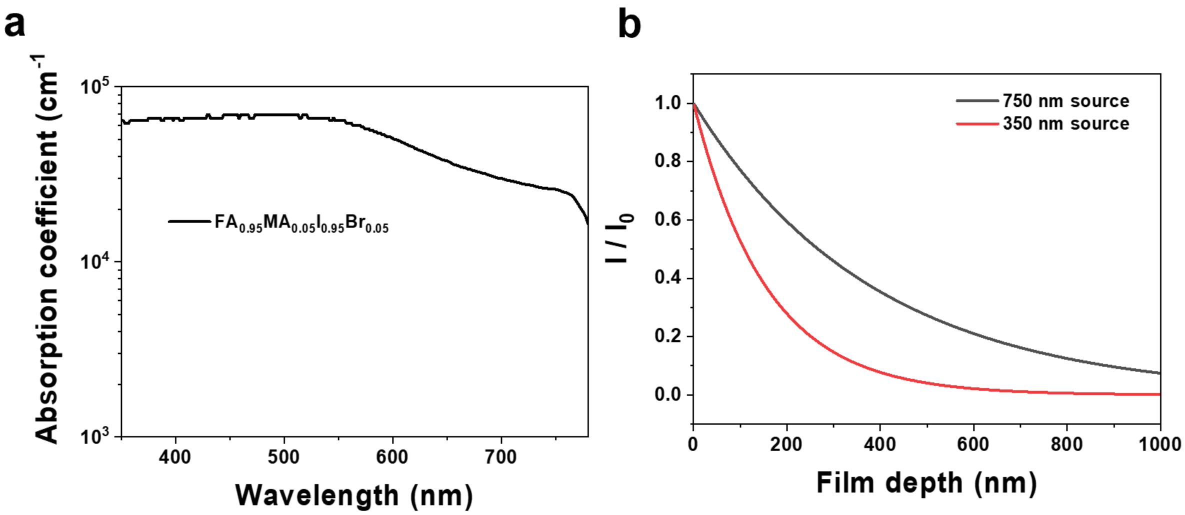
For complete device stacks, the top metal electrode was first removed using Kapton tape. The same peeling protocol described above was then applied to expose the buried perovskite/ETL interface.

Supplementary Figures

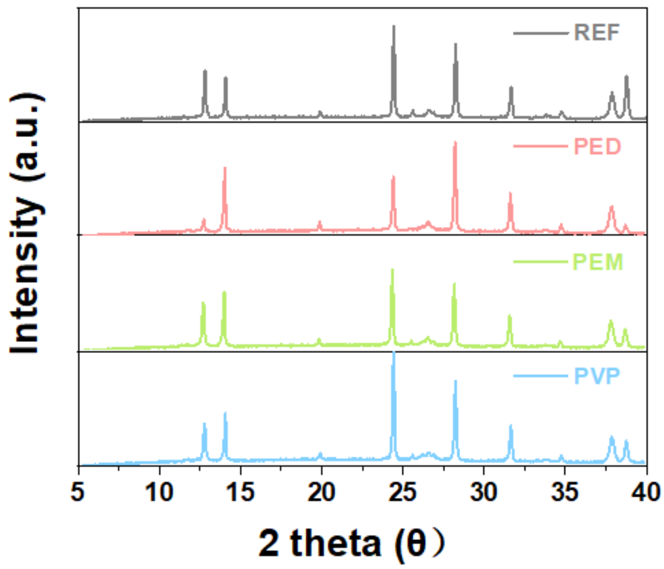
Supplementary Fig. 1. ^{1}H NMR of PED.



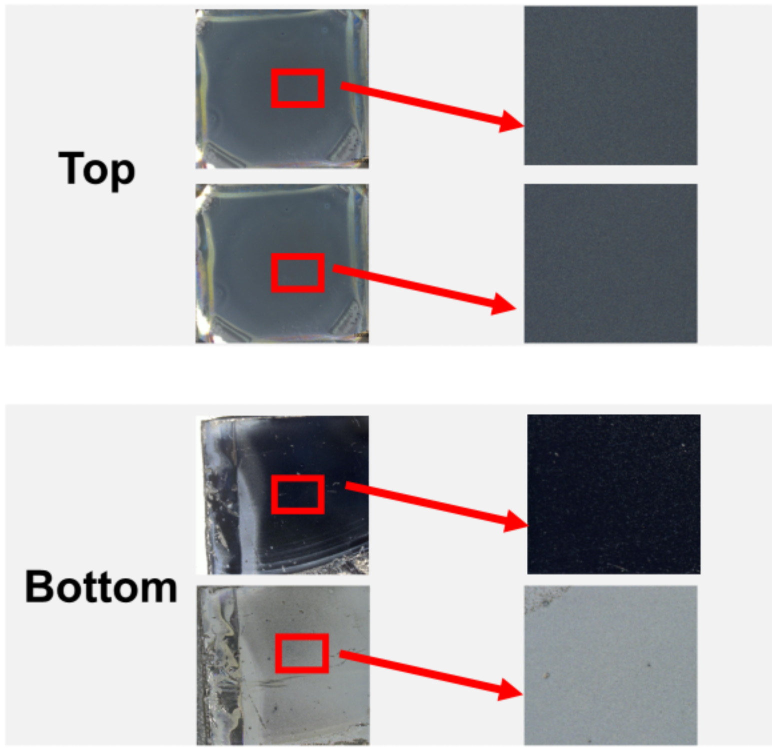
Supplementary Fig. 2. ^{1}H NMR of PED.



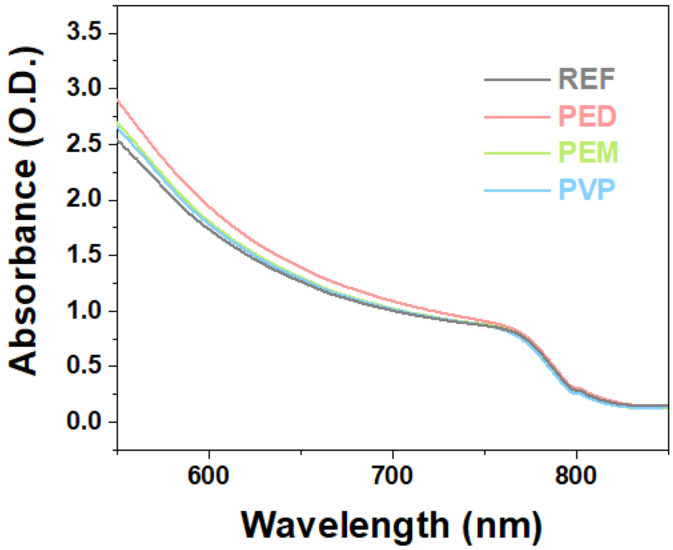
Supplementary Fig. 3 Absorption spectra of perovskite film (a) Absorption coefficient of $FA_{0.95}MA_{0.05}I_{0.95}Br_{0.05}$. (b) Depth dependent intensity attenuation of incident light (I_0) with different light source wavelength.



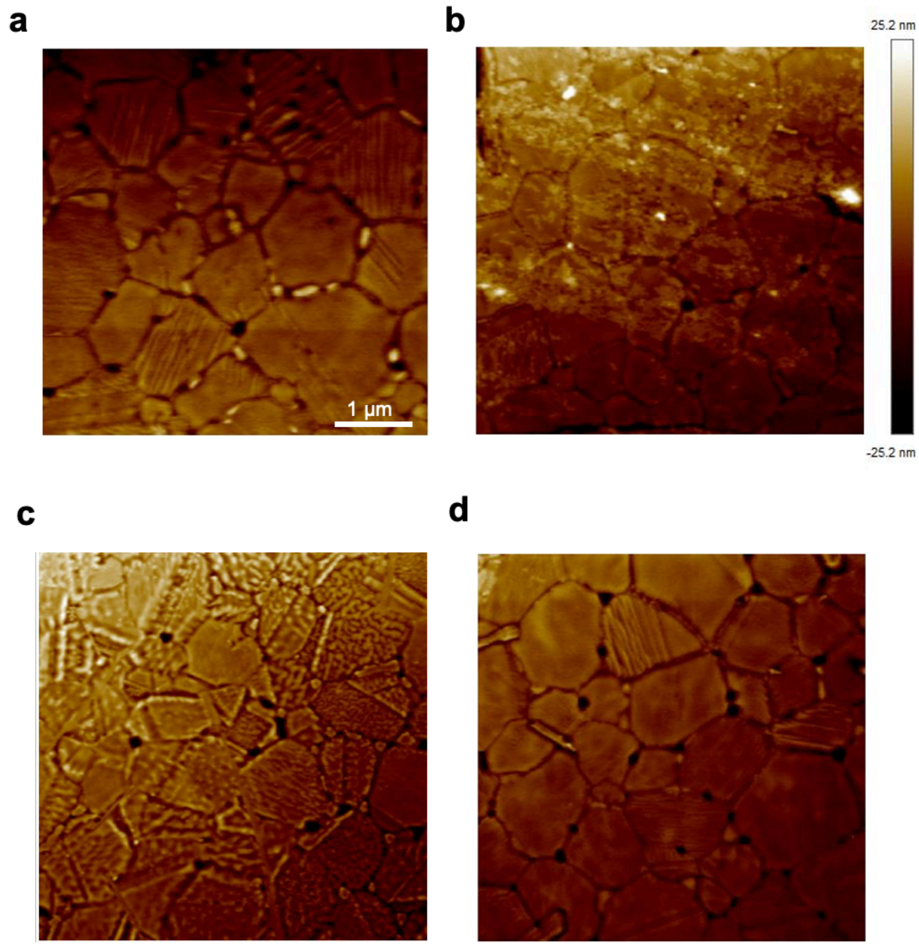
Supplementary Fig.4 XRD spectra of fresh samples (X-ray incident from bottom interface).



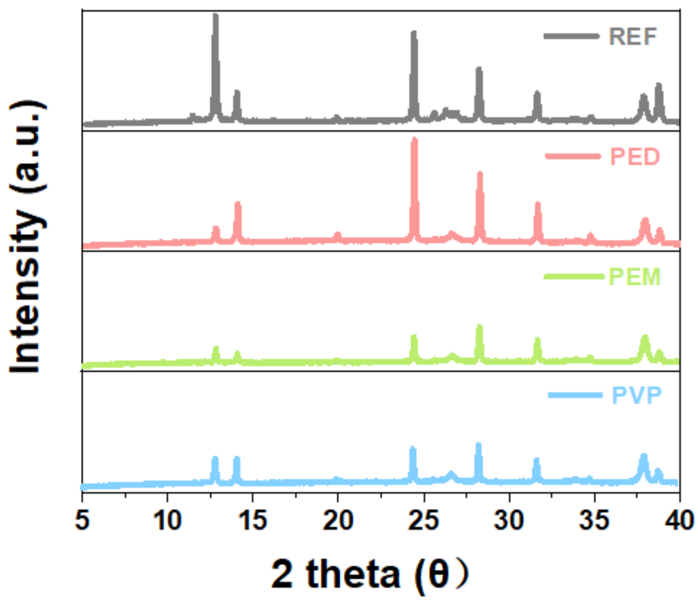
Supplementary Fig. 5. Optical images of top and bottom interface comparison after incandescent lamp illumination aging under ambient condition (~40% humidity, room temperature).



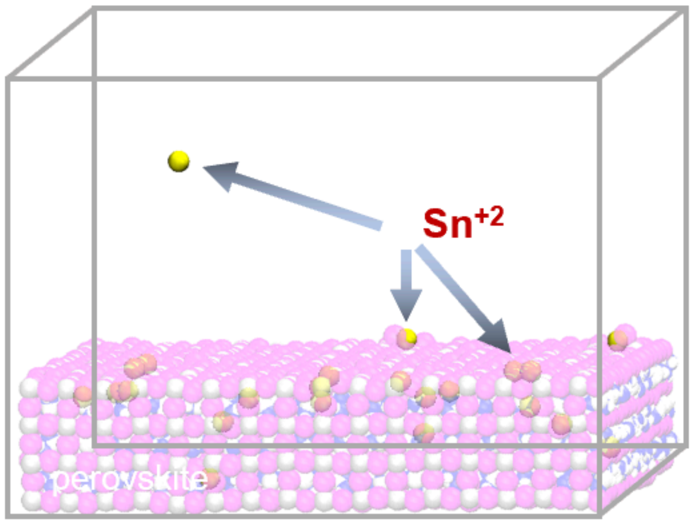
Supplementary Fig. 6. UV-vis spectra of perovskite thin film deposited on ITO/(polymeric interlayers) substrate.



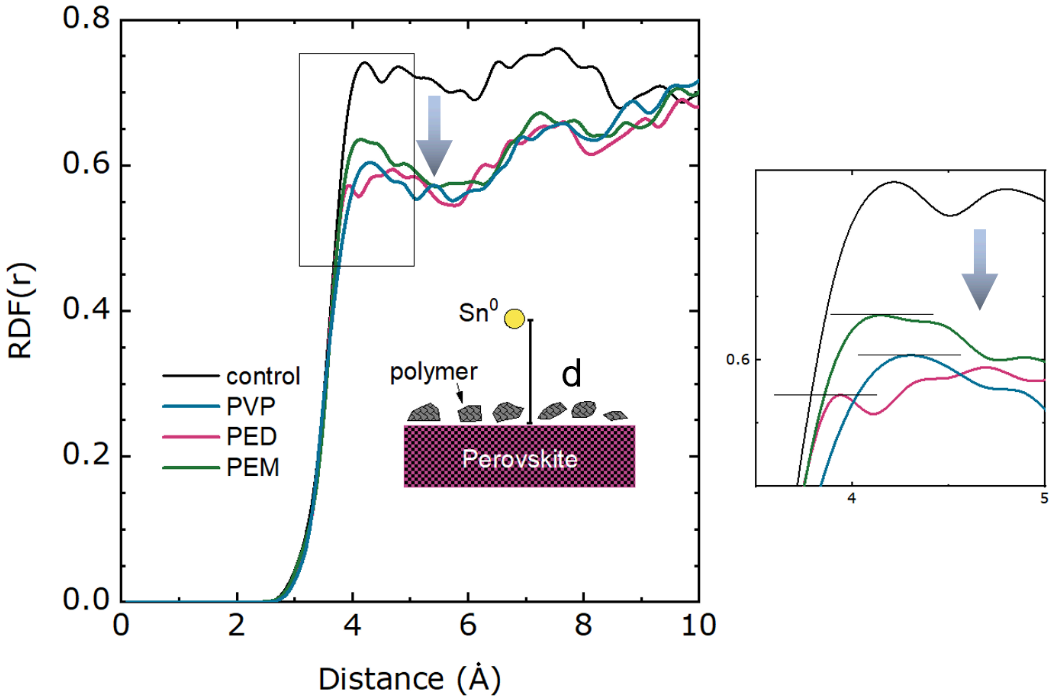
Supplementary Fig. 7. AFM images for bottom interface for fresh samples (a) REF(b) PED(c) PEM(d) PVP.



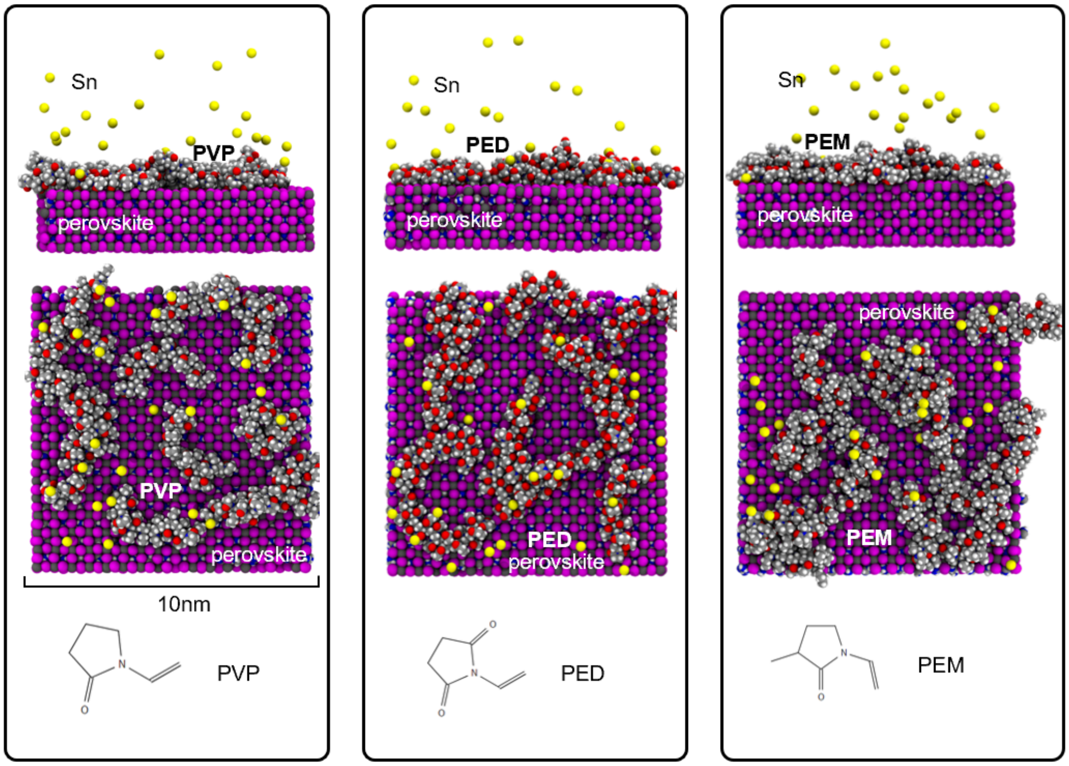
Supplementary Fig. 8. XRD spectra of aged samples (X-ray incident from bottom interface).



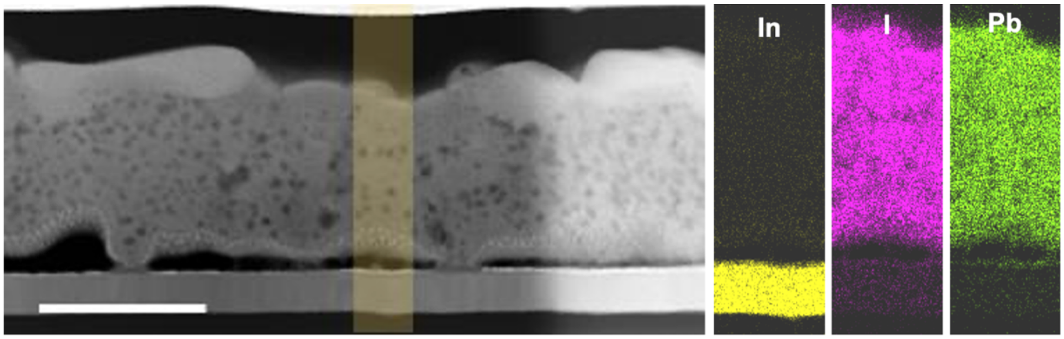
Supplementary Fig. 9. Illustration of Sn migration near perovskite for MD simulations.



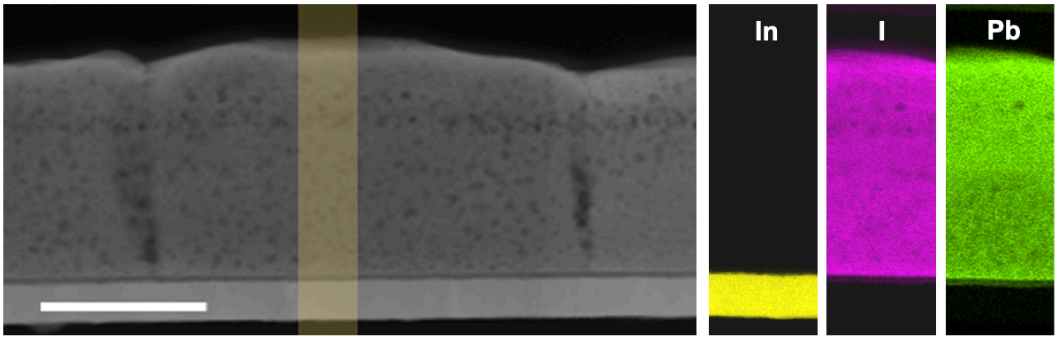
Supplementary Fig. 10. MD simulations for the amount of Sn migration across different polymers.



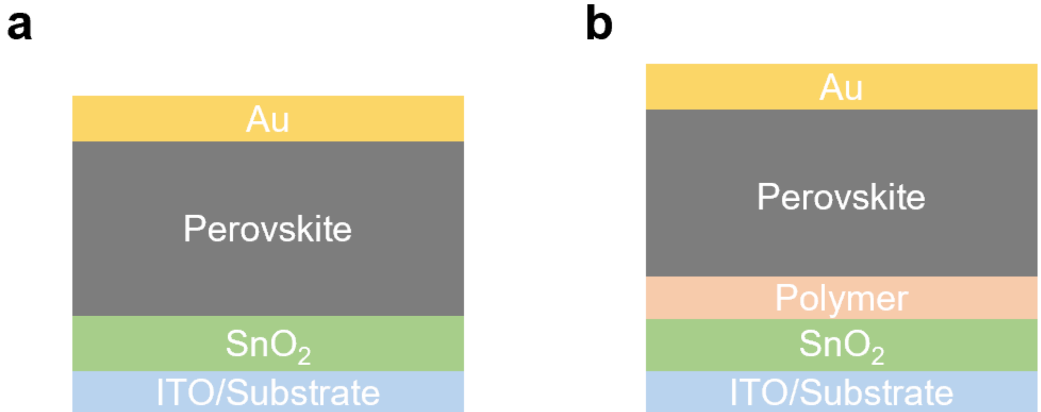
Supplementary Fig. 11. Molecular Dynamic simulations for Sn migration across different polymers.



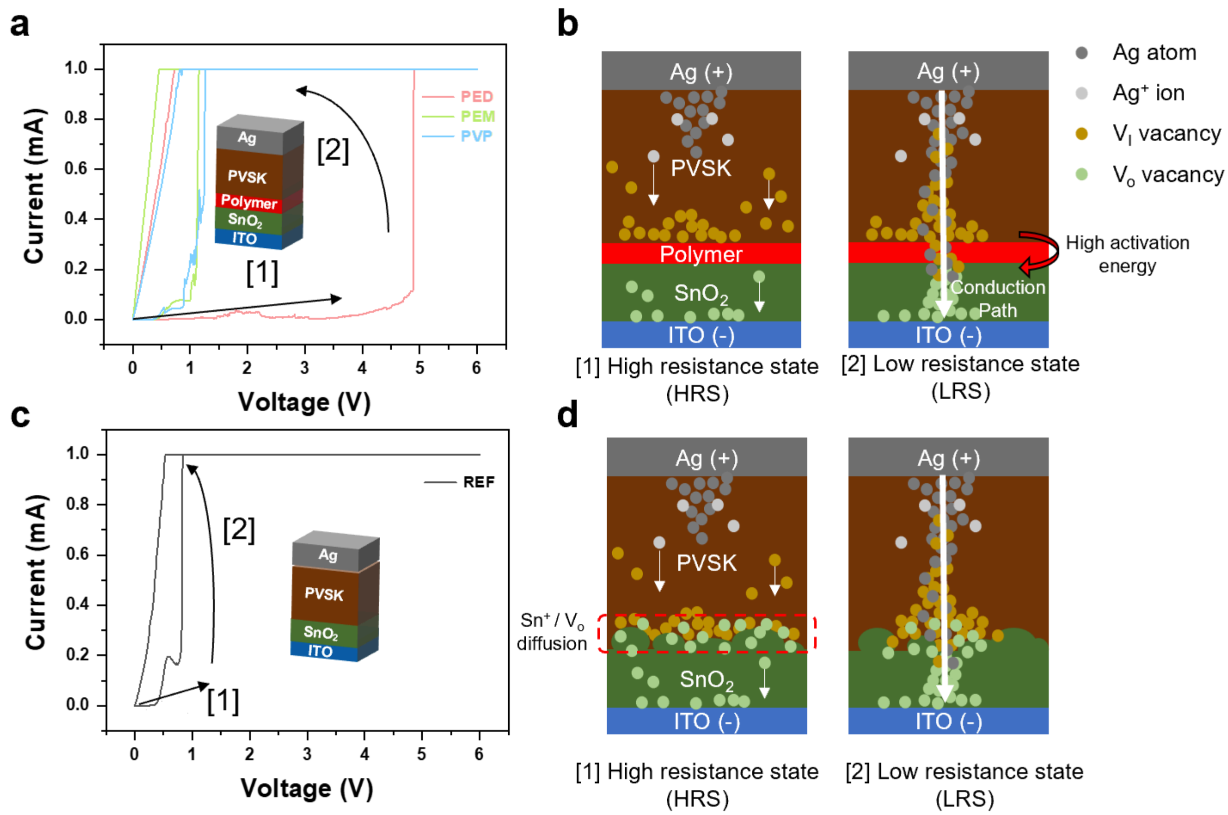
Supplementary Fig. 12. STEM image (left) and EDS elemental maps (right) of In, I and Pb from the highlighted image area of an aging reference device.



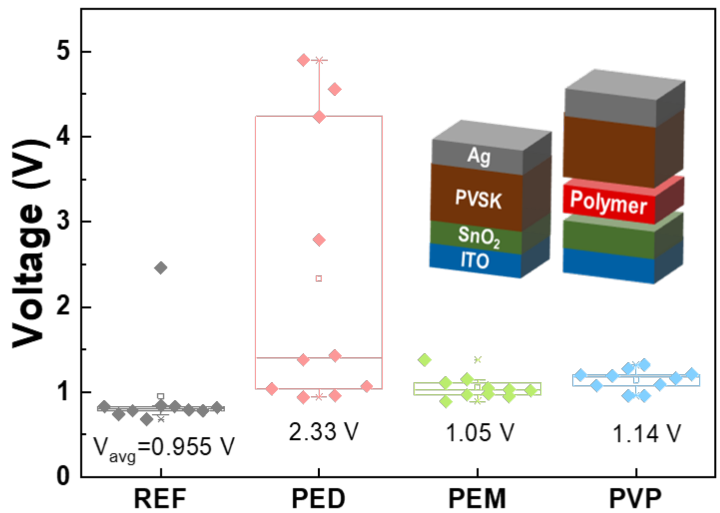
Supplementary Fig. 13. STEM image (left) and EDS elemental maps (right) of In, I and Pb from the highlighted image area in an aging device with PED interlayer.



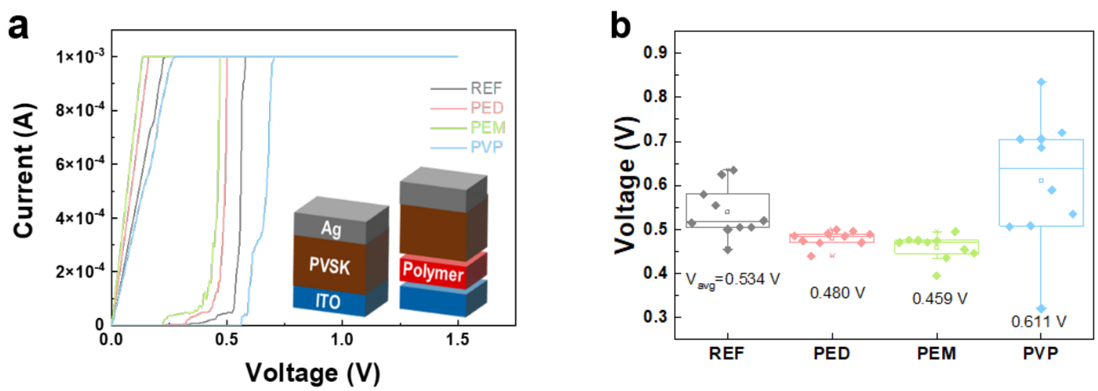
Supplementary Fig. 14. Device illustration for temperature-dependent conductivity tests (a) reference device; (b) device with different polymeric interlayers



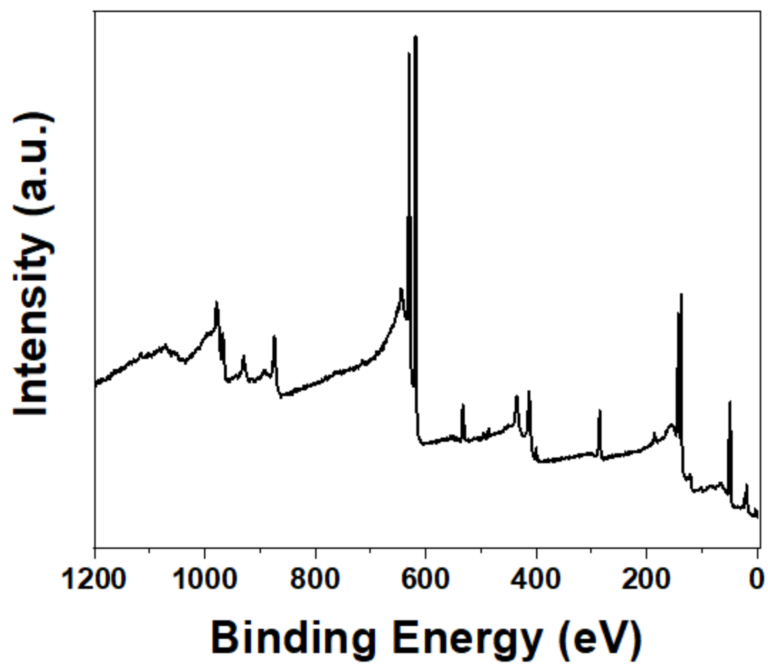
Supplementary Fig. 15. I-V characteristics of resistivity switching test and corresponding schematics for (a,b) with polymeric interlayers and (c,d) without layers. For the region of [1], the conductive filament is not fully formed, maintaining high resistance state (HRS). The resistance state is abruptly switched to low resistance state (LRS) at the region [2] due to the formation of conductive filaments via mobile ion migrations.



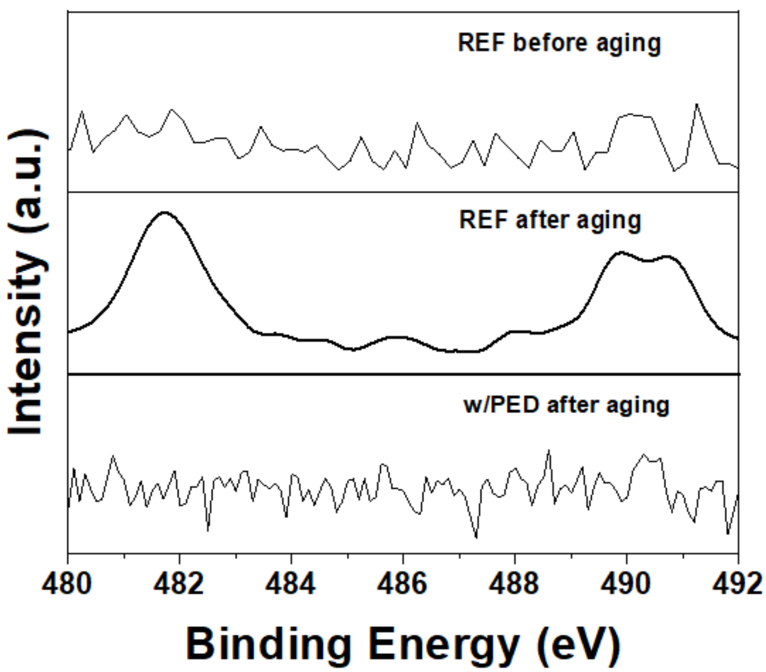
Supplementary Fig. 16. Resistivity switching tests for polymeric interlayers with SnO2
(Extracted from 10 different cells)



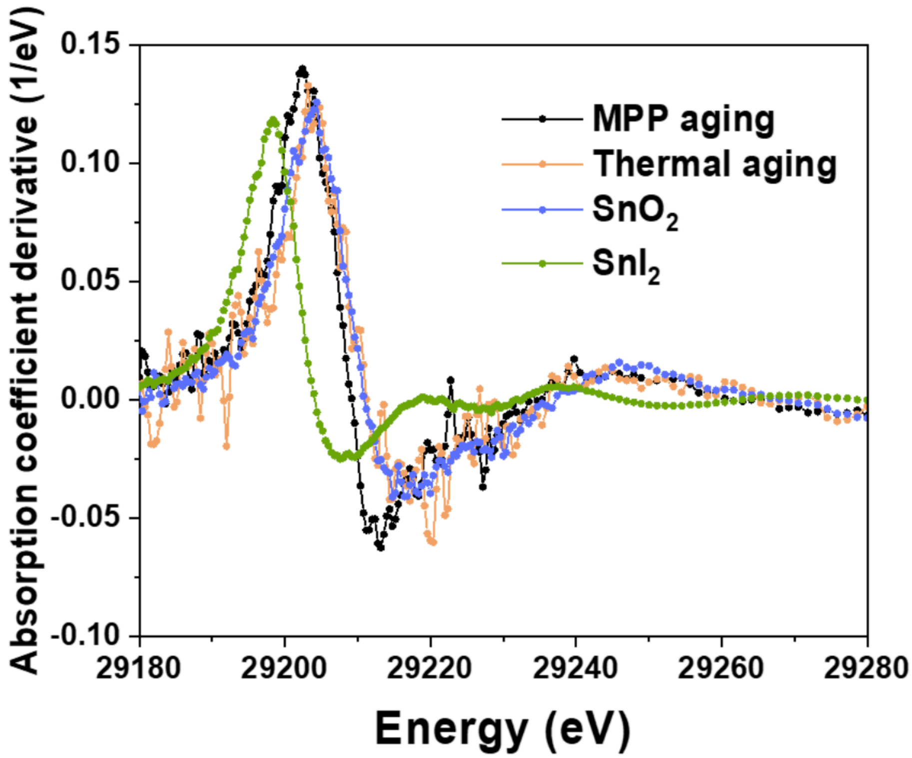
Supplementary Fig. 17. Resistivity switching tests for polymeric interlayers without SnO2 (Extracted from 10 different cells).



Supplementary Fig. 18. XPS survey spectrum for aged reference sample.



Supplementary Fig. 19. XPS spectra of the bottom interface before aging and after aging.



Supplementary Fig. 20. Derivative of X-ray absorption coefficient in the Sn K-edge region for the MPP and thermal aging samples, as well as SnO_2 and SnI_2 references.

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Test Report
No. TRPVP01062/26P/01

Commission Testing
according to IEC 61215-2 / EN IEC 61215-2

Applicant: **Lanzhou University**
No. 222 Tianshui South Road, Lanzhou, Gansu Province, P. R. China, 730000

File No.: PVP01062/26P-01

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Reviewed: (Technical Certifier) by: 数字签名者: Henry Huang 日期: 2026.01.23 13:23:38 +08'00'

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Test Report

File No.: PVP01062/26P-01 Test Report No.: TRPVP01062/26P/01

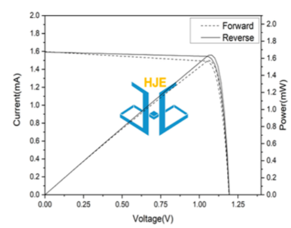
IEC 61215-2 / EN IEC 61215-2			
Clause	Requirement + Test	Result - Remark	Verdict

Test results of IEC 61215-2 / EN IEC 61215-2
Perovskite solar cell

4.2 Maximum power determination - MQT 02		—
Test date [YYYY-MM-DD] ....:	2026-01-20	—
Test method ....:	☒ Solar simulator / ☐ Natural sunlight	—
Module temperature [°C] ....:	25±5	—
Irradiance [W/m²] ....:	1000	—

Sample #	I_{sc} [mA]	V_{oc} [V]	I_{mp} [mA]	V_{mp} [V]	P_{max} [mW]	FF [%]	η [%]
1-forward	1.598	1.192	1.490	1.060	1.58	82.94	25.64
1-reverse	1.593	1.194	1.545	1.060	1.64	86.06	26.58

Supplementary information:
The tests are performed according to client's application.
During this maximum power determination, the spectral mismatch was not considered. And the lab did not perform light soaking procedure prior to measurements.
η [%] = Pmax [W] / area [m²] / 1000 [W/m²] x 100% (designated illuminated area: 0.0616 cm²).
The measurements were performed with a steady state solar simulator class AAA according to IEC 60904-9:2020.
Sample#-forward: The electrical resistance of solar simulator was scanned from 0 to +∞.
Sample#-reverse: The electrical resistance of solar simulator was scanned from +∞ to 0.
And the IV measurement characteristic was listed as below:



Supplementary Fig. 21. Independent efficiency certification of PSCs.

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Test Report
No. TRPVP01062/26P/07

Commission Testing
according to IEC 61215-2 / EN IEC 61215-2

Applicant: **Lanzhou University**
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File No.: PVP01062/26P-07

Designed: (Project Engineer) by: Bella Liu 数字签名者：bella liu 日期：2026.01.23 12:39:18 +08'00'

Reviewed: (Technical Certifier) by: Henry Huang 数字签名者：Henry Huang 日期：2026.01.23 13:25:10 +08'00'

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Test Report

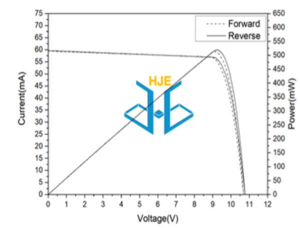
File No.: PVP01062/26P-07 Test Report No.: TRPVP01062/26P/07

IEC 61215-2 / EN IEC 61215-2			
Clause	Requirement + Test	Result - Remark	Verdict

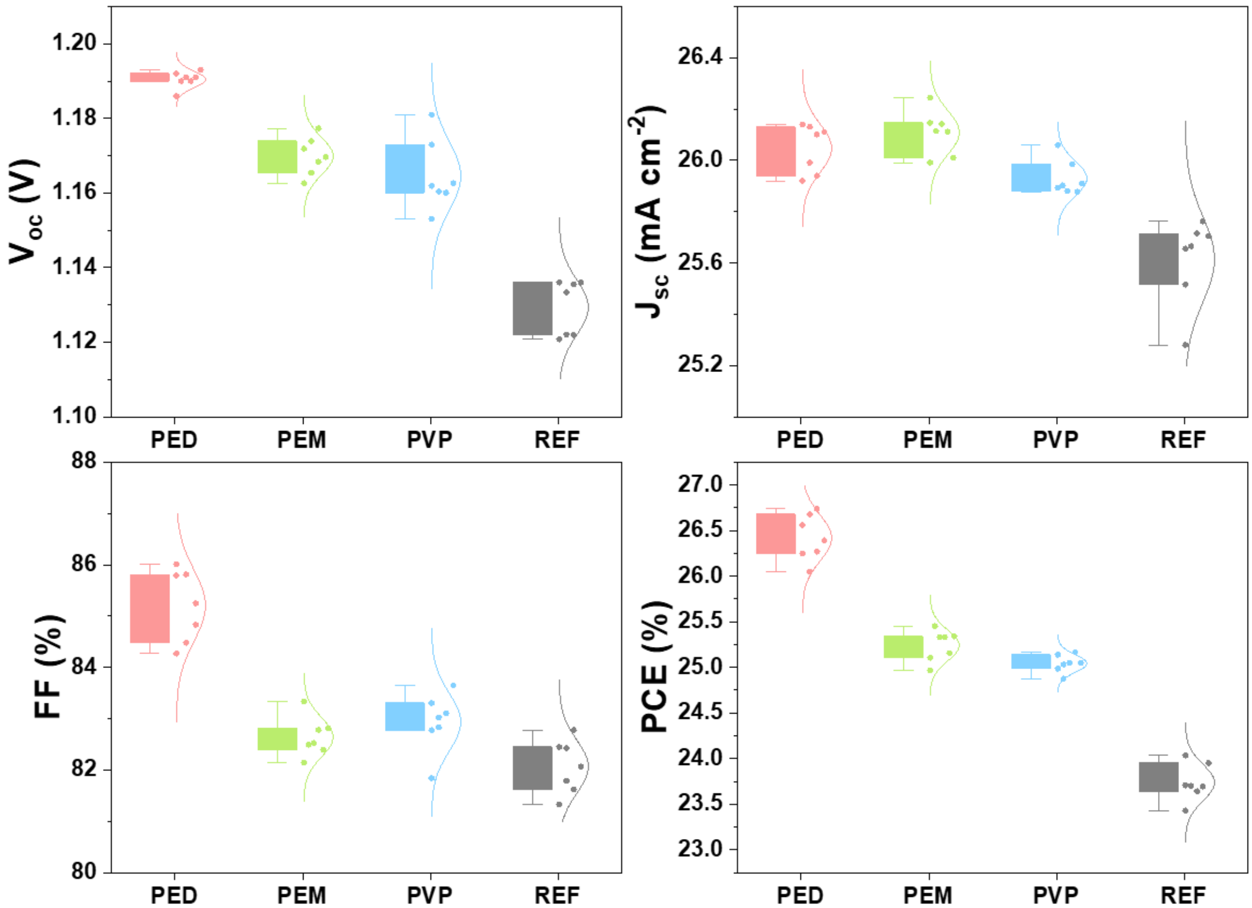
Test results of IEC 61215-2 / EN IEC 61215-2
Perovskite solar module

4.2 Maximum power determination - MQT 02							—
Test date [YYYY-MM-DD] ....:	2026-01-20						—
Test method ....:	☒ Solar simulator / ☐ Natural sunlight						—
Module temperature [°C] ....:	25±5						—
Irradiance [W/m²] ....:	1000						—
Sample #	I_{sc} [mA]	V_{oc} [V]	I_{mp} [mA]	V_{mp} [V]	P_{max} [mW]	FF [%]	η [%]
1-forward	59.334	10.692	56.897	9.050	514.91	81.16	23.95
1-reverse	59.310	10.771	56.803	9.150	519.75	81.36	24.17

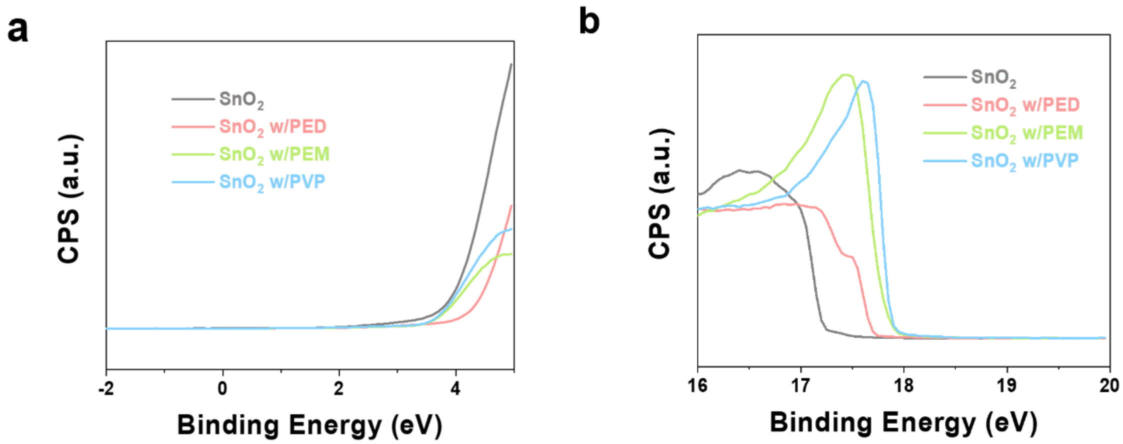
Supplementary information:
The tests are performed according to client's application.
During this maximum power determination, the spectral mismatch was not considered. And the lab did not perform light soaking procedure prior to measurements.
η [%] = Pmax [W] / area [m²] / 1000 [W/m²] x 100% (designated illuminated area: 21.5 cm²).
The measurements were performed with a steady state solar simulator class AAA according to IEC 60904-9:2020.
Sample#-forward: The electrical resistance of solar simulator was scanned from 0 to +∞.
Sample#-reverse: The electrical resistance of solar simulator was scanned from +∞ to 0.
And the IV measurement characteristic was listed as below:



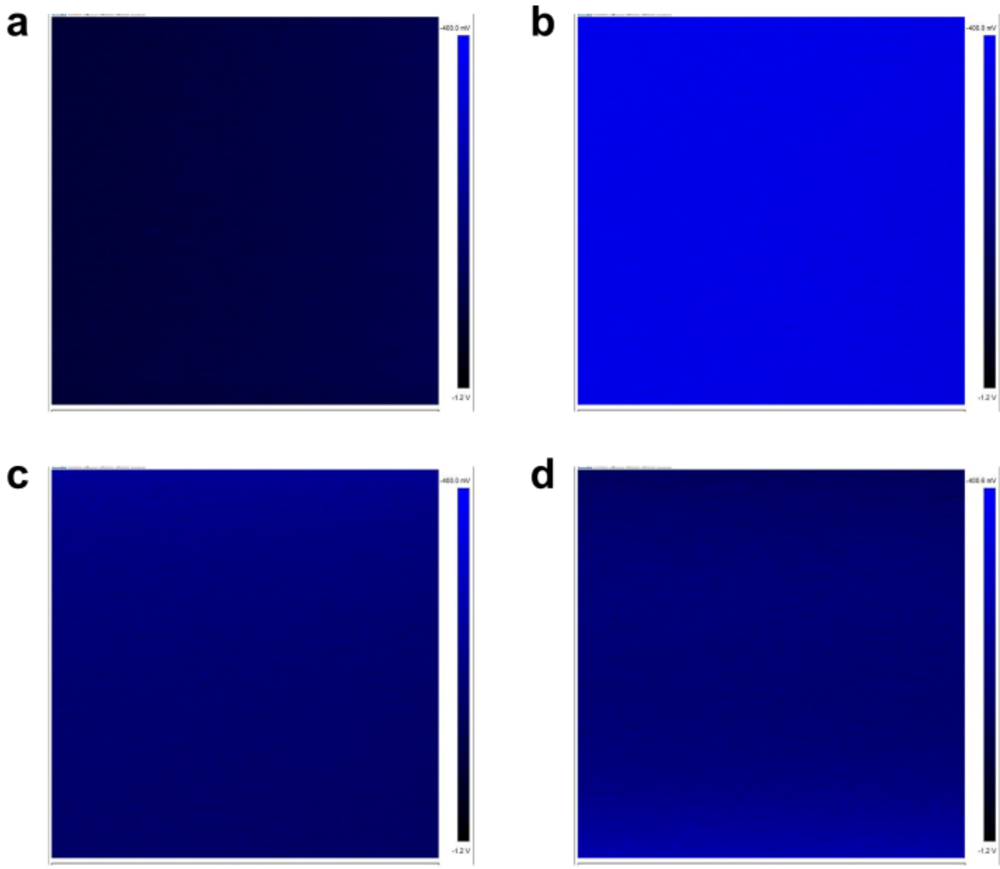
Supplementary Fig. 22. Independent efficiency certification of PSC Module.



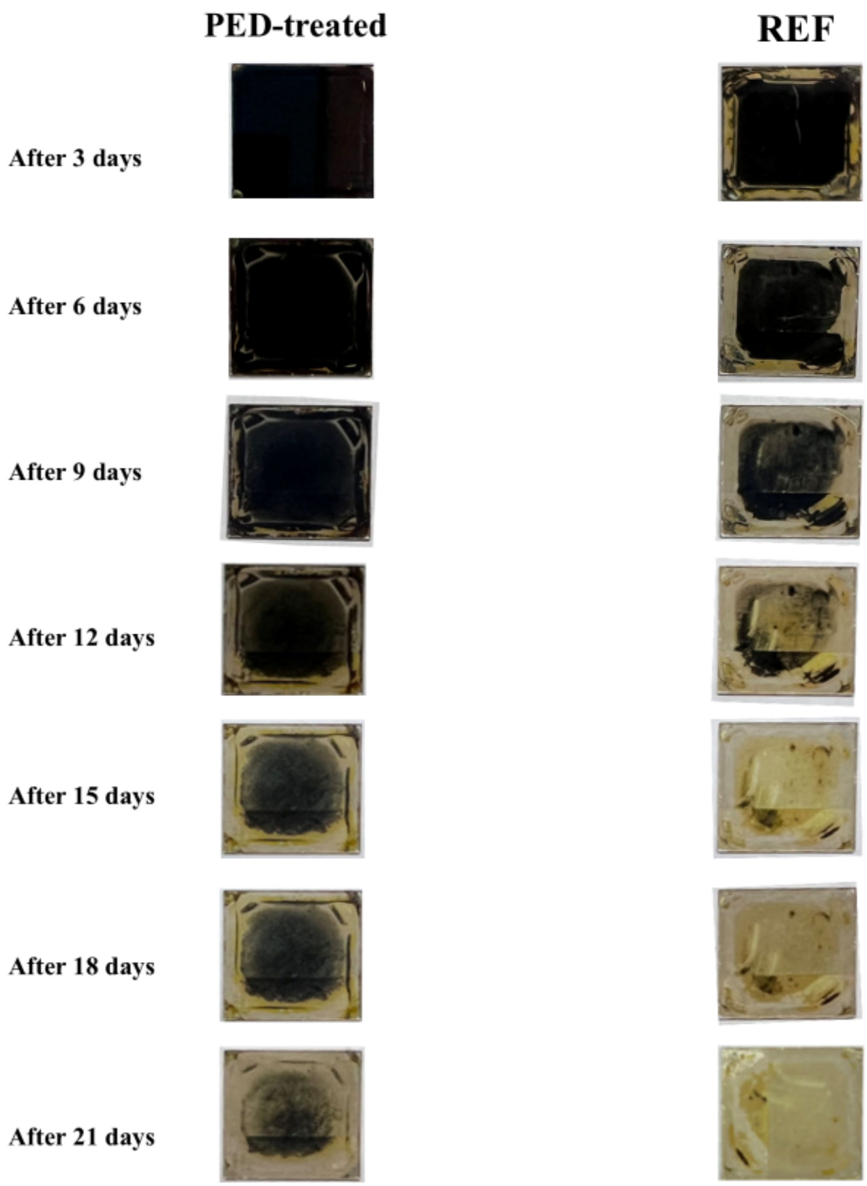
Supplementary Fig. 23. Statistical photovoltaic parameters of device with different polymeric interlayers and references.



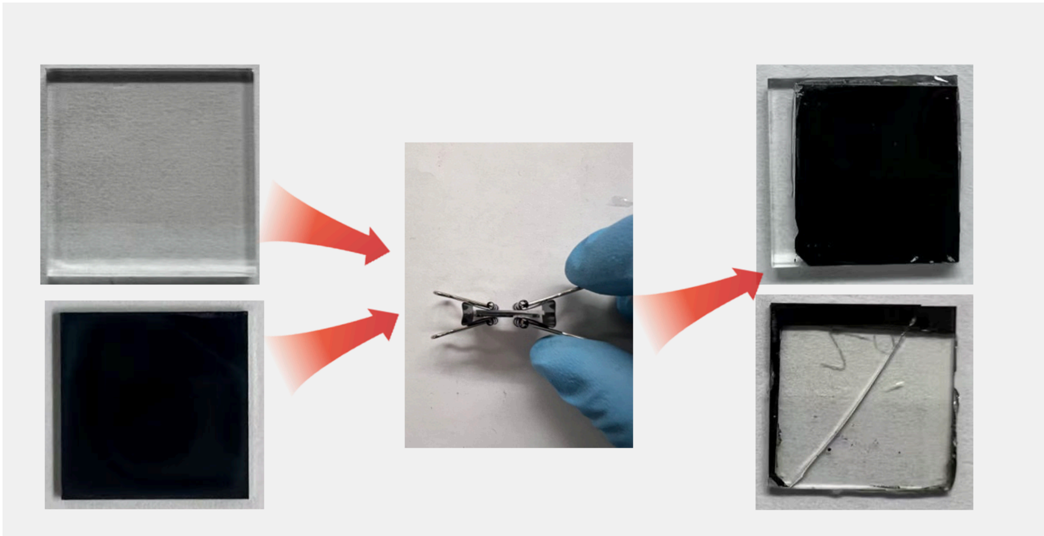
Supplementary Fig. 24. UPS spectra for the bottom interface (a) fermi edge and (b) cut-off energy.



Supplementary Fig. 25. KPFM for the bottom interface work function (a) REF; (b) PED; (c) PEM; (d) PVP.



Supplementary Fig. 26. Perovskite film under 40% RH with light bulb illumination.



Supplementary Fig. 27. Illustration of the Perovskite film peeling-off process.

Supplementary Tables

Supplementary Table 1. Fresh sample XRD peak ratio of PbI_2 and α-$FaPbI_3$.

Condition	Intensity of PbI_2 (a.u.)	Intensity of (001) α-$FAPbI_3$ (a.u.)	Ratio
REF	4865	4241	0.87
PED	1918	6091	3.18
PEM	4488	5372	1.20
PVP	4082	4917	1.20

Supplementary Table 2. Aged sample XRD peak ratio of PbI_2 and α-$FaPbI_3$.

Condition	Intensity of PbI_2 (a.u.)	Intensity of (001) α-$FAPbI_3$ (a.u.)	Ratio
REF	10533	3490	0.33
PED	2224	4312	1.94
PEM	2027	1739	0.86
PVP	3118	3155	1.01

Supplementary Table 3. XPS survey spectrum for aged reference sample.

Name	Pos.	FWHM	Area	At%
N 1s	399.91	2.16	1473.86	4.92
C 1s	284.91	3.19	9729.99	58.5
O 1s	532.91	2.83	6427.29	13.19
Sn 3d	485.91	2.54	1041.87	0.25
Pb 4f	137.91	2.22	42939.04	11.35
I 3d	617.91	2.41	53716.62	9.6
Br 3p	185.91	3.03	1824.88	2.18

Supplementary Table 4. Photovoltaic parameters of champions device for different conditions.

Condition	*Voc* (V)	*Jsc* (mA/cm^2)	FF (%)	Eff (%)
REF R	1.136	25.20	80.95	23.17
REF F	1.136	25.28	81.62	23.43
PED R	1.191	26.10	86.01	26.74
PED F	1.187	26.19	84.36	26.19
PEM R	1.184	25.89	81.95	25.12
PEM F	1.168	25.74	83.92	25.23
PVP R	1.163	25.80	83.65	25.12
PVP F	1.181	25.91	81.84	25.05

Supplementary Table 5. Calculated VBM from UPS results.

Condtion	SnO_2	SnO_2 w/PED	SnO_2 w/PEM	SnO_2 w/PVP
Calculated VB (eV)	-7.95	-7.94	-7.00	-6.99