Sino-Germany Workshop on Printable Photovoltaics

May 21st – 23rd, Erlangen, Germany

Wide-bandgap hybrid perovskites based indoor photovoltaics and tandems

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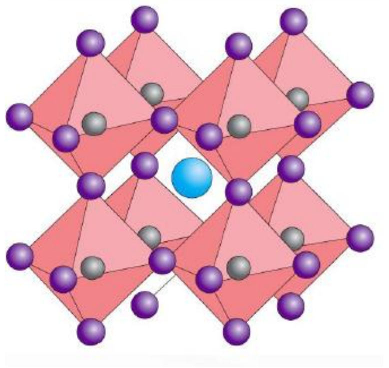
Good memories!

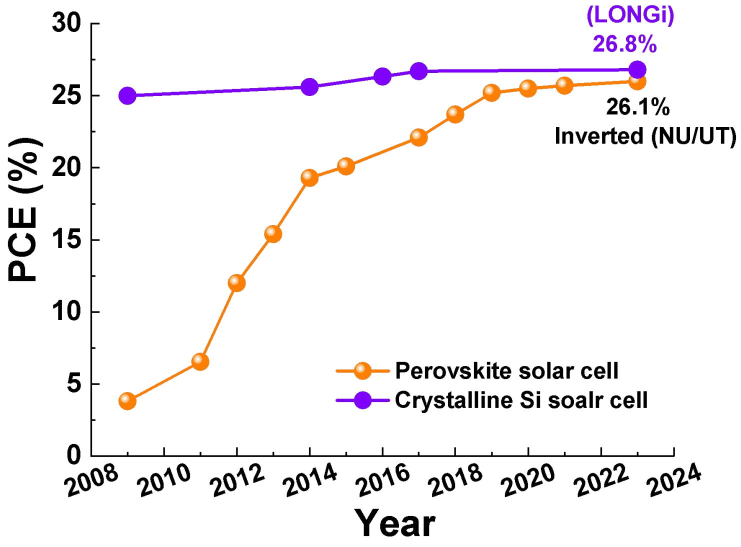
Outline

- Brief introduction of our NiO_x based solar cells and modules;
- Wide-bandgap perovskites for NiO_x based indoor cells and modules
- Modification of interconnecting layers for Perovskite/Silicon Tandems
- Summary

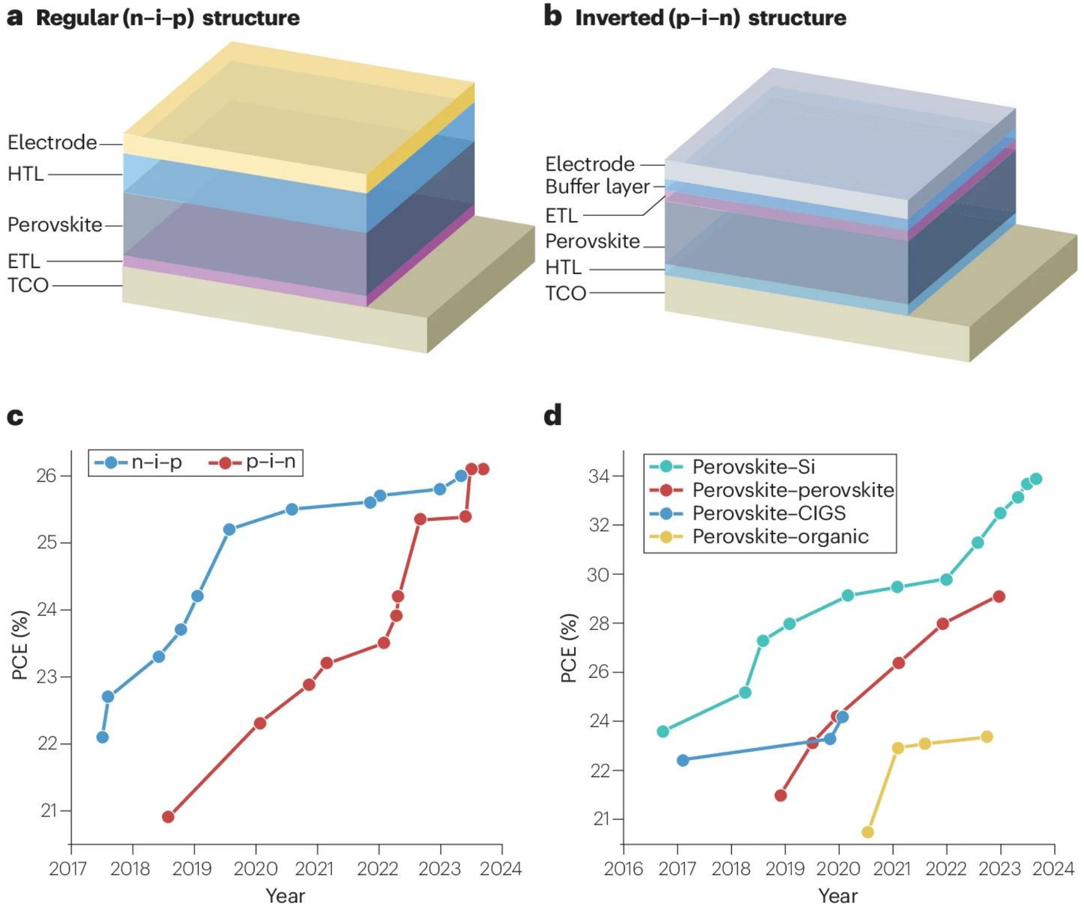
Perovskites—Amazing Optoelectronic Materials



- A: $CH_3NH_3^+$; $CHNH_2NH_2^+$; Cs^+
- B: Pb^{2+}; Sn^{2+}
- X: Cl^-; Br^-; I^-



Recent advances on single-junction cells and tandems



Jiang et al., Nat. Rev. Mater. 2024,

Advantage of perovskite solar cells:

- high carrier mobility and absorption coefficient;
- long diffusion lengths and broad absorption wavelength;
- Tunable band gap
- low-cost and low-temperature process
- Flexible devices
- Tandem cells

Perovskite solar modules and tandems

Recent advances on large-area devices

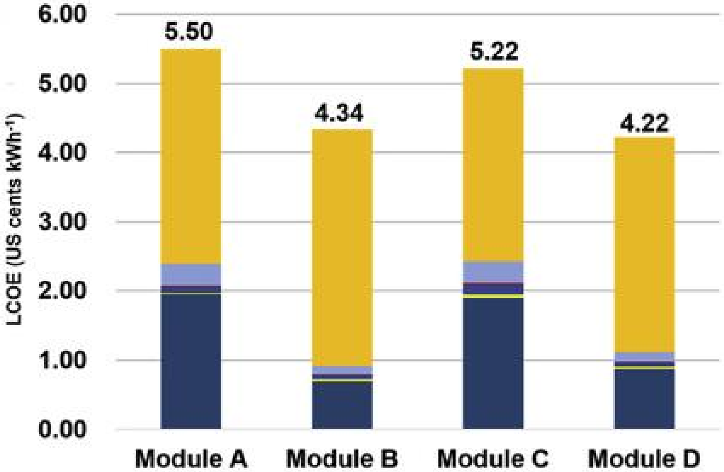
(1) 22.57% (30 cm ×40 cm), Guang Yin;

(2) 22.86% (30 cm ×30 cm), Mellow Energy;

(3) 17.18% (1.2 m × 0.6 m), UtmoLight;

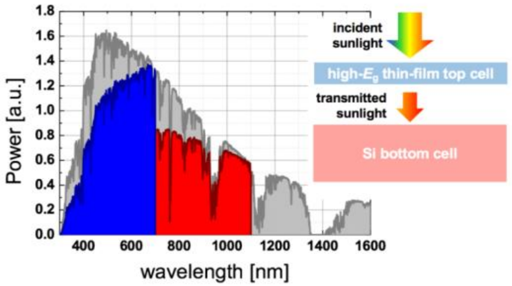
(4) 28.6% (258.15 cm² Perovskite/Si), Oxford PV;

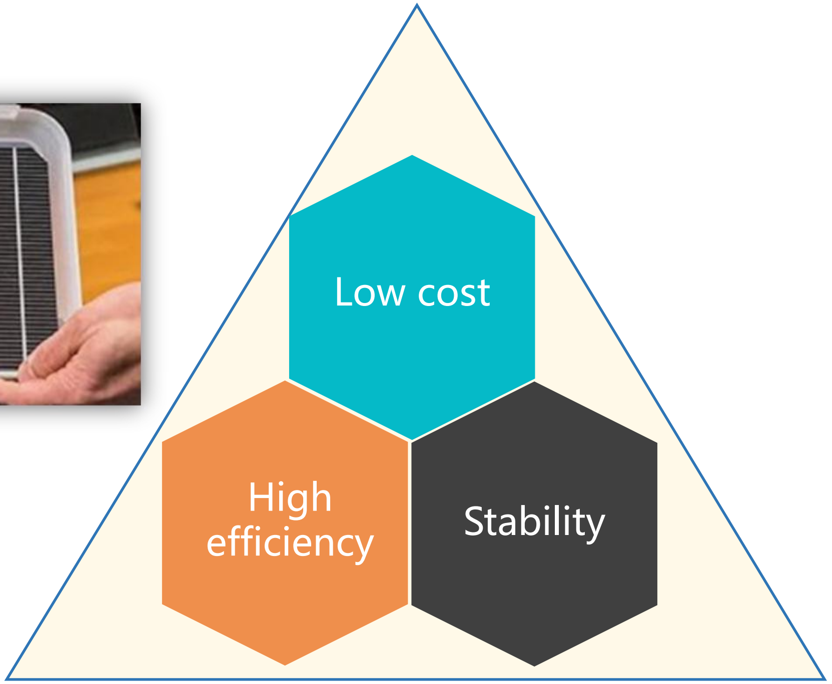
……



A: traditional silicon cells.
B: planar perovskite cells.
C: silicon/perovskite tandem cells.
D: perovskite/perovskite tandem cells.

Z. Li, et al., Joule 2018, 2, 1559–1572





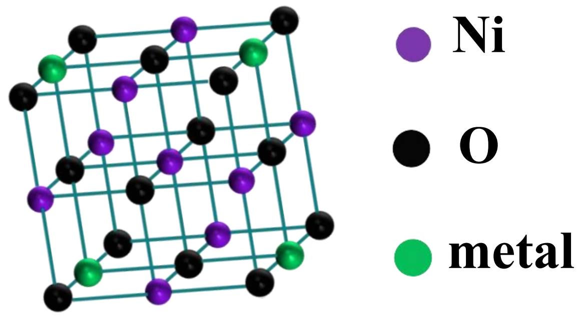
Perovskite-silicon tandem: **33.9% / 42%**

All perovskite tandem: **29.1% / 44%**

Stability challenge:

IEC61215、IEC61730

Why NiO_x is appropriate for development of perovskite solar cells and tandems?

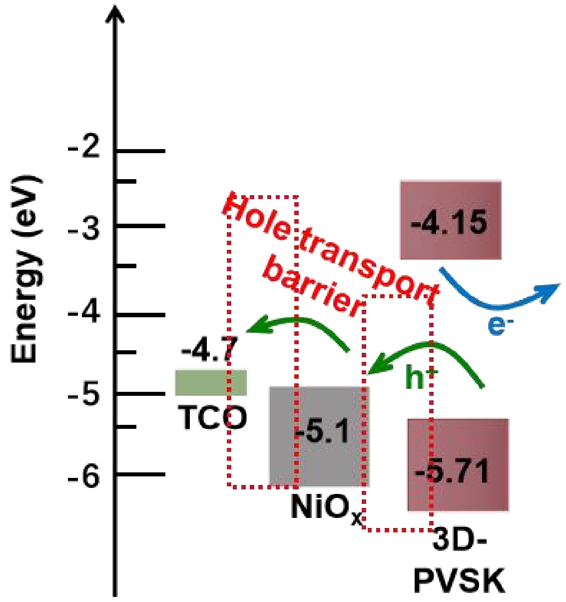


(1) High-transparent, air- and thermal stable, material;

(2) Low-cost p-type material;

(3) High electron-blocking property due to high conduction band of ~ -1.8 eV;

(4) Efficient interconnecting layer for tandem solar cells;



Inverted device structure

Defects of NiO_x

(1) Surface defects;

(2) NiO_x/Perovskite heterointerface defects;

(3) Hole-transport barrier;

Y. Wang, et al., Nano Energy, 2019, 64, 103964.

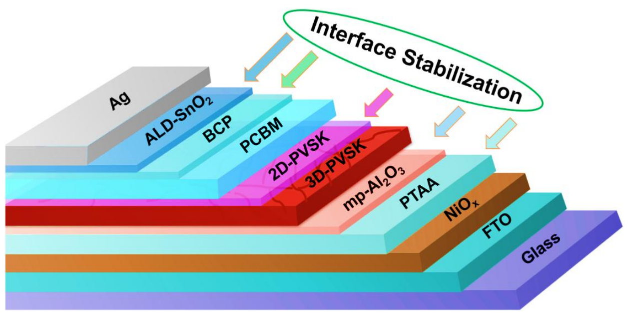
Y. Wang, et al., Adv. Energy Mater., 2020, 10, 2000967

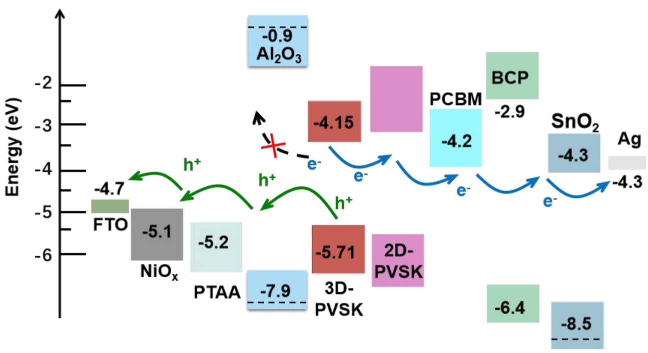
Y. Mai, et al., J. Energy Chem., 2023, 82, 25-30

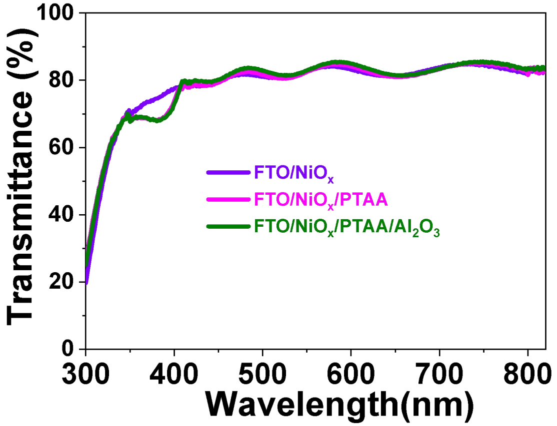
Y. Mai, et al., Adv. Mater., 2023, 35, 2202447

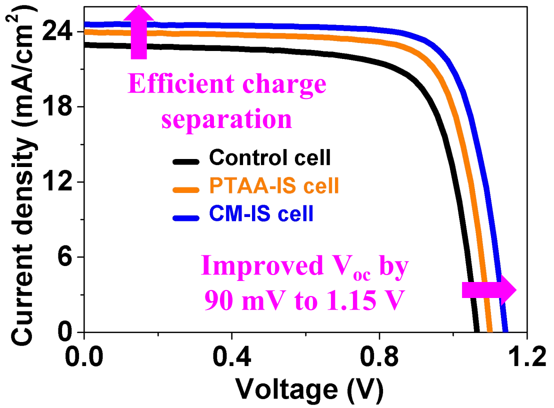
Brief introduction of our NiO_x based solar cell and modules

Charge transportation improvement by cascade energy alignment

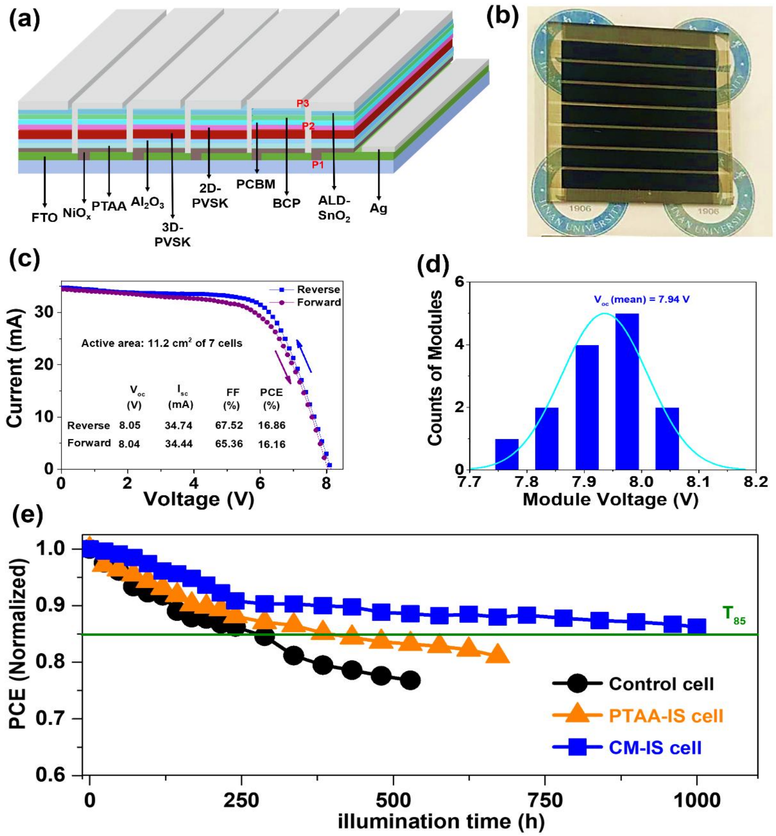








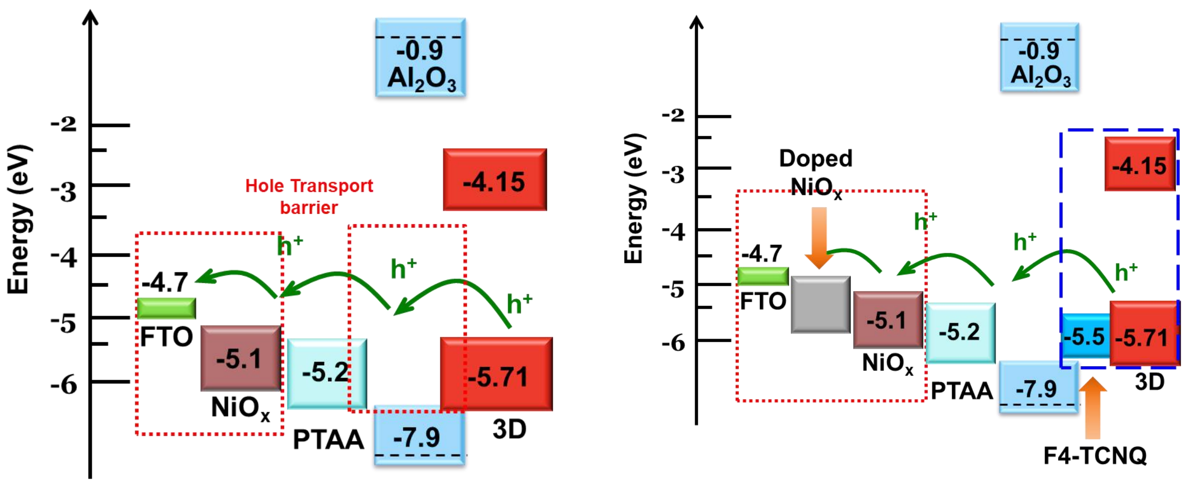
- No light absorption loss of $FTO/NiO_x/PTAA/Al_2O_3$ structure;
- Improvements of energy level match in $PTAA/NiO_x$ and $PCBM/BCP/SnO_2$ structure;
- Improvement of interface contacts and suppression of non-radiative recombination by Al_2O_3;



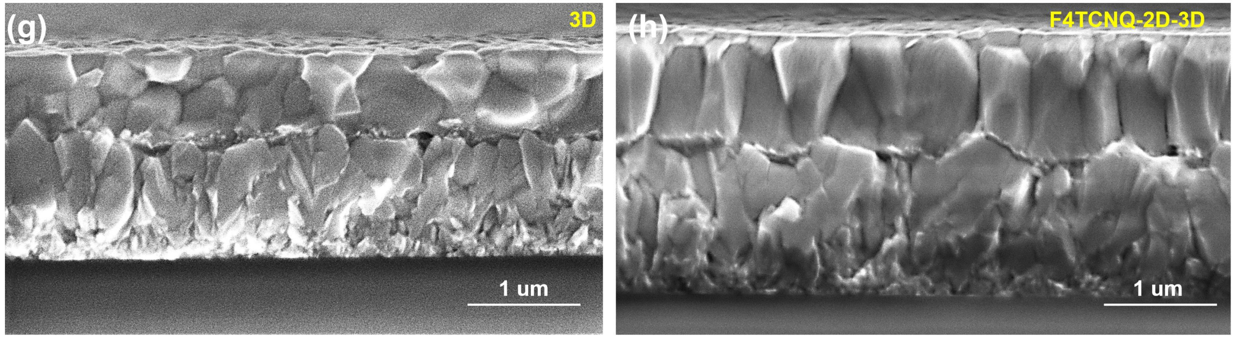
- PSM configuration with 7 sub-cells;
- PSMs of PCE near 17% and high V_{oc} with 8.05 V;
- Better stability;

Y. Wang* Y. Mai* et. al, *Nano Energy*, 2021, 88, 106285.

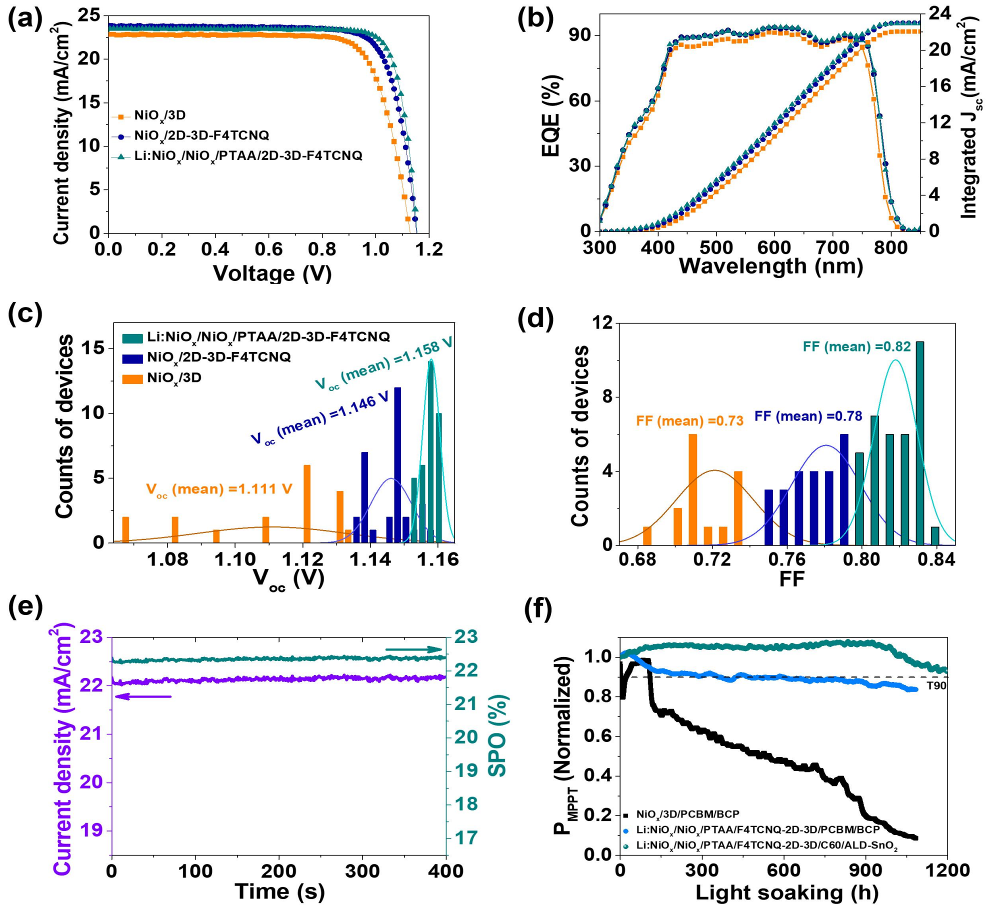
Hole-Transport Management for efficient charge transportation



Hole transport barrier | Efficient hole extraction and transport



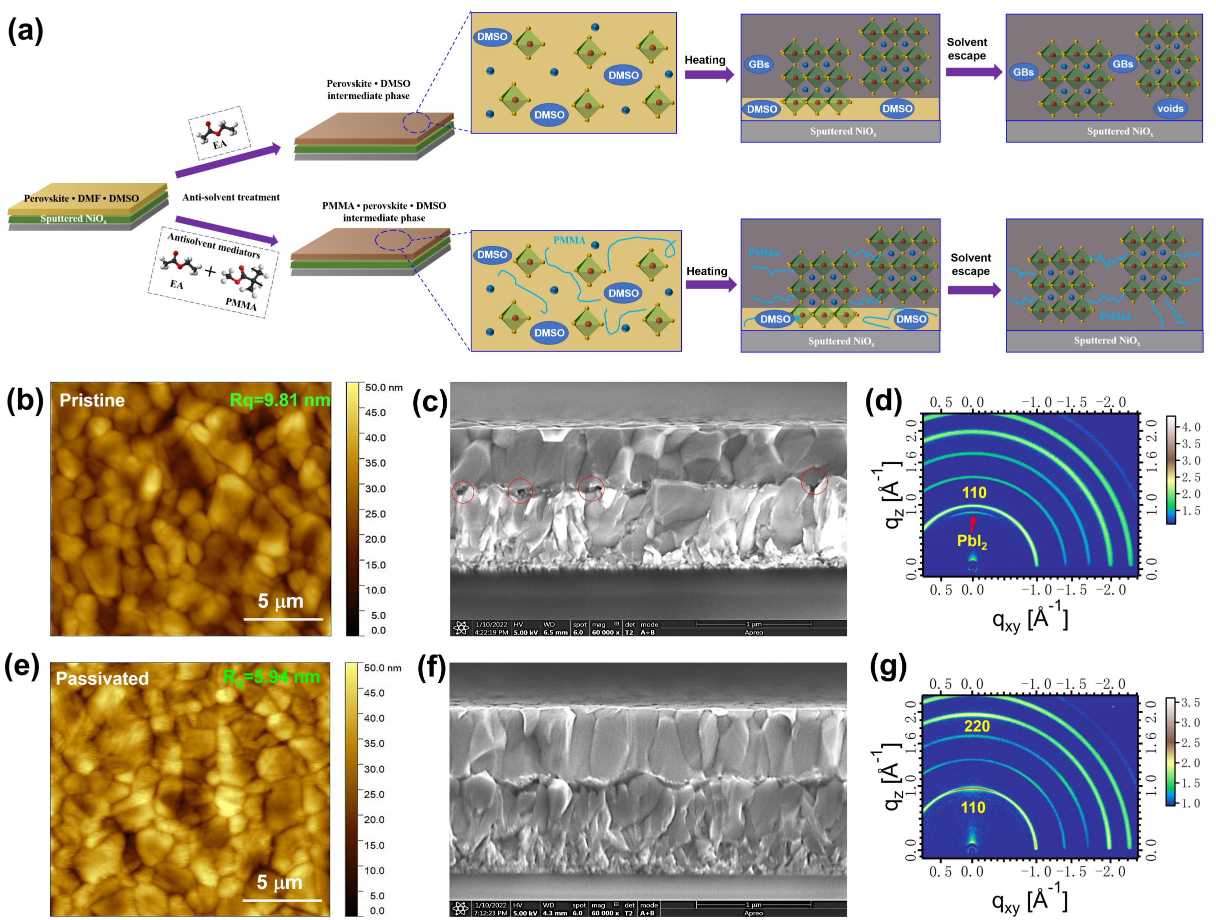
- ➢ Reduced non-radiative recombination by an effecient cascade energy alignment;
- ➢ Excellent perovskite crystals with vertical growth for efficienct charge transport;



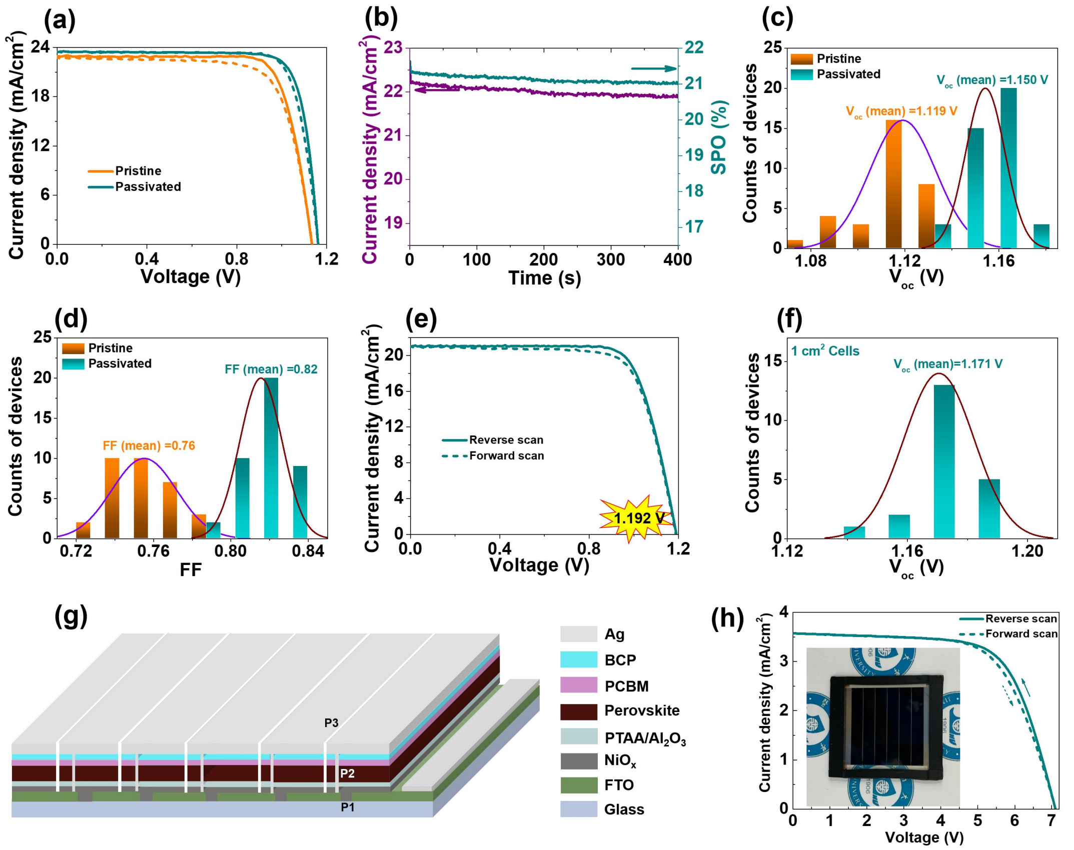
- ➢ PCE>23%
- ➢ Operational stability T_{90}>1200小时

L. Liu, Y. Wang*, Y. Mai*, et. al, *Nano-Micro Letters*, 2023, 15, 117.

Green antisolvent-mediators stabilize perovskites



- Excellent perovskite crystals with vertical growth;
- Passivation of GBs and buried interface defects by PMMA.

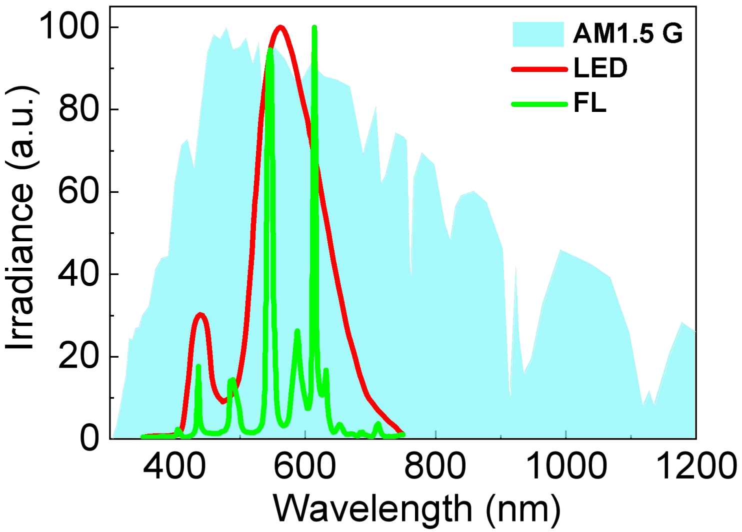


- **High V_{oc} and reproducibility;**
- **1cm² cell: V_{oc}=1.192 V， module: V_{oc}=7.044 V**

Z. Wang, Y. Wang*, Y. Mai* et. al, *Chem. Eng. J.*, 2023, 457, 141204.

Wide-bandgap perovskite for NiO_x based indoor cells and modules

The spectrum of indoor light

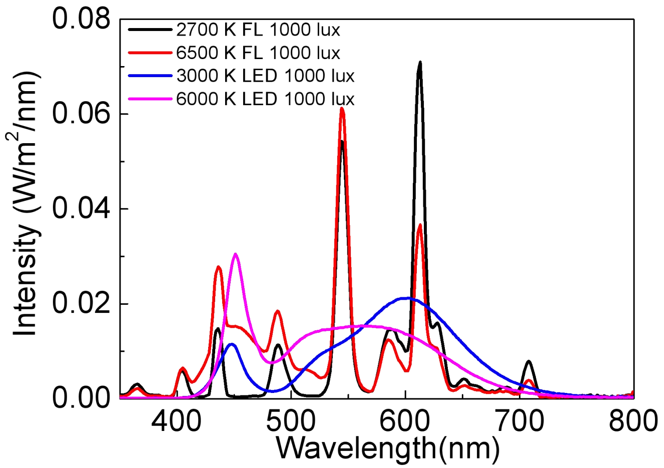


Indoor：

Narrow wavelength （Visible Light)

Low irradiance （200-1000 lux ）

Mild and unchangeable environment

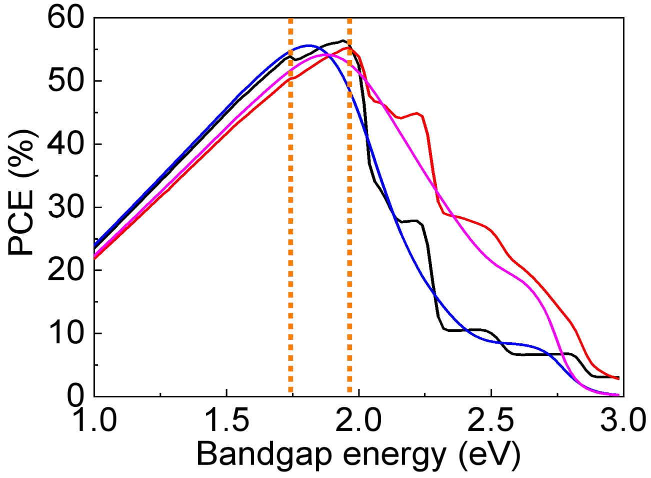


Outdoor：

Wide spectrum wavelength

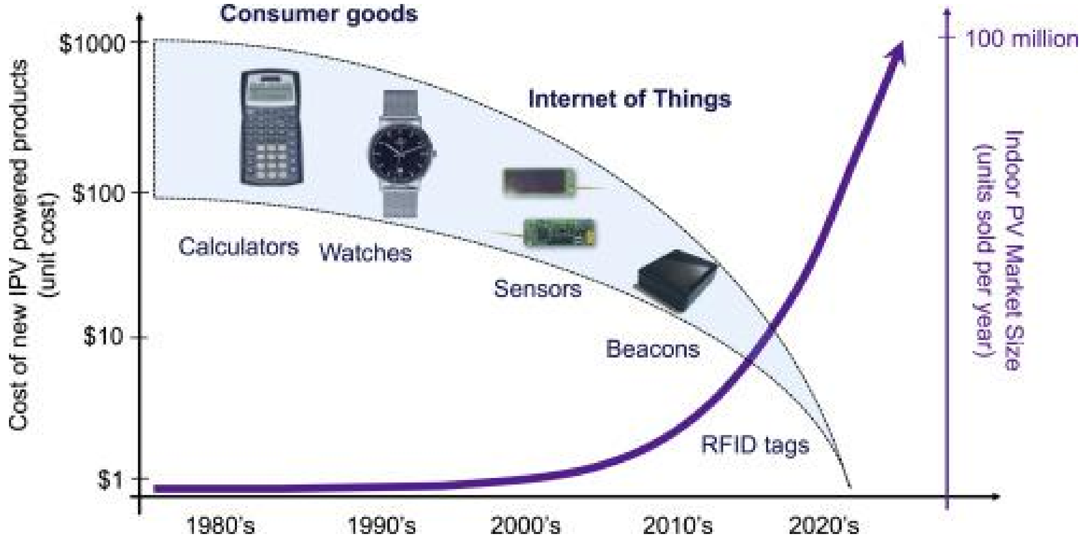
Strong irradiance （100000 lux ）

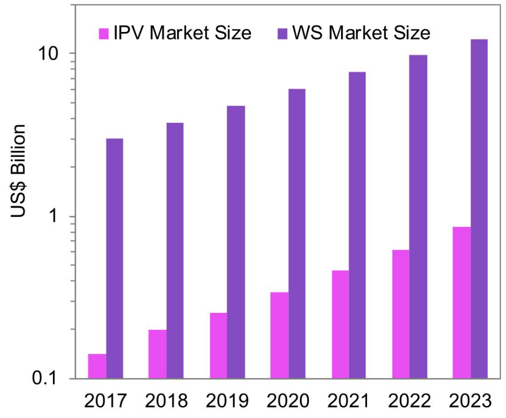
Harsh environment （high temperature and humidity, etc)

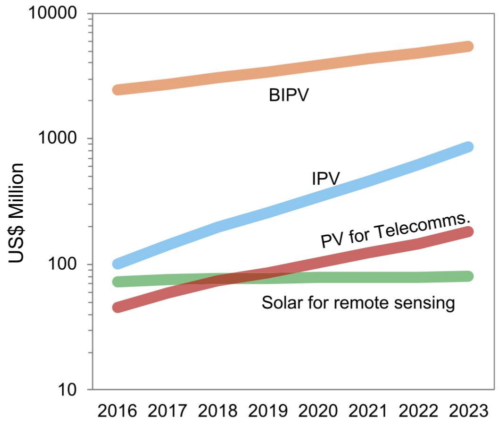


Suitable bandgap (1.7-1.9 eV) for IPVs

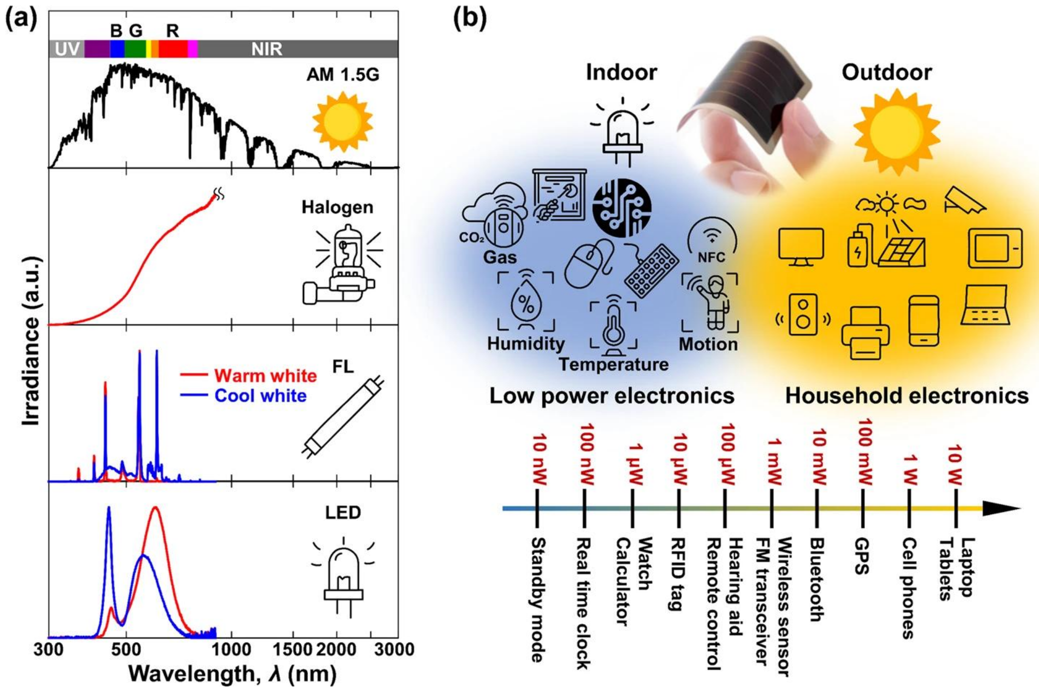
Perovskite indoor photovoltaics for IoTs







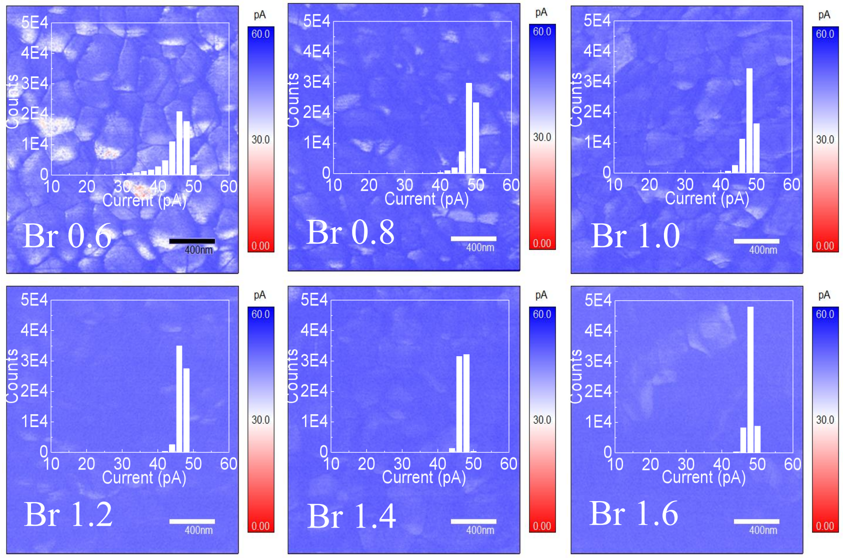
I. Mathews, et al., Joule 2019, 3, 1415-1426

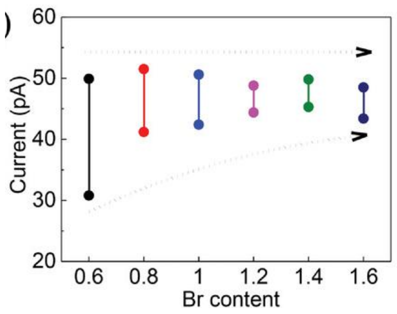


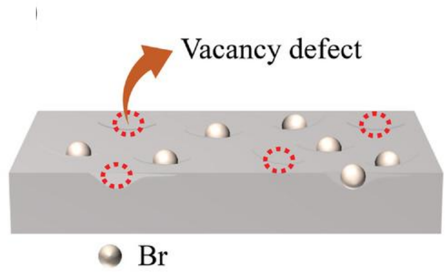
S. Hwang, et al., Polymer Journal 2023, 55, 297-316

- **Billions of wireless sensors by IoT system to be installed;**
- **Perovskite IPVs as one of the most promising energy supply candidates for IoT;**
- **Perovskite IPVs can provide safe and reliable power supply for such a huge of IoT system.**

Defects of wide-bandgap perovskites

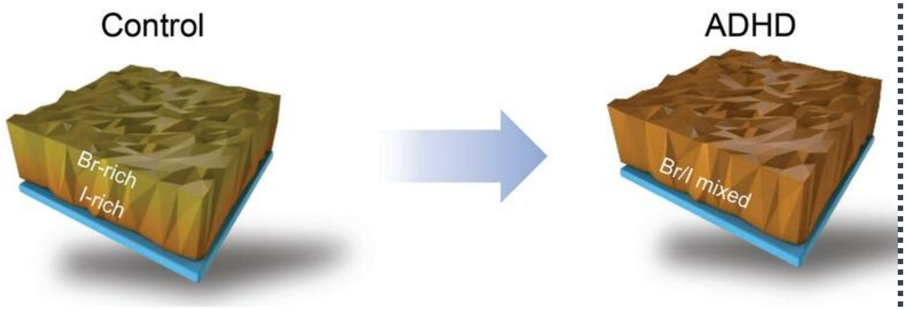


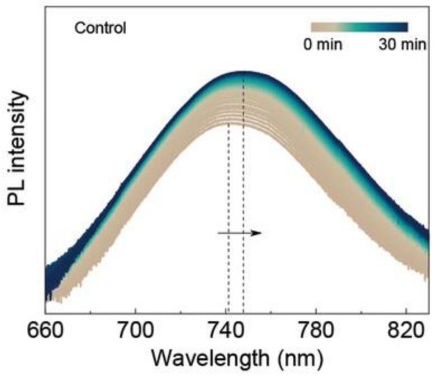


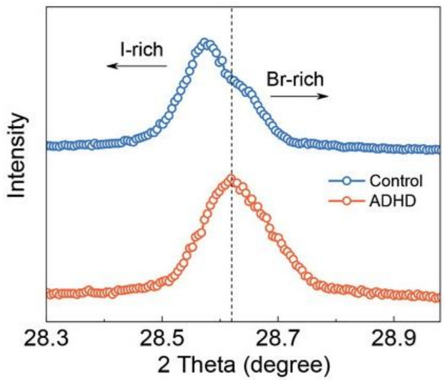


Br vacancy (V_{Br}) defects

C. Zhang et al., Adv. Sci. 2022, 9, 2204138

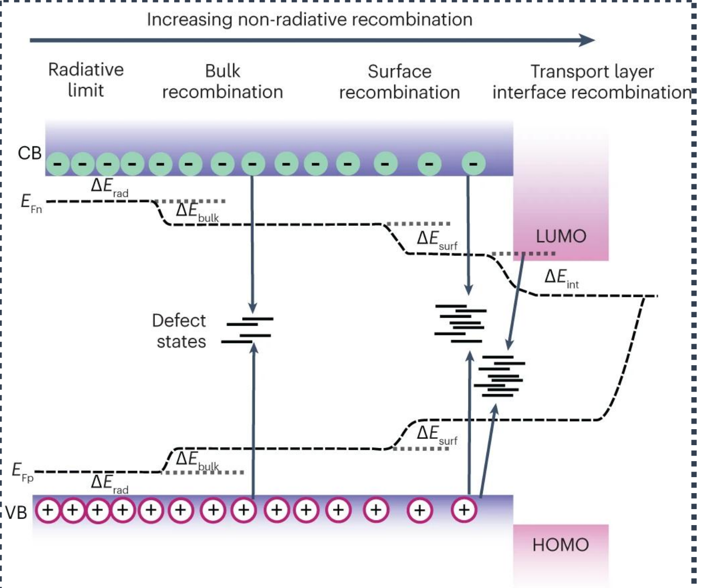




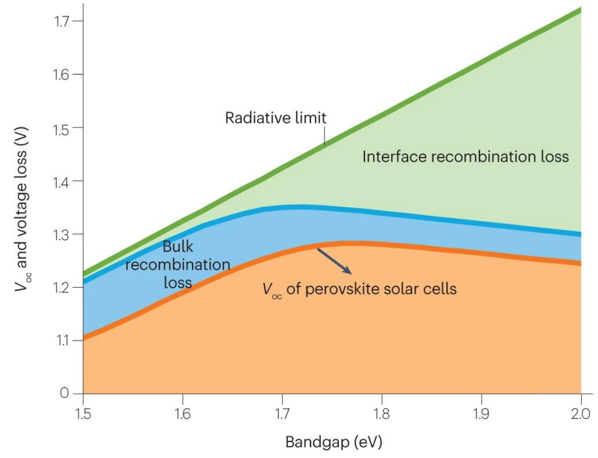


High-Br systems experience halide segregation and form heterogeneous phases

W. Yang, et al., Adv. Funct. Mater. 2022, 32, 2110698



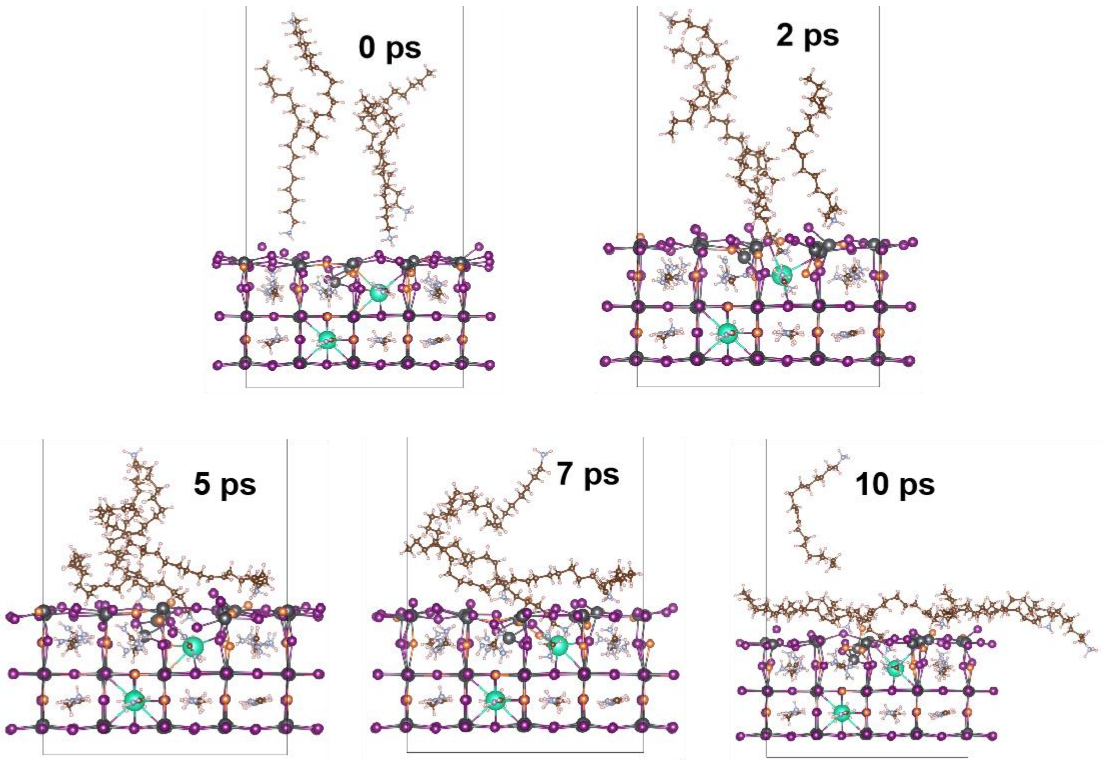
Ramadan et al., Nat Rev Mater, 2023

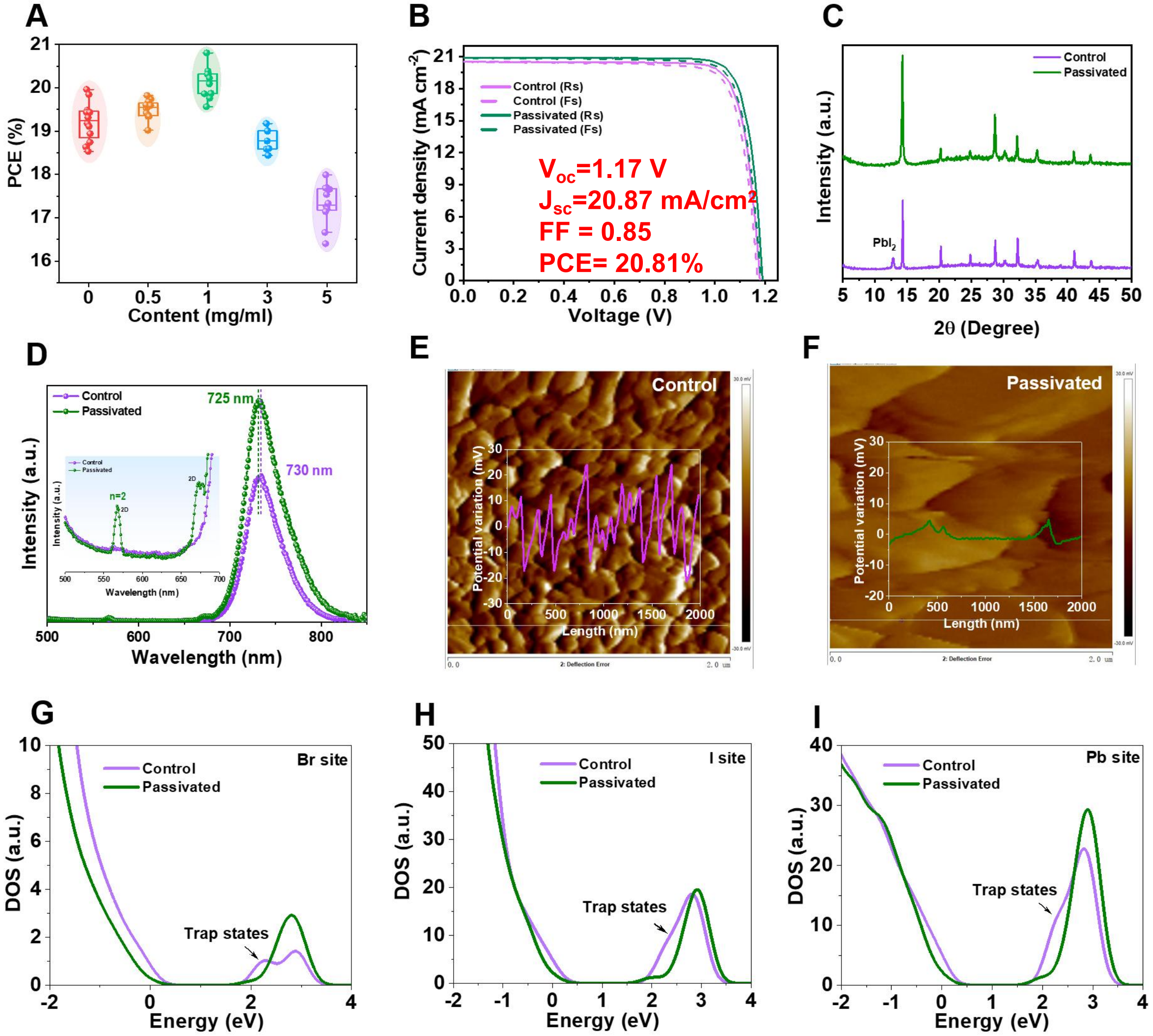


V_{oc} loss mechanism

Passivation of perovskite bulk defects

ab initio molecular dynamics (AIMD) simulation

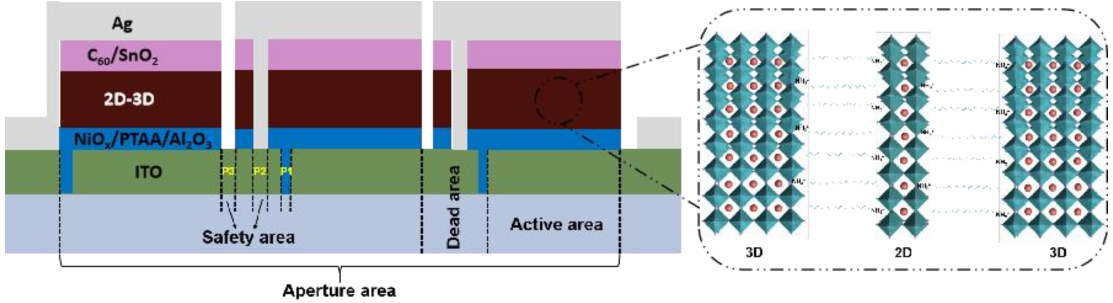


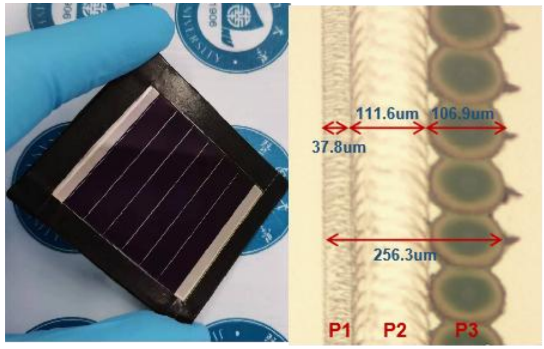


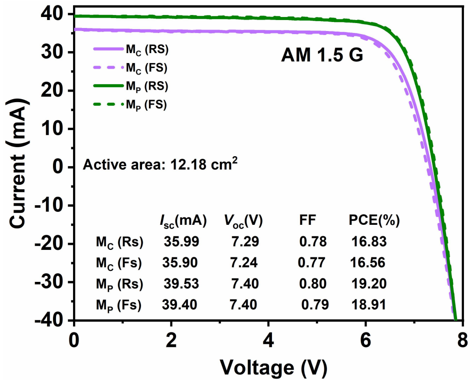
- ➢ Passivation of trap defects by OAm^+ ligands interaction;
- ➢ High-quality film with large-size crystals;
- ➢ Formation of 2D-3D perovskite heterostructures;
- ➢ Lower potential fluctuation.

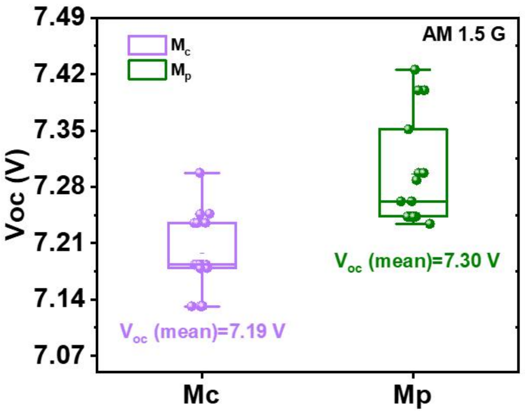
Q. Ma, Y. Wang*, Y. Mai* et. al, *Device*, 2023, 1, 100174

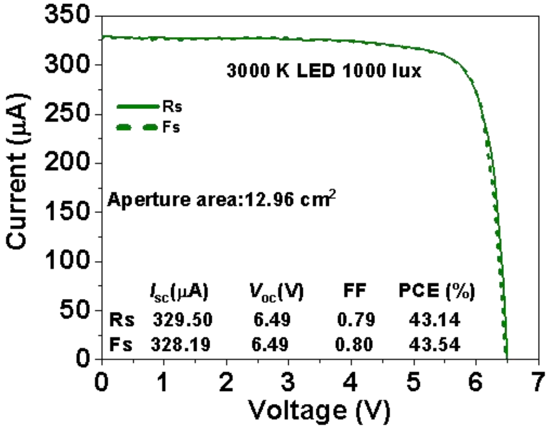
Indoor module performance

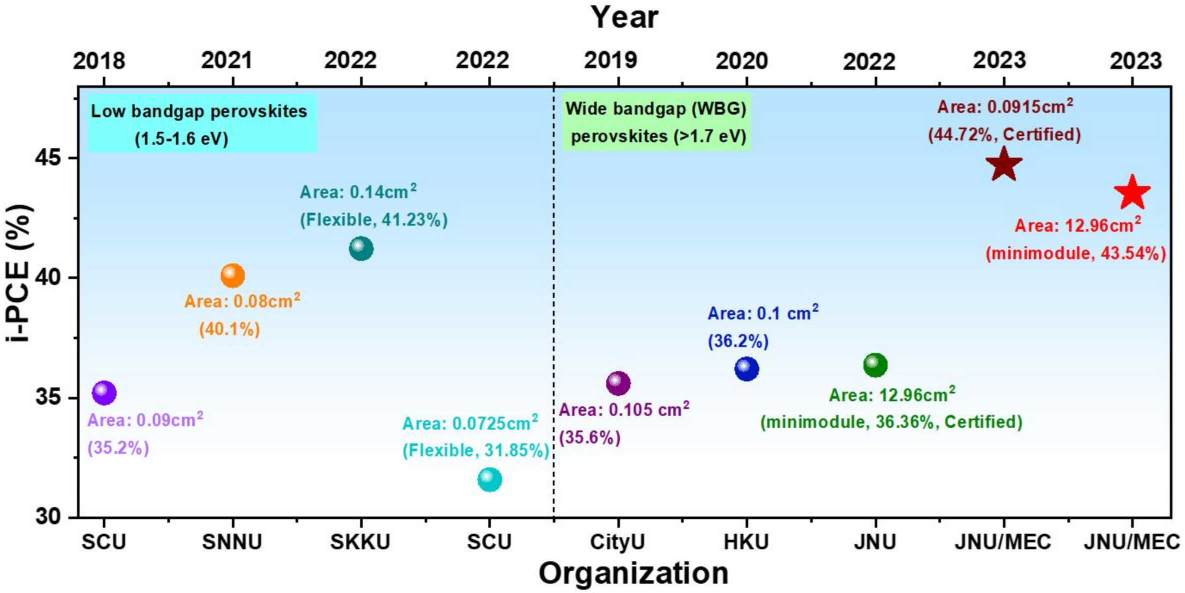








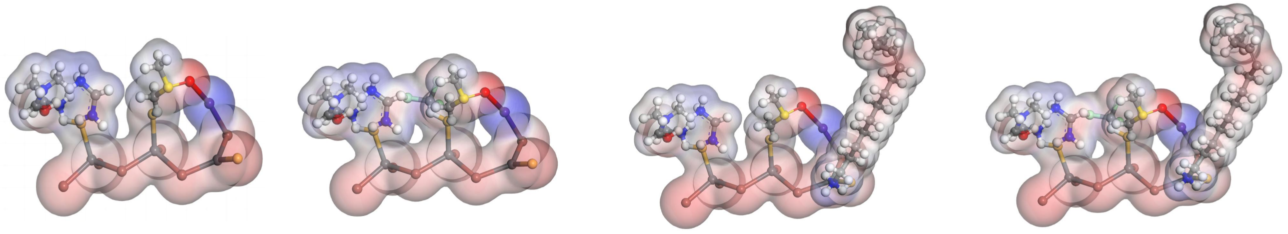




- **43.54% record indoor efficiency achieved by perovskite modules;**
- **80 % of the theoretical maximum (i.e., 54.40%) for 1.71 eV WBG-perovskites;**
- **High and reproducible V_{oc};**

Q. Ma, Y. Wang*, Y. Mai* et. al, *Device*, 2023, 1, 100174

One-step processed WBG perovskite composite-based adducts

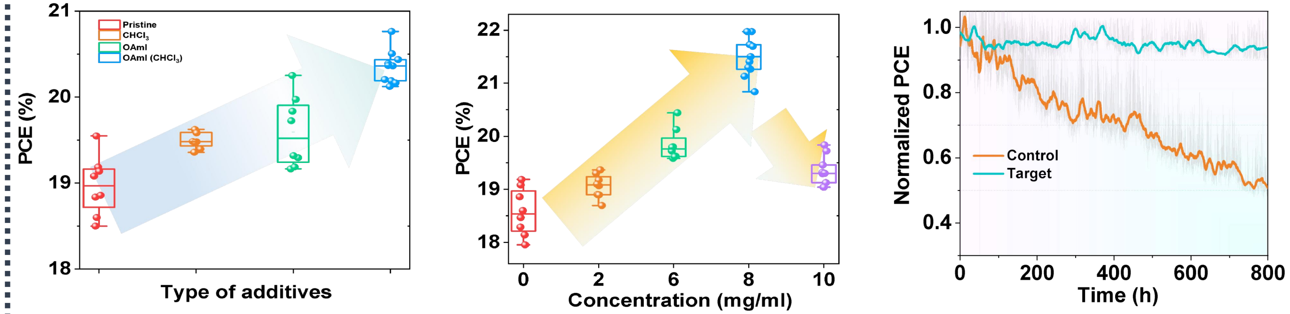


ΔE_b = -1.04 eV — perovskite-DMF-DMSO adducts

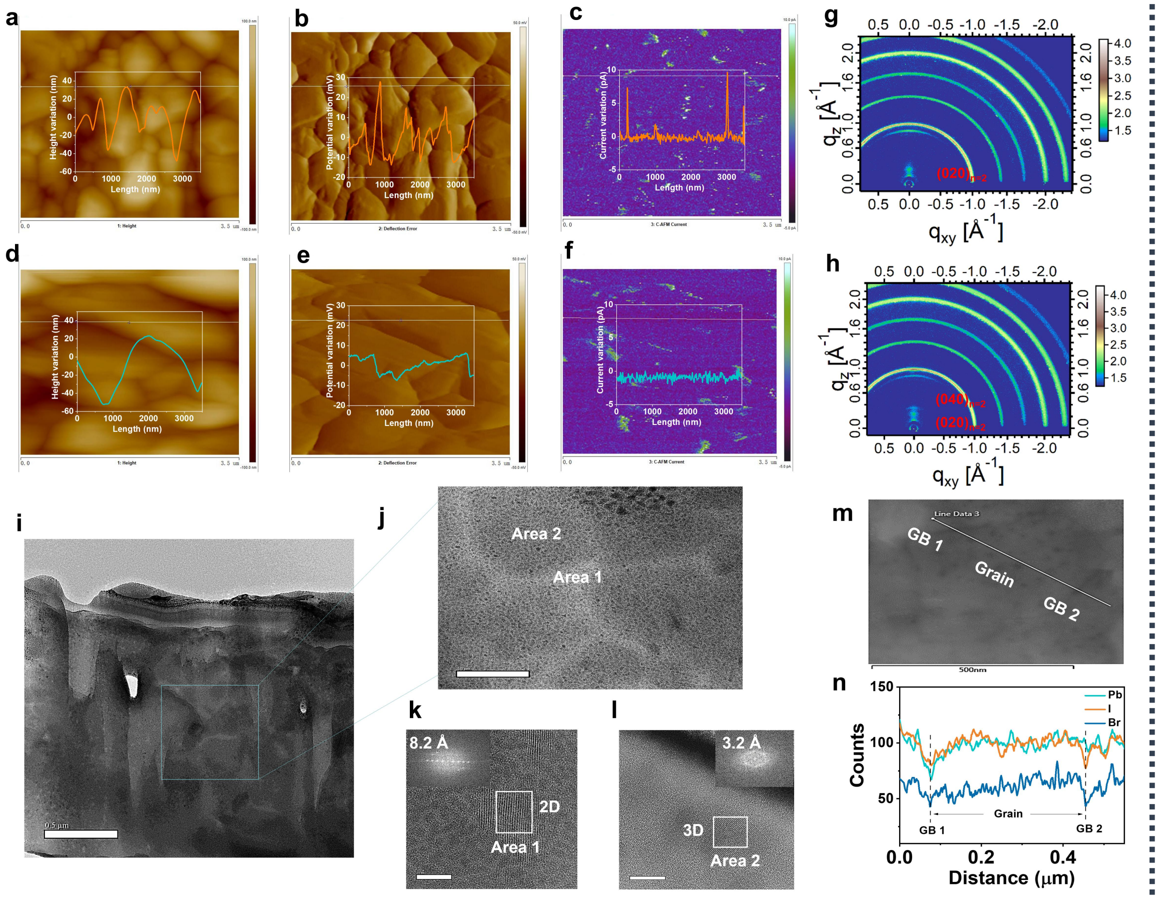
ΔE_b = -2.19 eV — perovskite-DMF-DMSO-$CHCl_3$ adducts

ΔE_b = -3.83 eV — perovskite-OAm+-DMF-DMSO adducts

ΔE_b = -4.46 eV — perovskite-OAm+-DMF-DMSO-$CHCl_3$ adducts



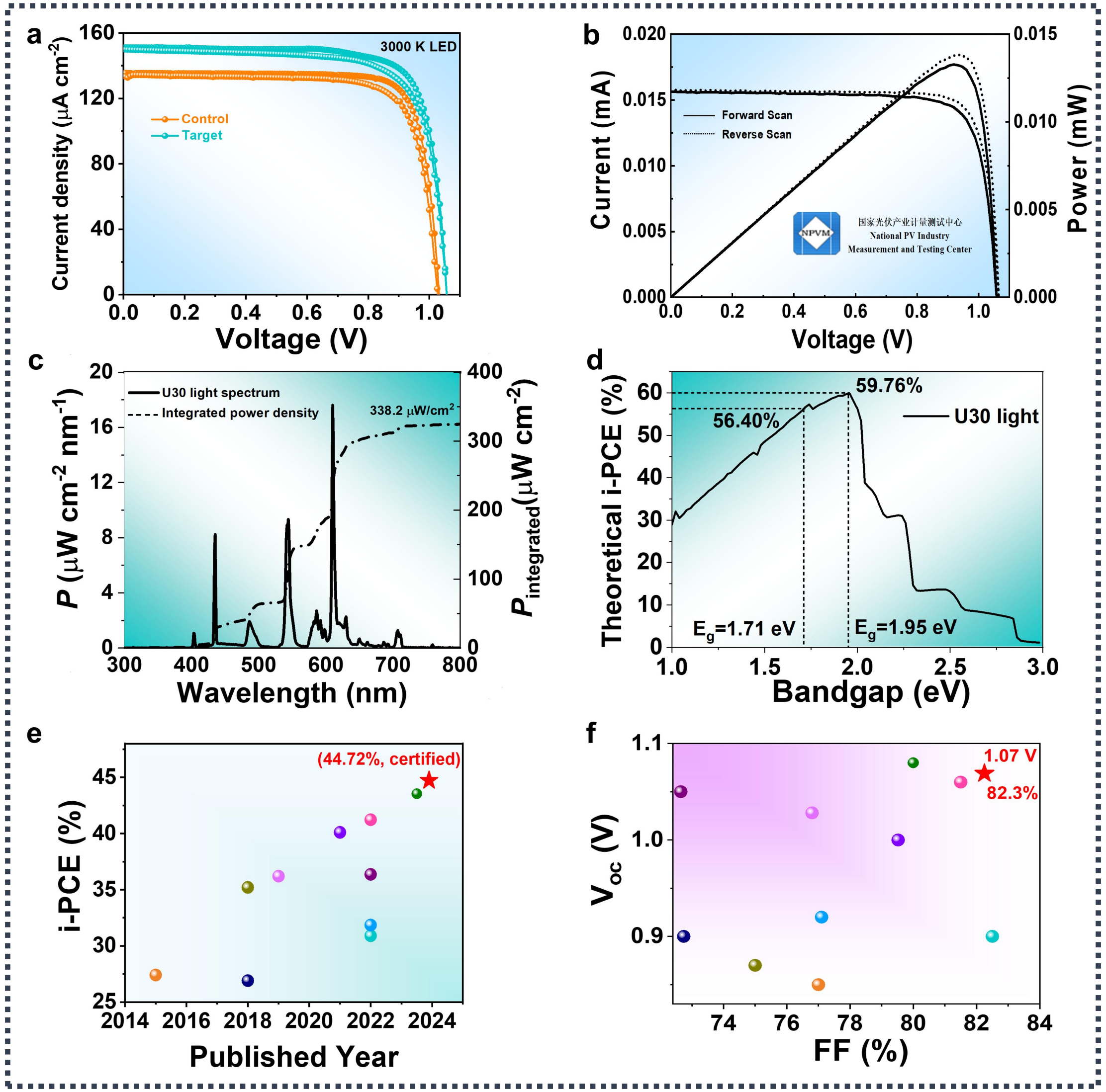
- Higher binding energy indicates higher affinity and improved interaction;
- PCE= 21.97% (20.77%, certified);
- High V_{oc} (1.25V) and FF (84%);
- High operational stability.

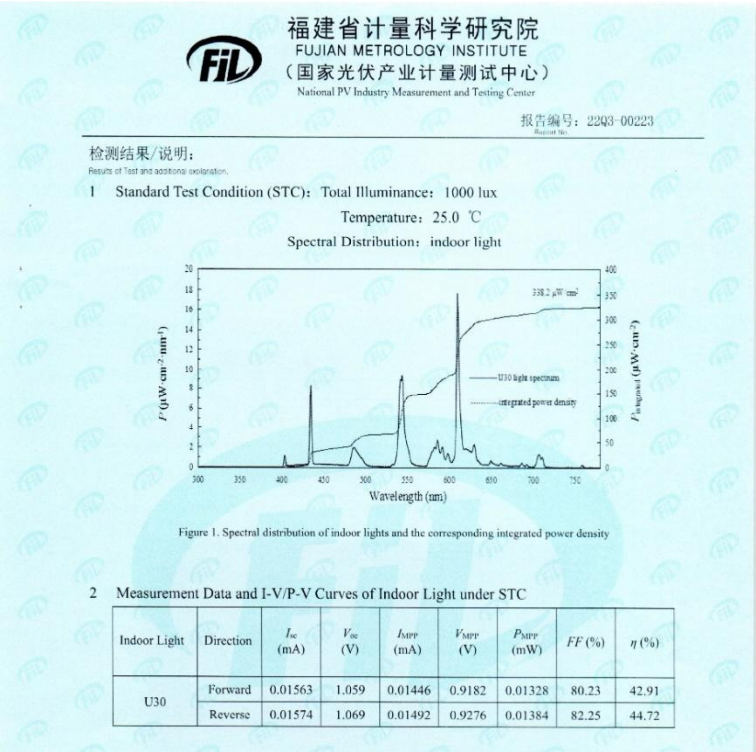


- Improved morphology and lower current leakage;
- Formation of 2D-3D heterostructures.

Q. Ma, Y. Wang*, Y. Mai* et. al, *Energy Environ. Sci.*, 2024, 17, 1637-1644.

Indoor cell performance





福建省计量科学研究院
FUJIAN METROLOGY INSTITUTE
（国家光伏产业计量测试中心）
National PV Industry Measurement and Testing Center

报告编号：2203-00223

检测结果/说明：
Results of Test and additional explanation

1 Standard Test Condition (STC): Total Illuminance: 1000 lux
Temperature: 25.0 ℃
Spectral Distribution: indoor light

Figure 1. Spectral distribution of indoor lights and the corresponding integrated power density

2 Measurement Data and I-V/P-V Curves of Indoor Light under STC

Indoor Light	Direction	I_{sc} (mA)	V_{oc} (V)	I_{MPP} (mA)	V_{MPP} (V)	P_{MPP} (mW)	FF (%)	η (%)
U30	Forward	0.01563	1.059	0.01446	0.9182	0.01328	80.23	42.91
	Reverse	0.01574	1.069	0.01492	0.9276	0.01384	82.25	44.72

- ➤ Certified record PCE of 44.72% under U30 light;
- ➤ High V_{oc} of 1.07 V and FF of 82.3%.

检测报告续页专用
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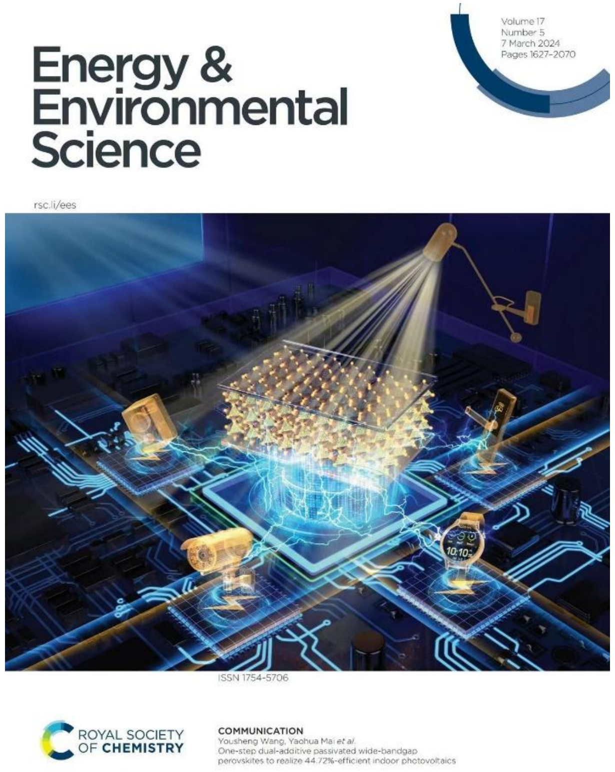
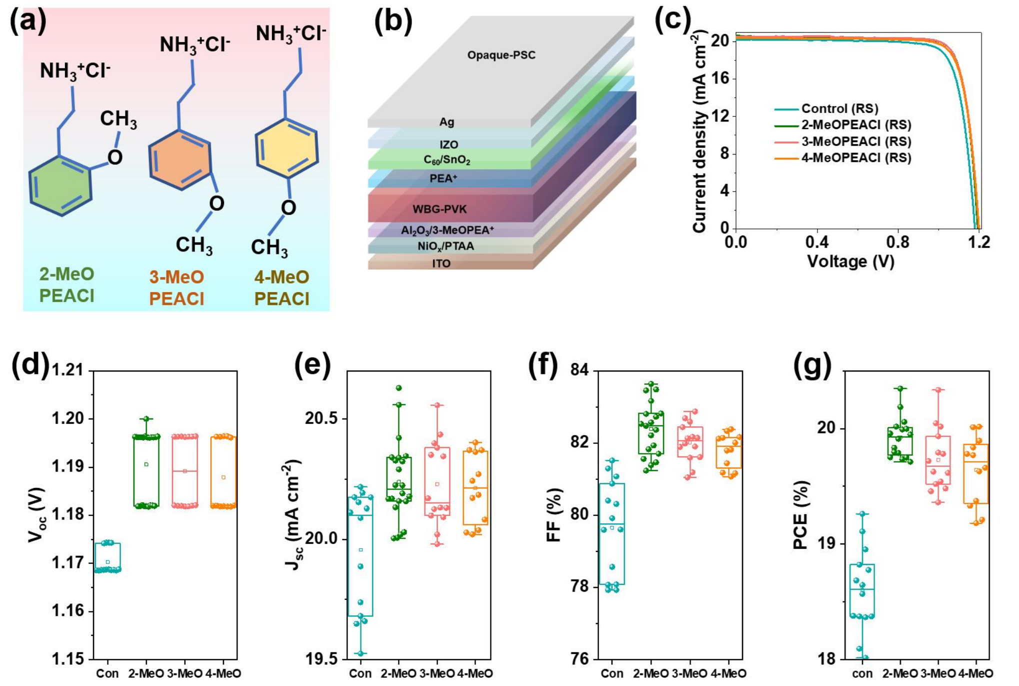
第 3 页/共 6 页



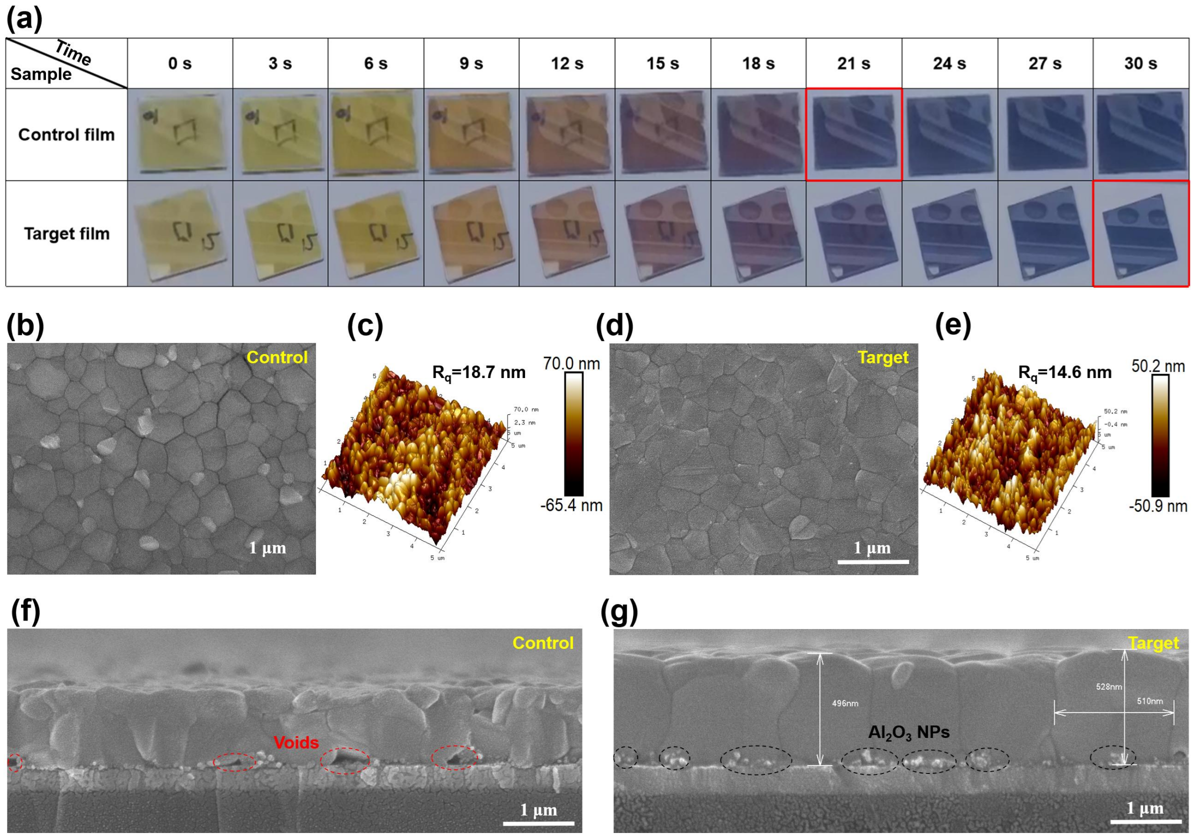
Q. Ma, Y. Wang*, Y. Mai* et. al, *Energy Environ. Sci.*, 2024, 17, 1637-1644.

Modification of interconnecting layers for perovskite/silicon tandems

Ligands improves nucleation and crystal growth, cell performance



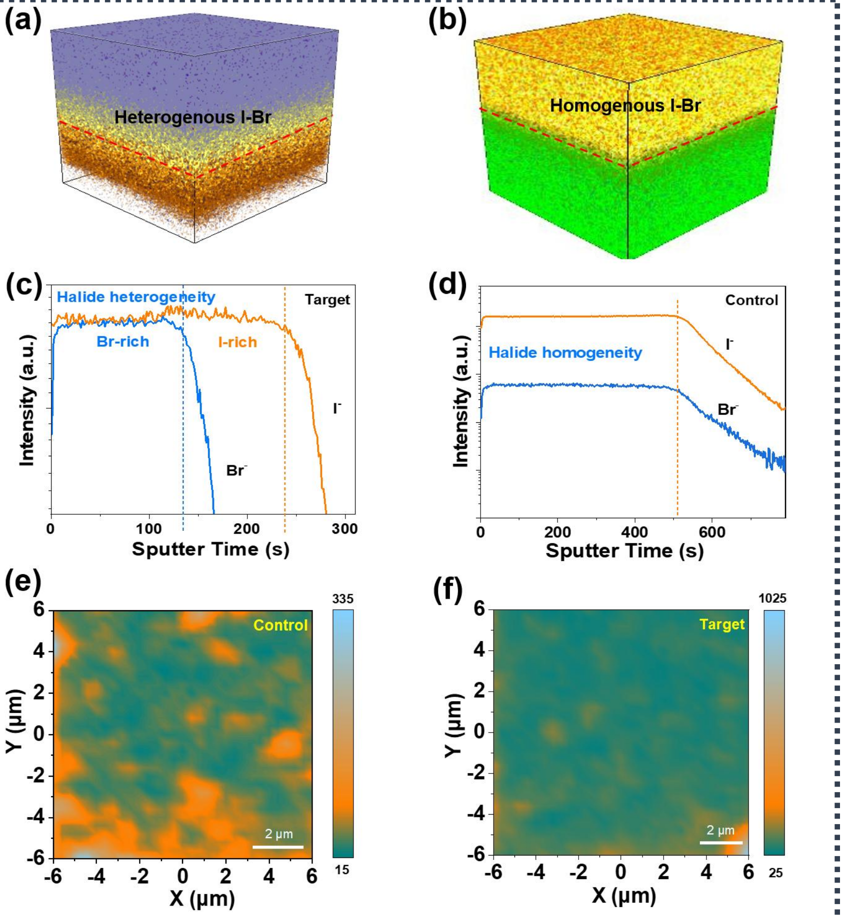
- Different positions based Methoxy-substituted phenyl ethyl ammonium chloride (*x*-MeO-PEACl) as heterointerface anchor ligands;
- A trace amount of any type of *x*-MeO-PEACl significantly improve solar cell performance.



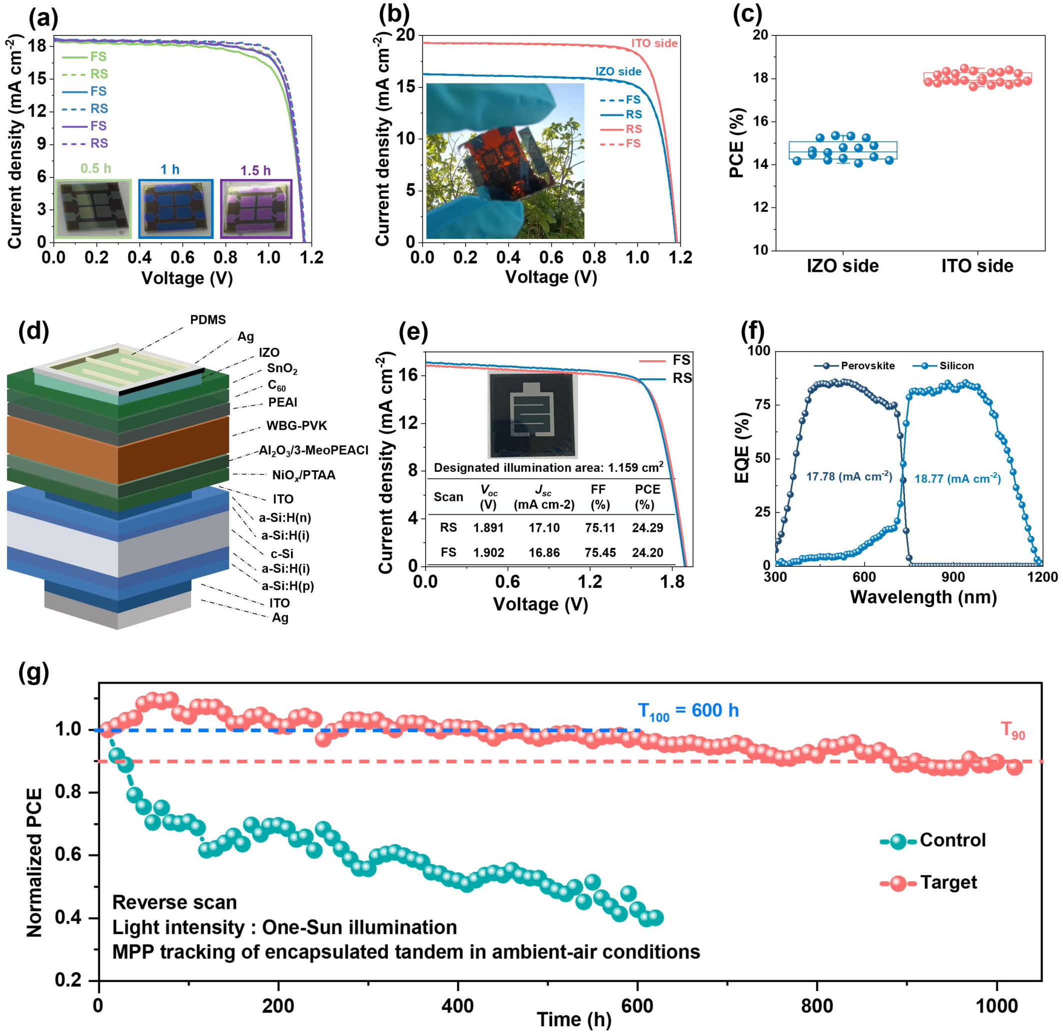
- The presence of 3-MeOPEACl at the heterointerface assists in the nucleation and crystal growth of WBG-perovskites;
- Excellent perovskite crystals (size ~ 510 nm) with vertical growth and no observable voids.

X. Zhang, Y. Wang*, Y. Mai* et. al, *ACS Nano*, Accepted

Ligand homogenized Br-I wide-bandgap perovskites



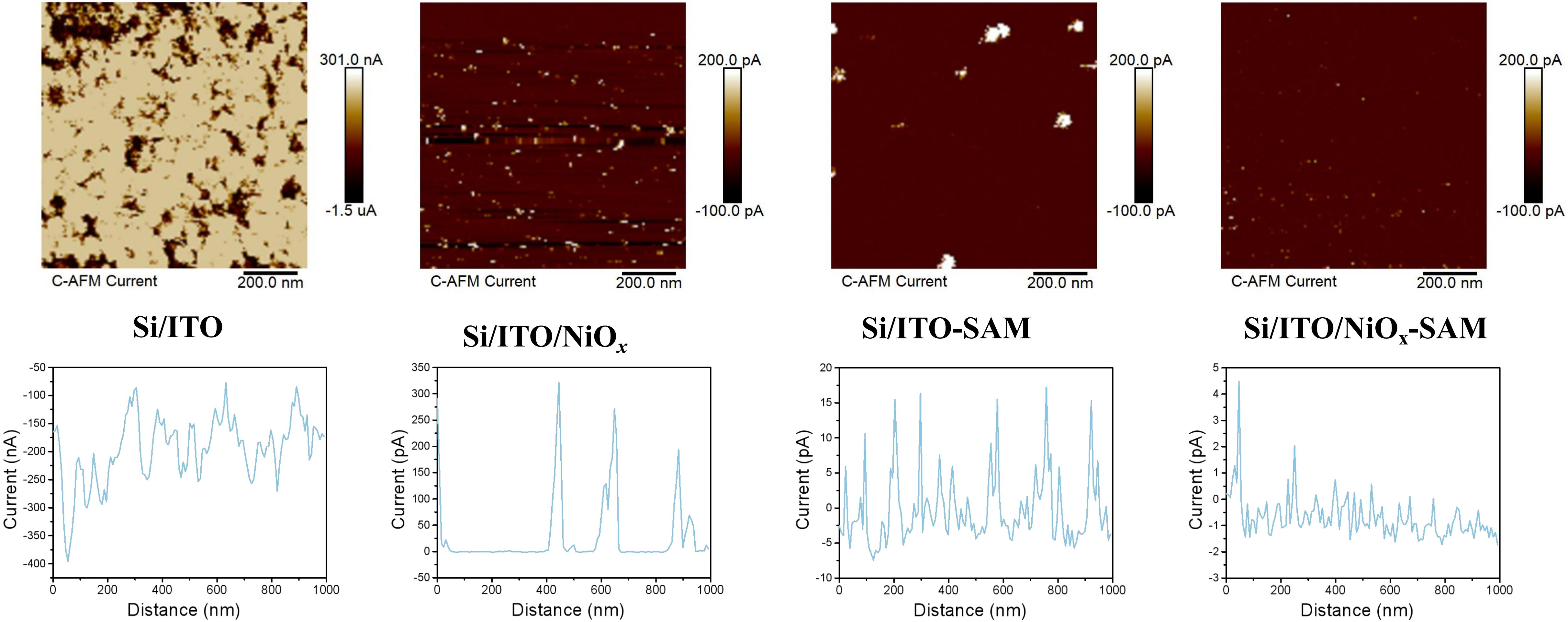
- Homogeneous I-Br distribution;
- The target film incorporated $MeOPEA^+$ ligands shows a more uniform distribution in PL emission (~725 nm).



- Optimazation of front IZO sputtering;
- Better performance and operational stability.

X. Zhang, Y. Wang*, Y. Mai* et. al, *ACS Nano*, Accepted

NiO_x based hybrid Interconnecting Layers (ICLs)

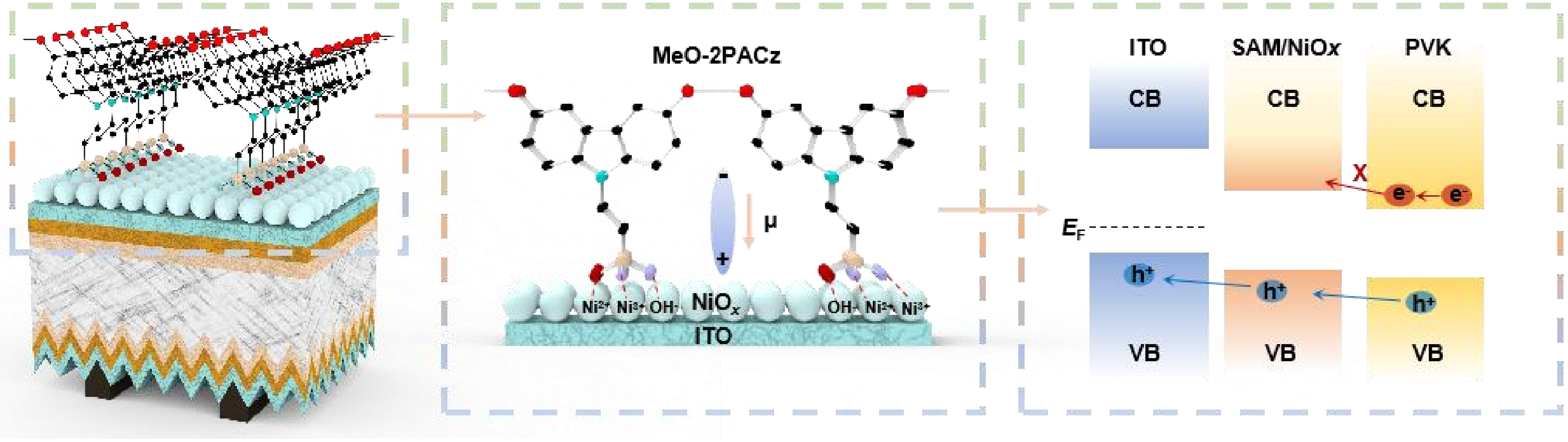


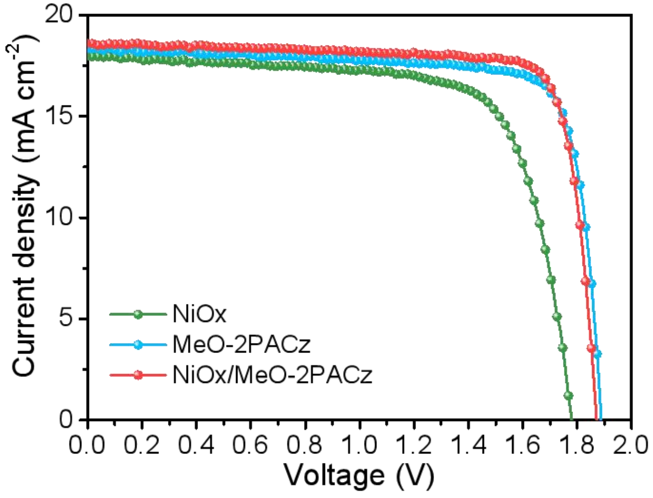
- **Reduced current leakage losses through hybrid ICLs ITO/NiO_x-SAMs;**
- **Suitable energy diagram for efficient hole transportation;**

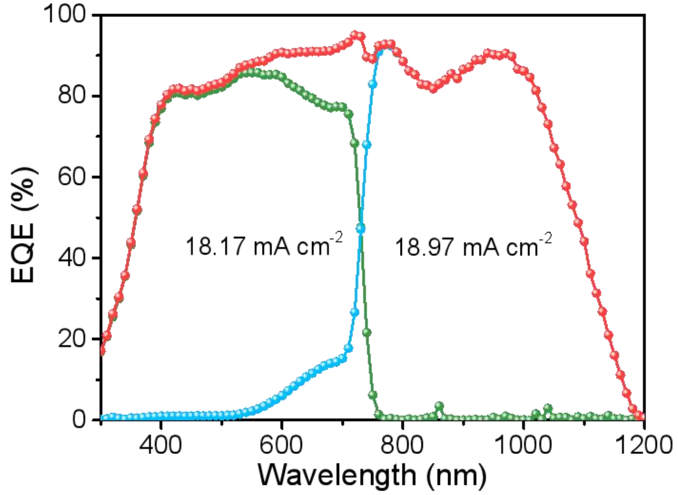
J. Zheng, Y. Wang*, W. Duan*, Y. Mai* et. al,

***Cell Reports Physical Science*, Under revision**

Perovskite-silicon tandem solar cell performance







- **Reduced interface induced non-radiative recombination；**
- **Improved FF up to 81.8%.**

Device	J_{SC}(mA cm^{-2})	V_{OC}(V)	FF (%)	PCE (%)
NiO_x	17.94	1.77	72.3	23.07
MeO-2PACz	18.34	1.88	80.0	27.70
NiO_x/MeO-2PACz	**18.59**	**1.87**	**81.8**	**28.47**

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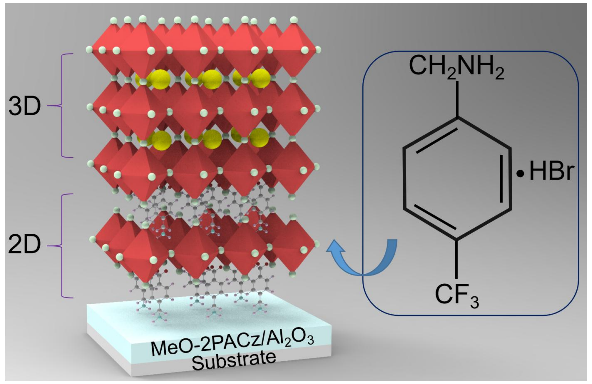
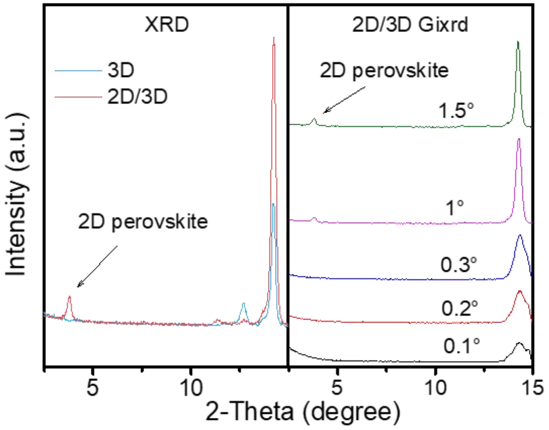
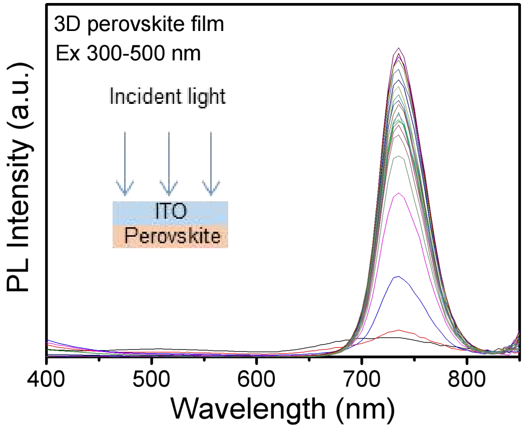
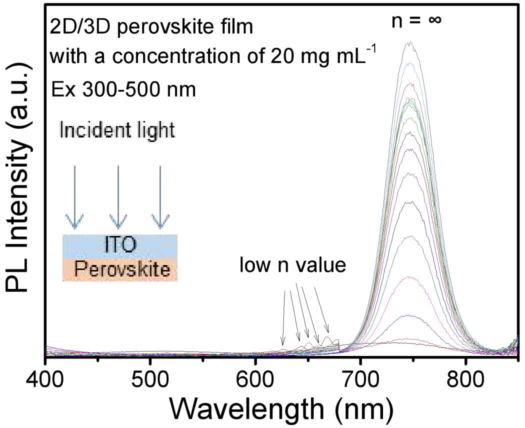
One-step processed 2D perovskite formation at buried interface

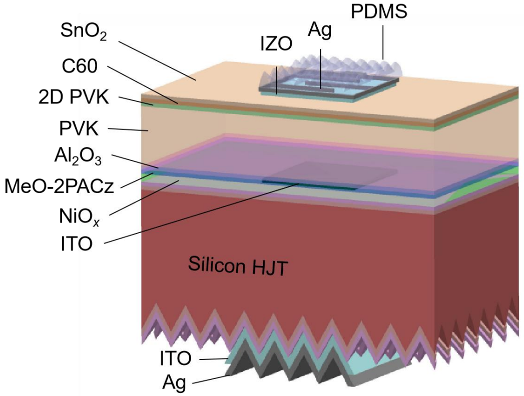


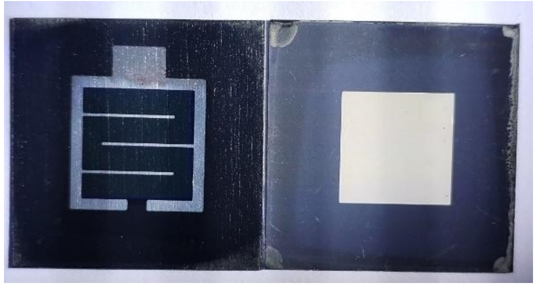


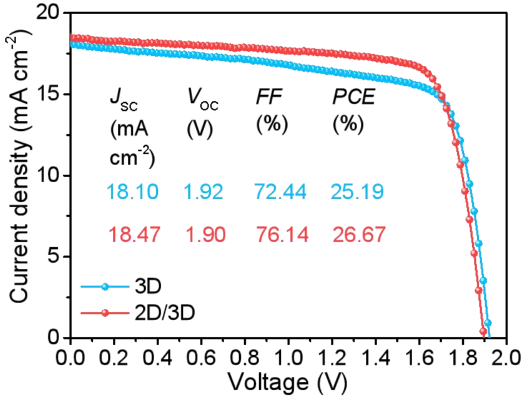


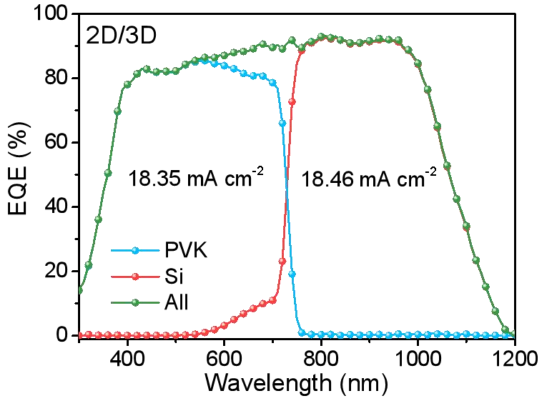


- ➢ **Excitation density dependence of PL spectra;**
- ➢ **Formation of 2D perovskites at buried interface near to substrate.**









- ➢ **A PCE over 26% for an aperture area of 1.158 cm² in tandam cell;**
- ➢ **Current matching in both front and bottom subcells.**

Manuscript in preparation

Summary

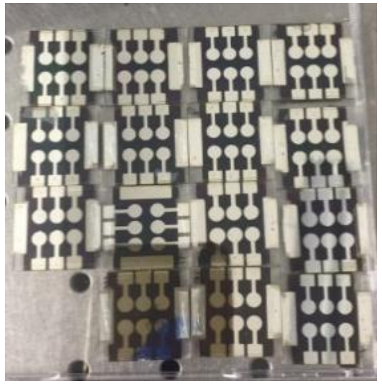
(1) Interface cascade energy alignment improves charge transport and suppresses ion migration;

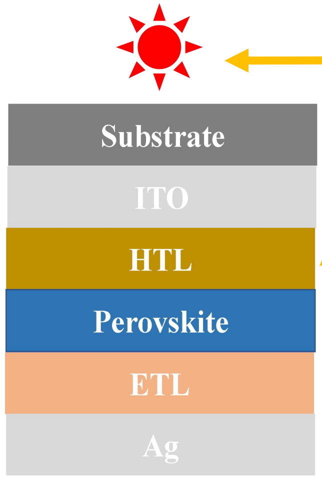
(2) Hole-transport-management facilitates hole transportation, resulted in a PCE over 23% in NiO_x-based inverted PSCs;

(3) Green antisolvent-mediators can effectively passivate defects presented at buried interfaces and GBs of perovskites;

(4) Bulk and interface defect engineering of wide bandgap perovskite enables 44.72% and 43%-efficient NiO_x based indoor perovskite solar cells and modules;

(5) Modification of interconnecting layers reduce current leakage and non-radiative recombination Losses for efficient perovskite/Si tandems.

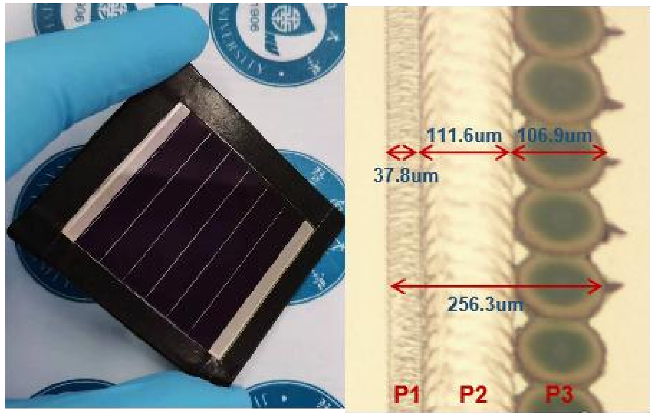




Fabrication of indoor and outdoor perovskite solar cells and modules;

Interface modification：modification of NiO_x defects and energy diagram;

Perovskite: Wide-bandgap perovskites for indoor photovotaics and tandem solar cells;



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Thank you for your attention!