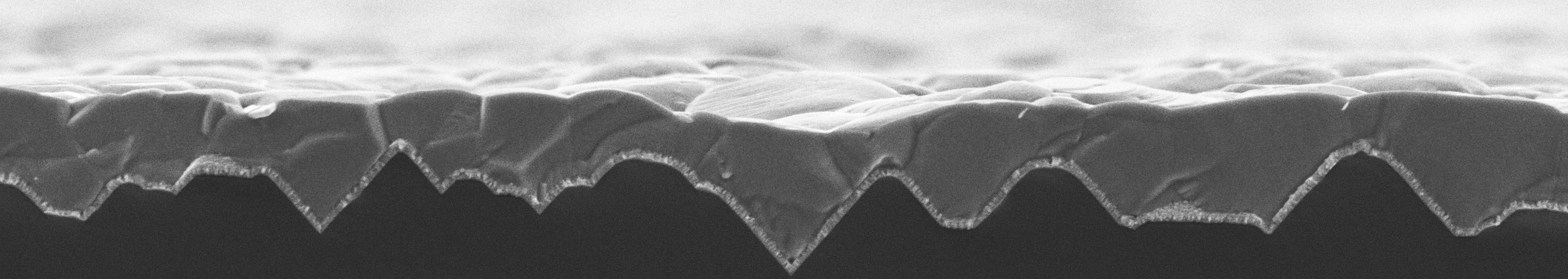
National University of Singapore | Department of Chemical & Biomolecular Engineering | College of Design and Engineering

National University of Singapore | SERIS Solar Energy Research Institute of Singapore



Unlocking the Efficiency Potential of Perovskite Solar Cells: from Single-junction to Tandem

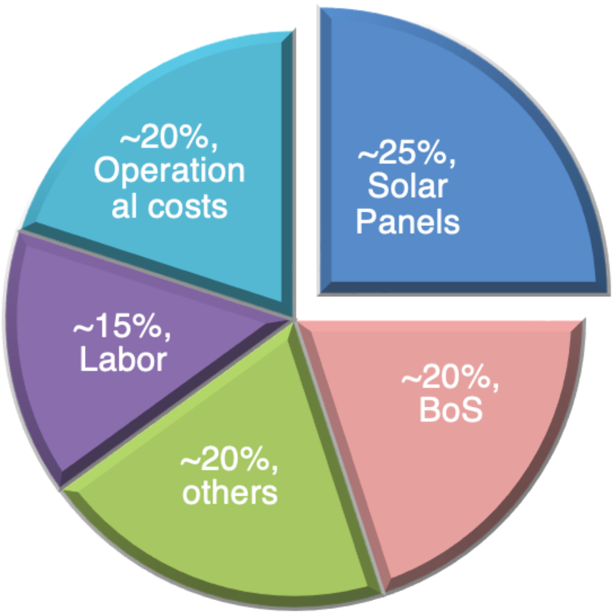
A/Prof. Yi Hou[1,2]

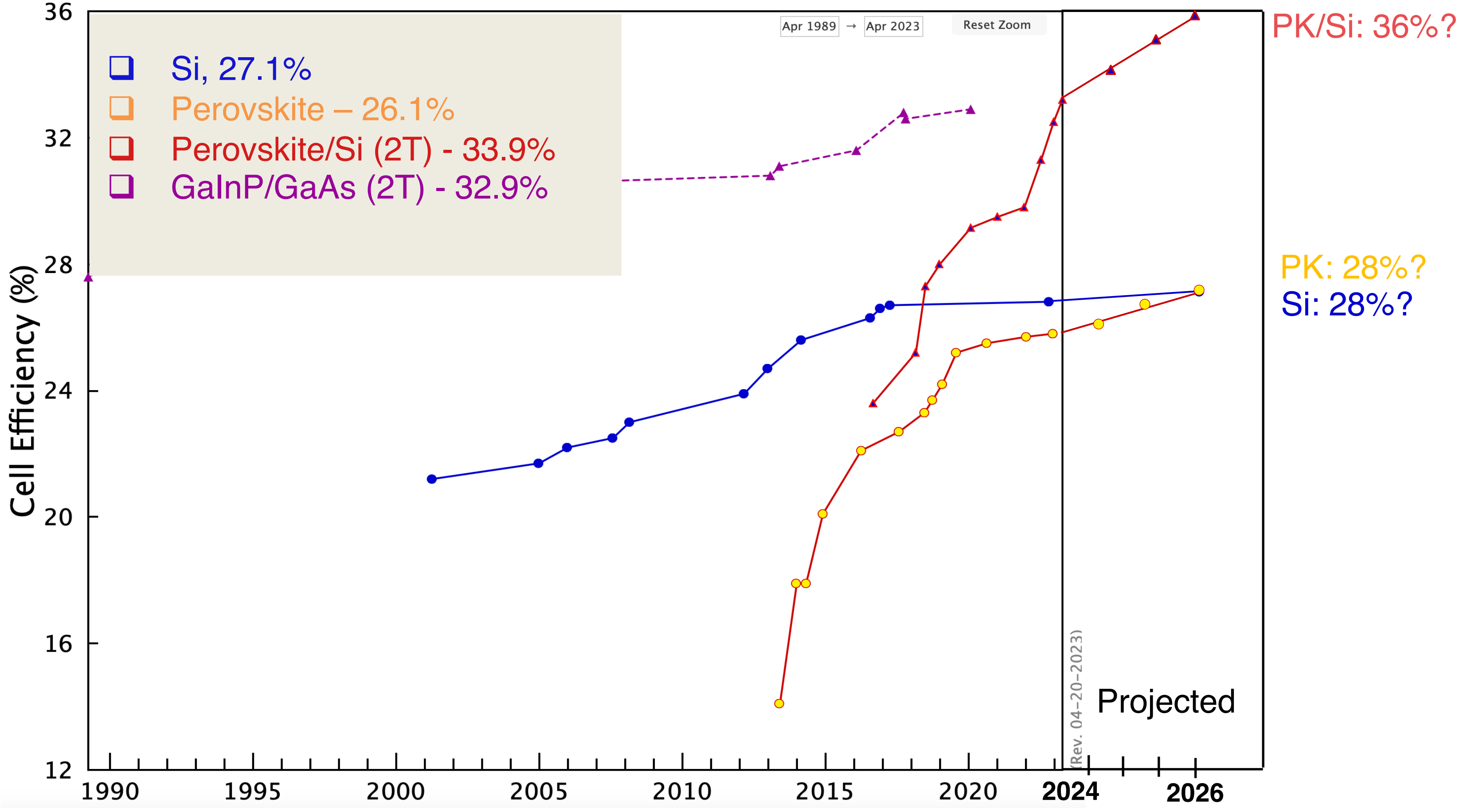
[1]Department of Chemical and Biomolecular Engineering, National University of Singapore
[2]Gp Head, Solar Energy Research Institute of Singapore (SERIS)

Email: yi.hou@nus.edu.sg

PV panel cost accounts for a small fraction of system

Solar cell system cost breakdown





- ❑ Single-junction perovskite exceeds the efficiency of silicon?
- ❑ Where is the limit of perovskite-based MJ?

https://www.nrel.gov/pv/interactive-cell-efficiency.html

PV Records
(cell area >1 cm^2)

- Perovskite has outperformed most thin-film PV technologies
- Reducing the PCE disparity with GaAs (**1.4eV**) and Si (**1.1eV**) by optimizing bandgaps

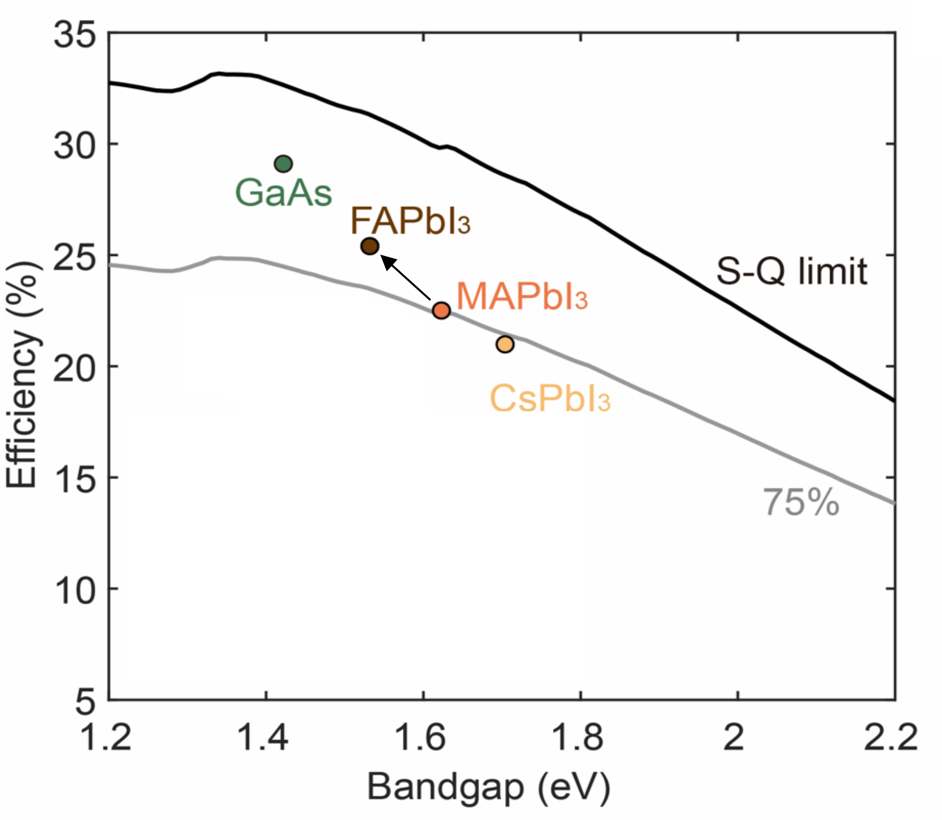
Thin-film-based PV technologies

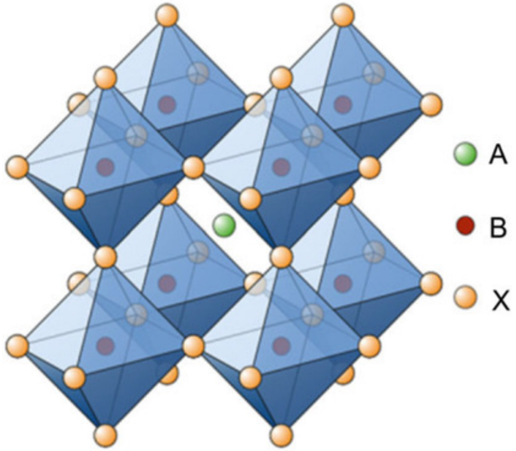
TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008 or ASTM G-173-03 global).

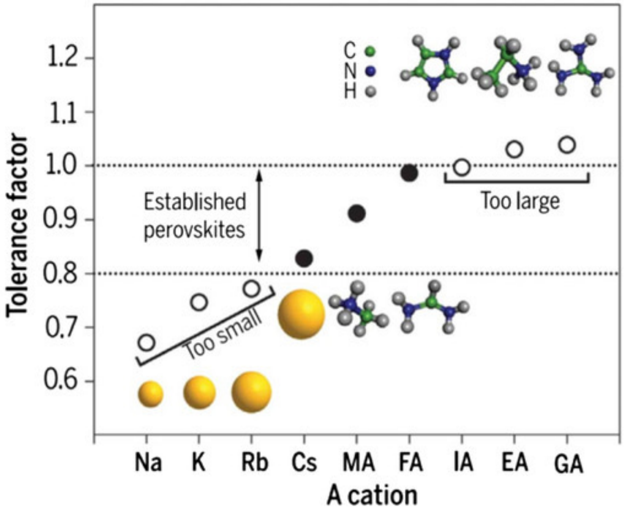
Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	26.8 ± 0.4[a]	274.4 (t)	0.7514	41.45[b]	86.1	ISFH (10/22)	LONGi, n-type HJT[4]
Si (DS wafer cell)	24.4 ± 0.3[a]	267.5 (t)	0.7132	41.47[c]	82.5	ISFH (8/20)	Jinko Solar, n-type
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[e]	38.50[d,e]	80.3	NREL (4/14)	Solexel (35 μm thick)[5]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[e]	29.7[d,f]	72.1	FhG-ISE (8/07)	CSG Solar (<2 μm on glass)[6]
III–V cells							
GaAs (thin-film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78[g]	86.7	FhG-ISE (10/18)	Alta Devices[7]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[8]
InP (crystalline cell)	24.2 ± 0.5[h]	1.008 (ap)	0.939	31.15[i]	82.6	NREL (3/13)	NREL[9]
Thin-film chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58[j]	80.4	AIST (11/18)	Solar Frontier[10]
CIGSSe (submodule)	**20.3 ± 0.4**	**526.7 (ap)**	**0.6834**	**39.55[dk]**	**75.1**	**NREL (5/23)**	**Avancis, 100 cells[11]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[e]	79.4	Newport (8/14)	First Solar, on glass[12]
CZTSSe (cell)	**12.1 ± 0.3**	**1.066 (da)**	**0.5379**	**35.29[k]**	**63.6**	**NPVM (4/23)**	**IoP/CAS[13]**
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77[i]	65.1	NREL (3/17)	UNSW[14]
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[L,h]	1.001 (da)	0.896	16.36[e]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	11.9 ± 0.3[h]	1.044 (da)	0.550	29.72[i]	75.0	AIST (2/17)	AIST[16]
Perovskite							
Perovskite (cell)	**24.35 ± 0.5[m]**	**1.007 (da)**	**1.159**	**25.60[k]**	**82.1**	**NPVM (4/23)**	**NUS/SERIS[17]**
Perovskite (minimodule)	22.4 ± 0.5[m]	26.02 (da)	1.127[d]	25.61[d,b]	77.6	NPVM (7/22)	EPFLSion/NCEPU, 8 cells[18]

Solar Cell Efficiency Tables (Version 62), June 2023

Approaching the ideal bandgap of GaAs





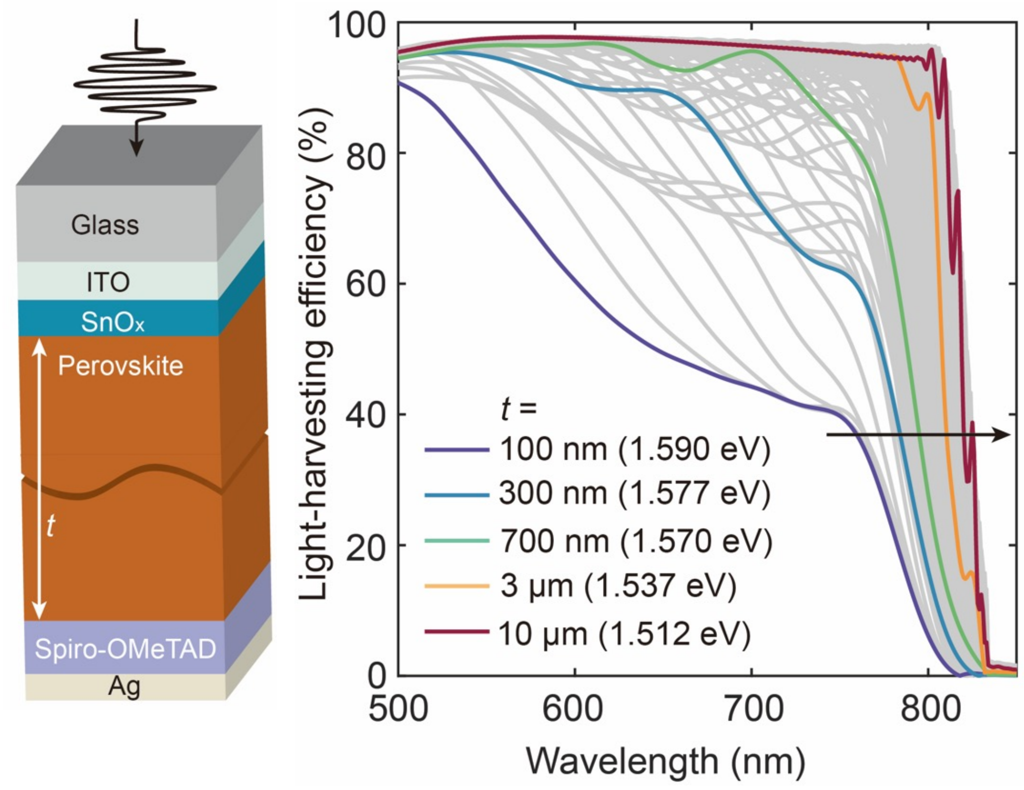


$$t = \frac{(r_A + r_X)}{\sqrt{2}(r_B + r_X)}$$

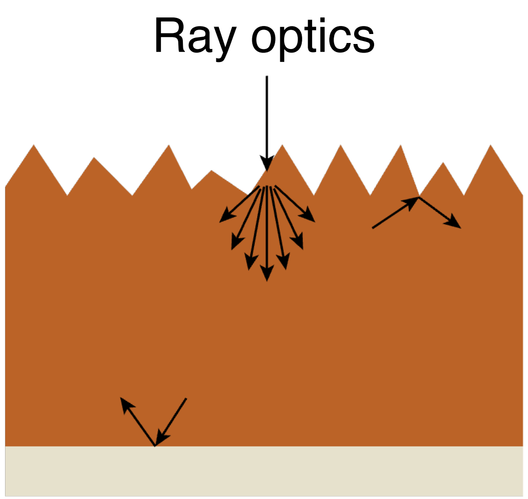
- ❑ Approaching the ideal bandgap of GaAs
- ❑ Composition engineering has reached its inherent limits

Feng, J.; …Hou, Y.* **Nature Communications**, 14, 5392 (2023)

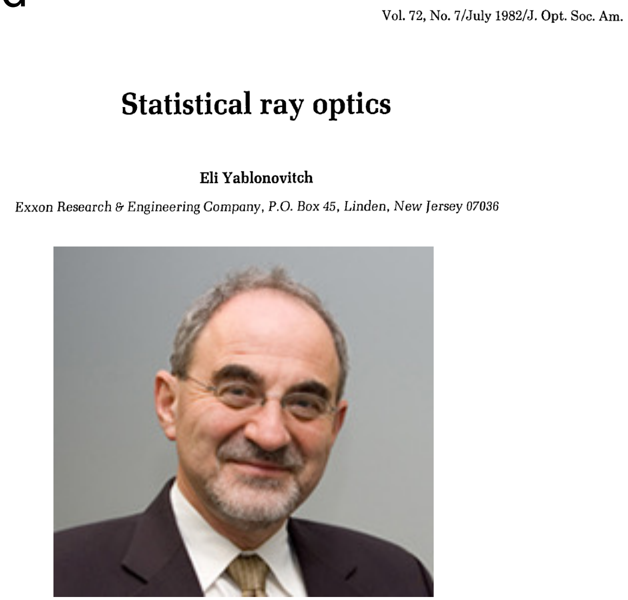
Traditional **light management** based on ray optics



Yablonovitch limit = **4*n*²** fold



n(Si): 3.7
n(GaAs): 3.7
n(Perovskite): 2.4



Eli Yablonovitch

- ❑ > 10 um-thick single crystal perovskite has a narrower PV bandgap
- ❑ Ray optics is not effective in extending perovskite band edge

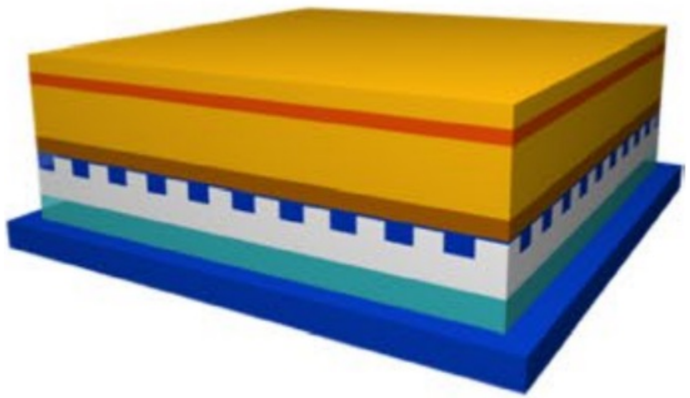
Feng, J.; …Hou, Y.* **Nature Communications**, 14, 5392 (2023)

Narrowing the PV bandgap of $FAPbI_3$

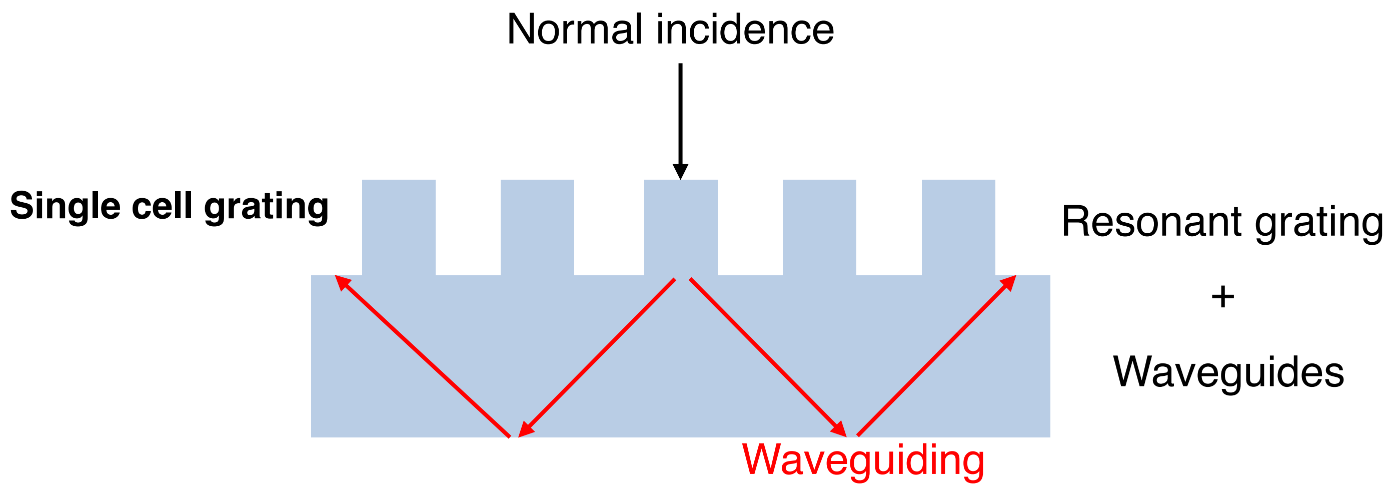
- without composition engineering and increasing thickness

Ultrathin GaAs solar cells (~200nm)

Wave optics
(single cell grating + high *n*)



Nature Energy 4, 761-767 (2019)

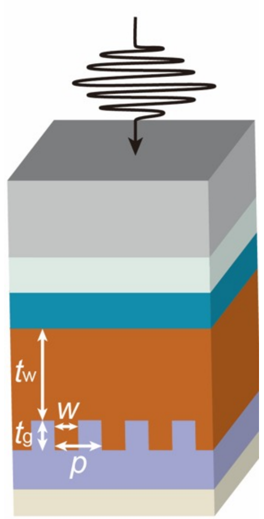


- ❑ Resonant grating for diffraction
- ❑ Strong light confinement and propagation in waveguides

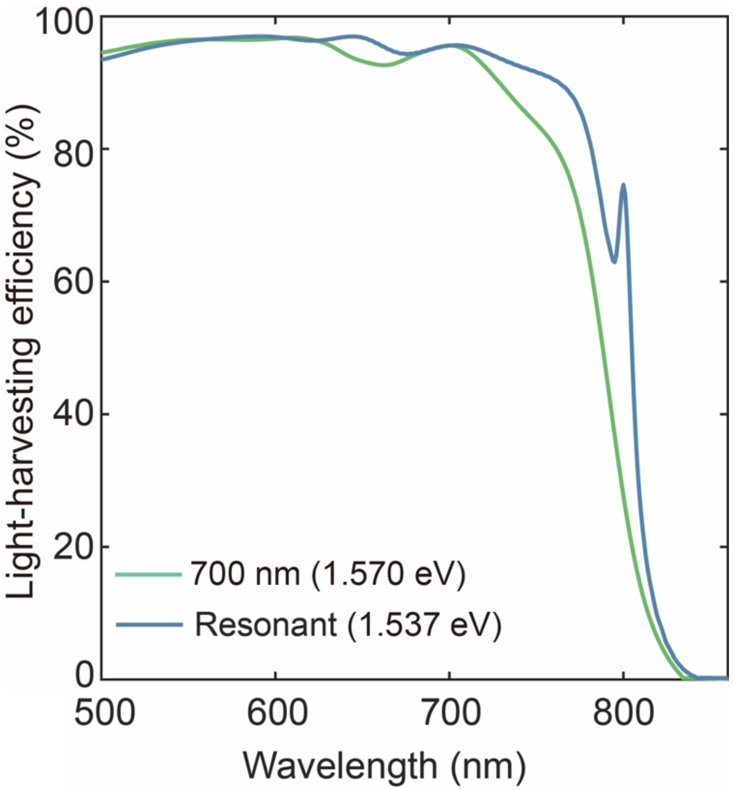
Feng, J.; … Hou, Y.* **Nature Communications**, 14, 5392 (2023)

Narrowing the PV bandgap of $FAPbI_3$

- without composition engineering and increasing thickness



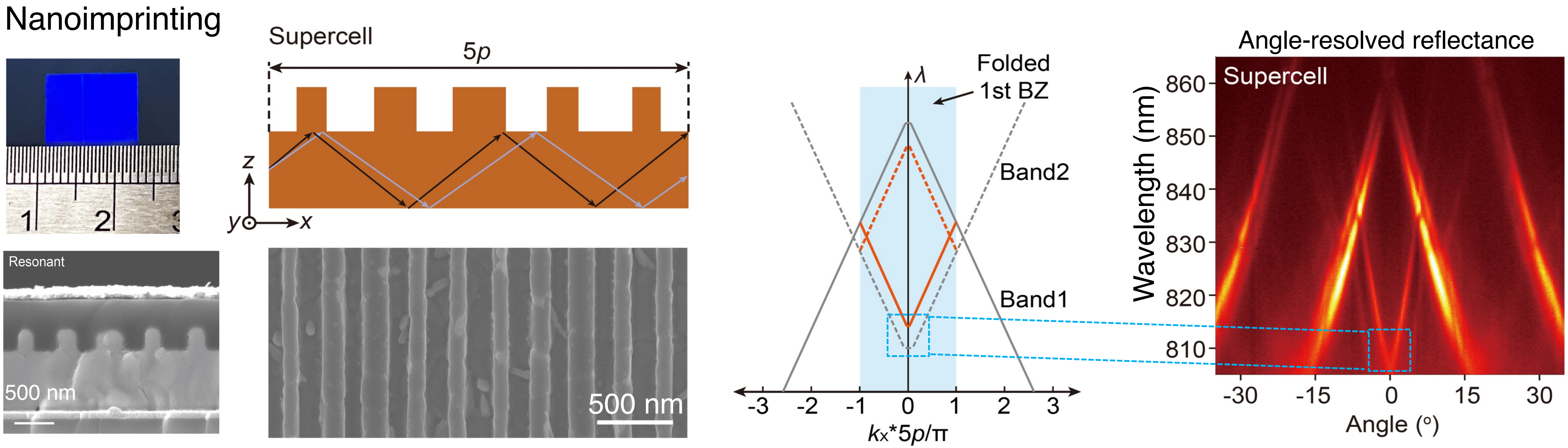
Resonant solar cells



- ❑ **Strong guided-mode resonances (GMRs)** couple normal incident light with waveguided modes
- ❑ GMRs significantly enhance light absorption even near band edge with **small absorption coefficients**

Feng, J.; … Hou, Y.* **Nature Communications**, 14, 5392 (2023)

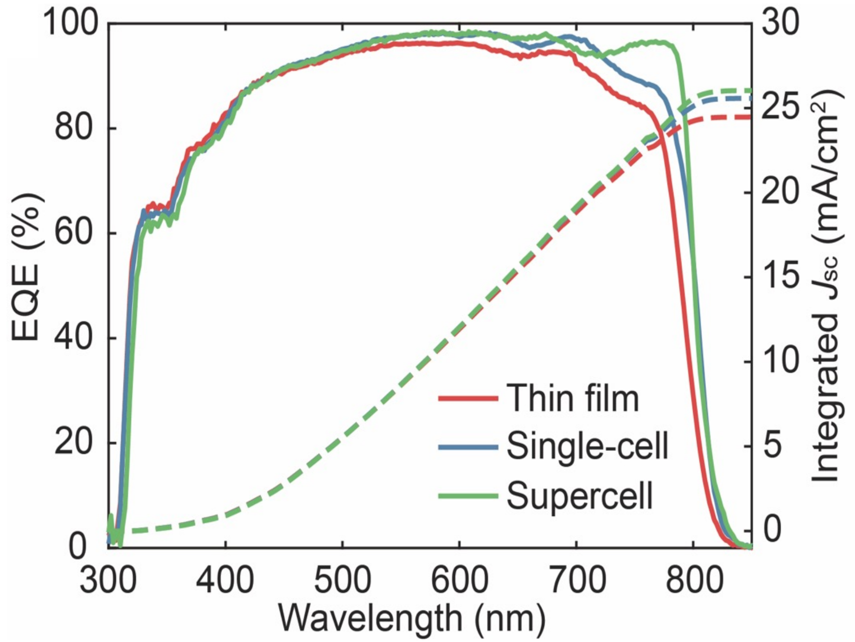
Resonant solar cells with Brillouin-zone folding

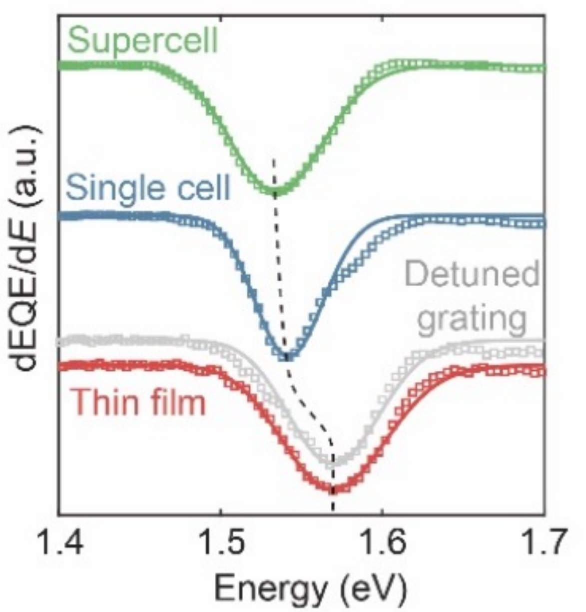


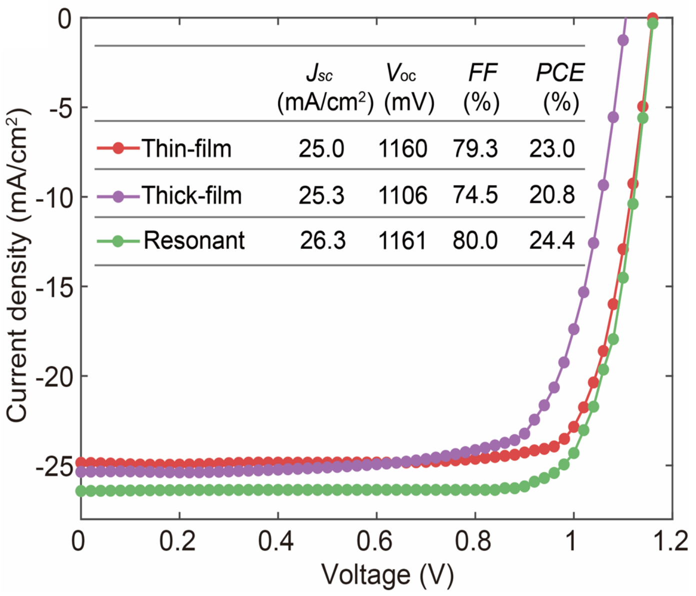
- ❑ Supercell can induce Brillouin-zone folding
- ❑ Brillouin-zone folding provides an approach to increase photonic density of states

Feng, J.; … Hou, Y.* **Nature Communications**, 14, 5392 (2023)

Resonant solar cells with improved Jsc



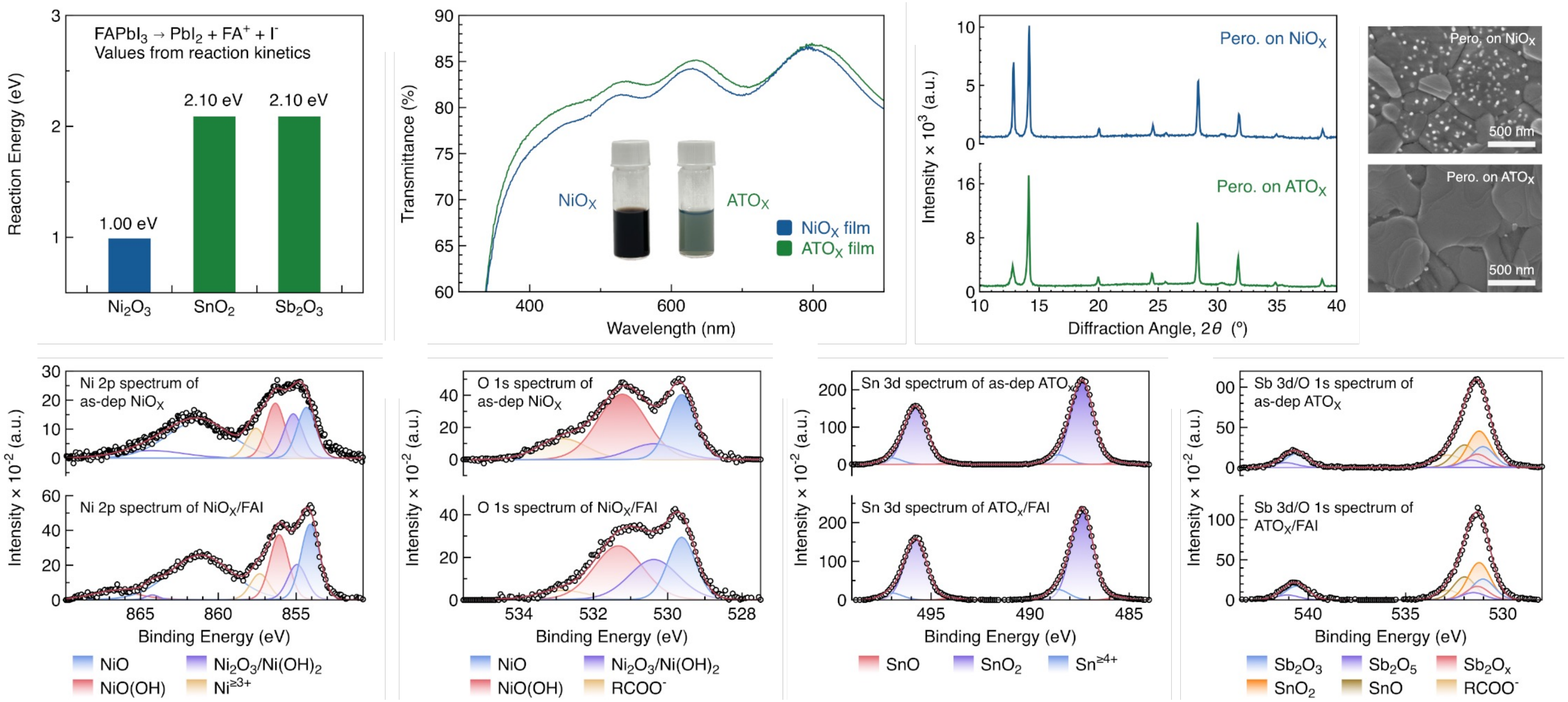




- ❑ Resonant solar cells: 18 nm spectral extension, 35 meV band-edge extension, 1.5 mA/cm² J_{sc} improvement

Feng, J.; … Hou, Y.* **Nature Communications**, 14, 5392 (2023)

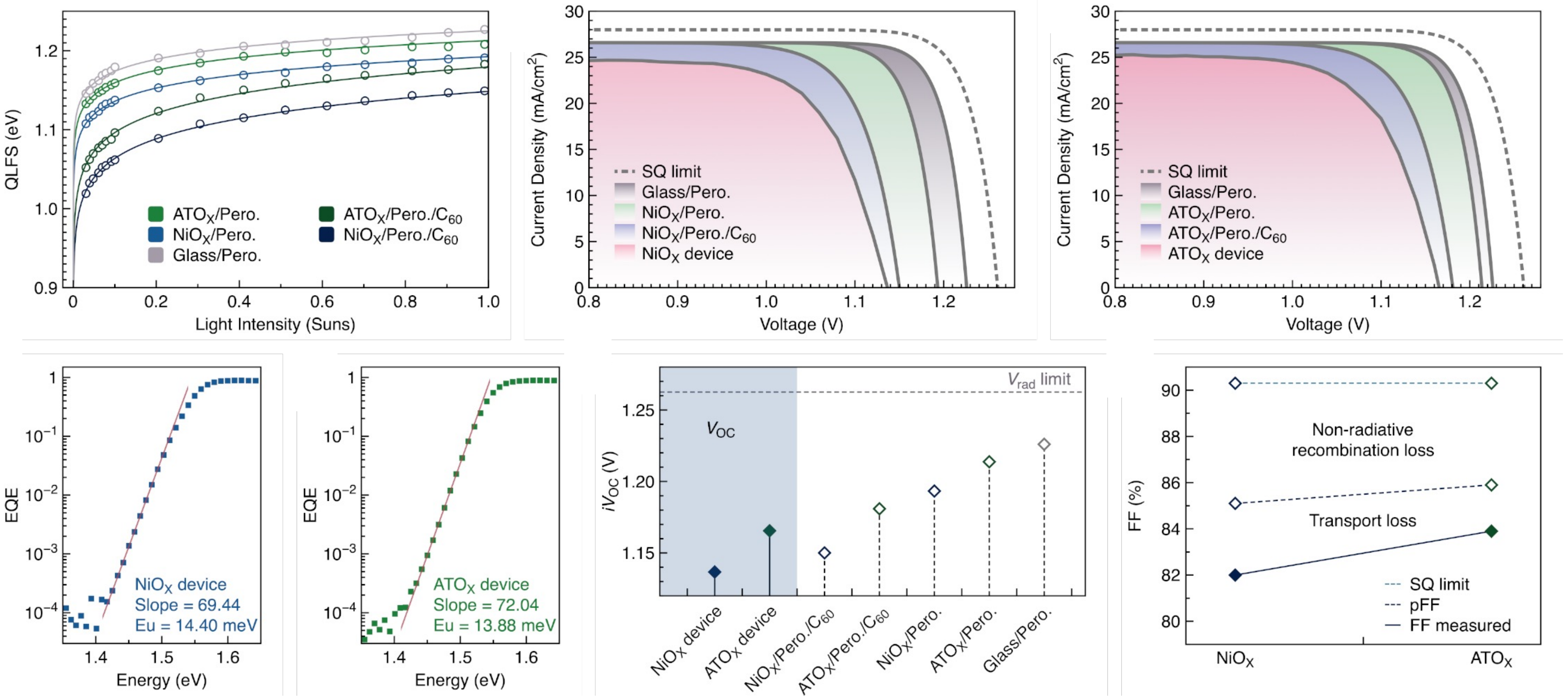
Carrier management: Antimony doped tin oxides (ATOx) HTL



❑ ATOx is a more stable and transparent HTL in "p-i-n" structured perovskite solar cell.

Li, J.; Liang, H.; … Hou, Y.* **Nature Energy** (2024) 10.1038/s41560-023-01442-1

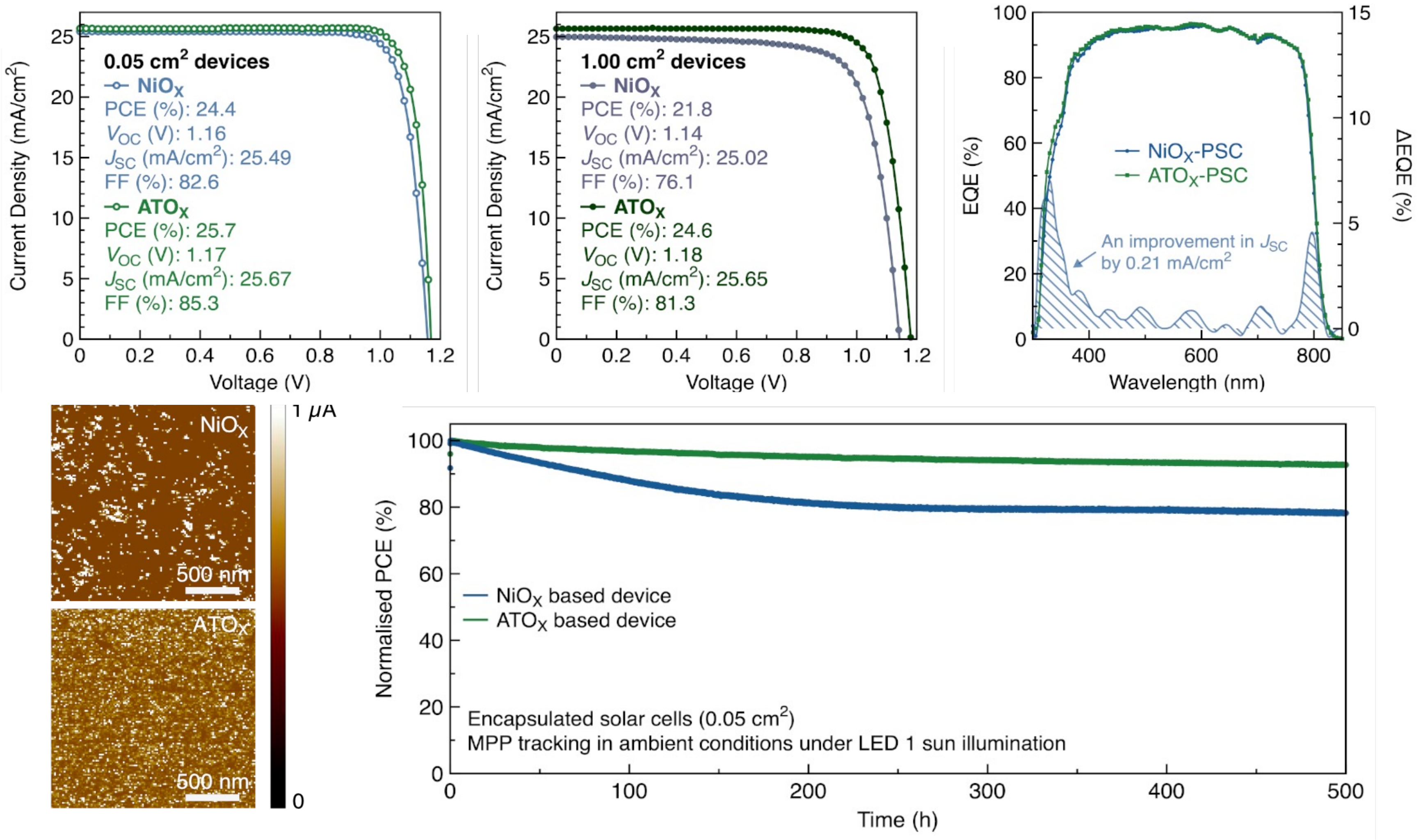
Voc improvement in ATOx cells



❑ ATO_x suppresses non-radiative recombination in perovskites

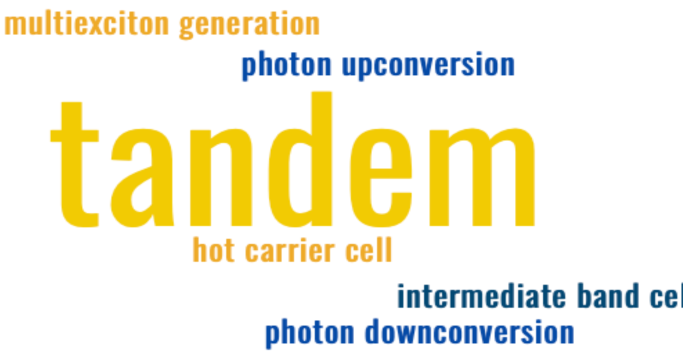
Li, J.; Liang, H.; … Hou, Y.* **Nature Energy** (2024) 10.1038/s41560-023-01442-1

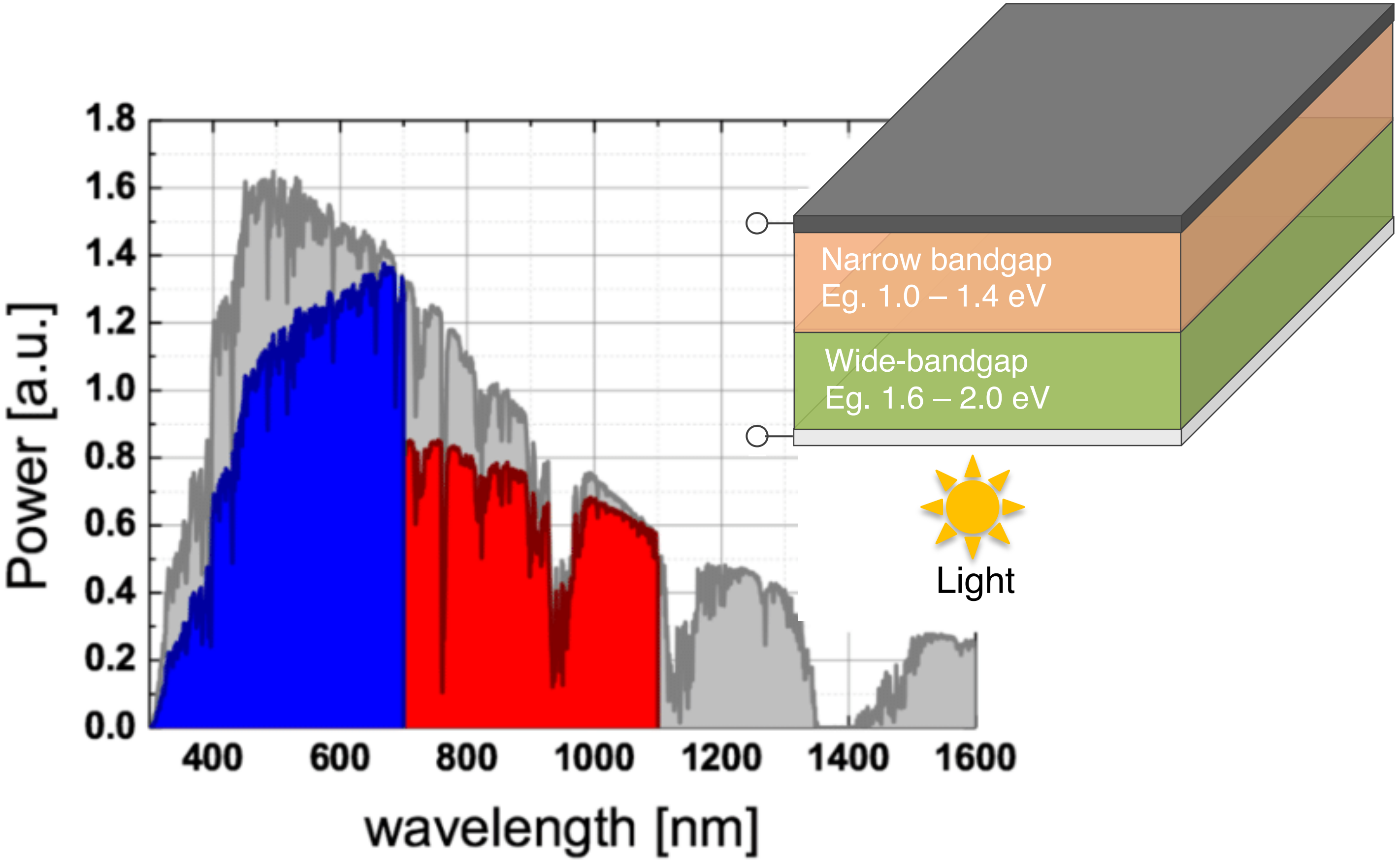
Reduced PCE gap for cell sizes ranging from 0.05 to 1 cm²



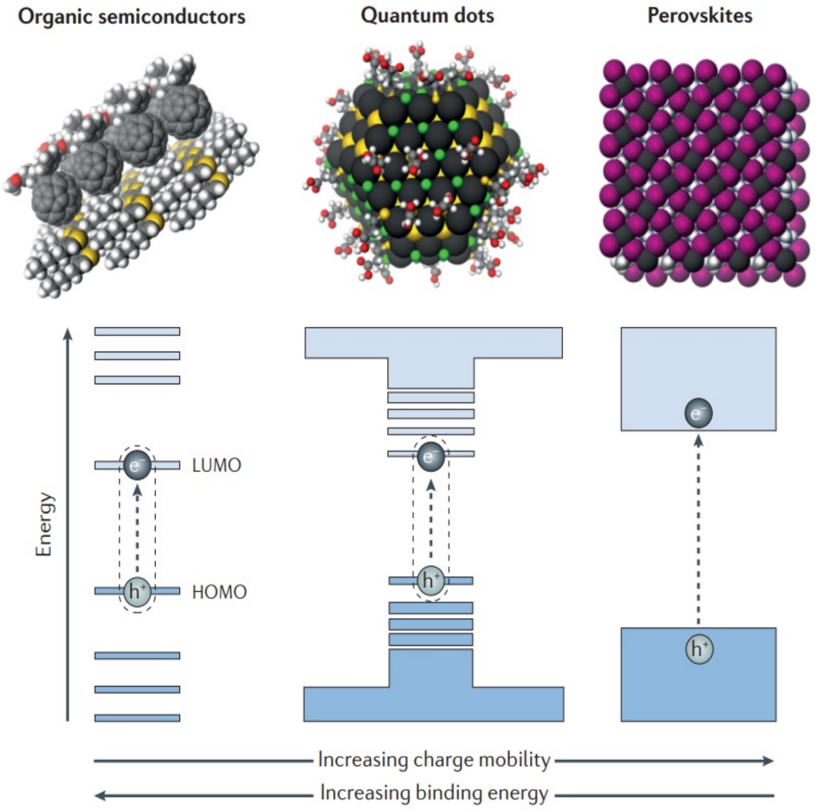
Li, J.; Liang, H.; … Hou, Y.* **Nature Energy** (2024) 10.1038/s41560-023-01442-1

Tandem is one of the most practical solutions to overcome SQ limit

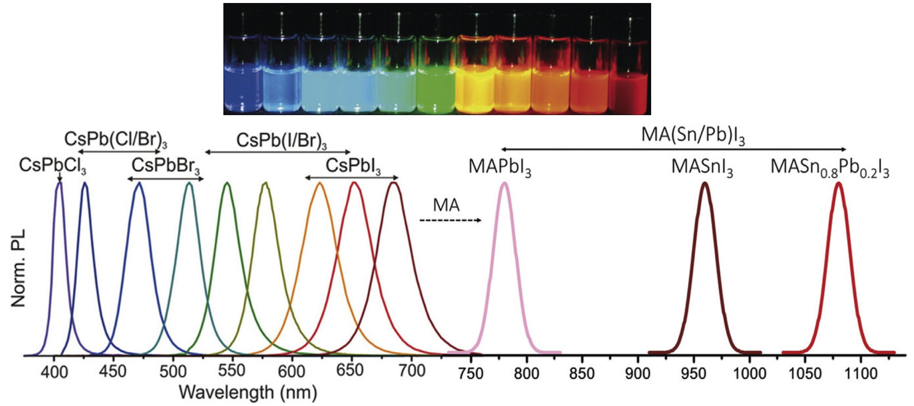




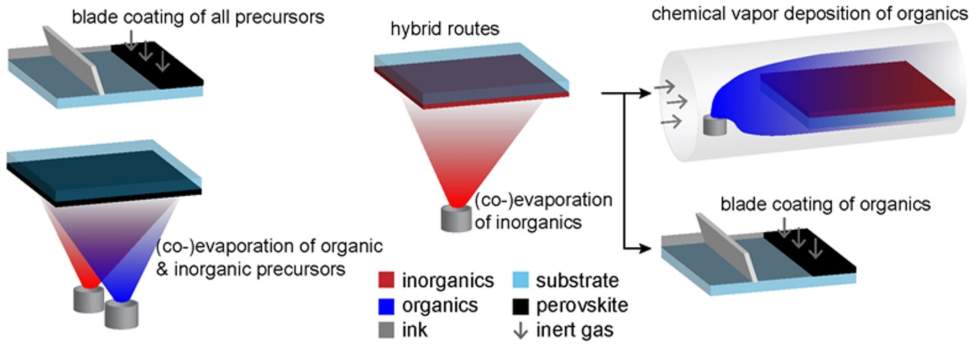
Perovskite – a fantastic wide-bandgap absorber



- ❑ Low exciton binding energy
- ❑ Long diffusion length
- ❑ Strong absorption



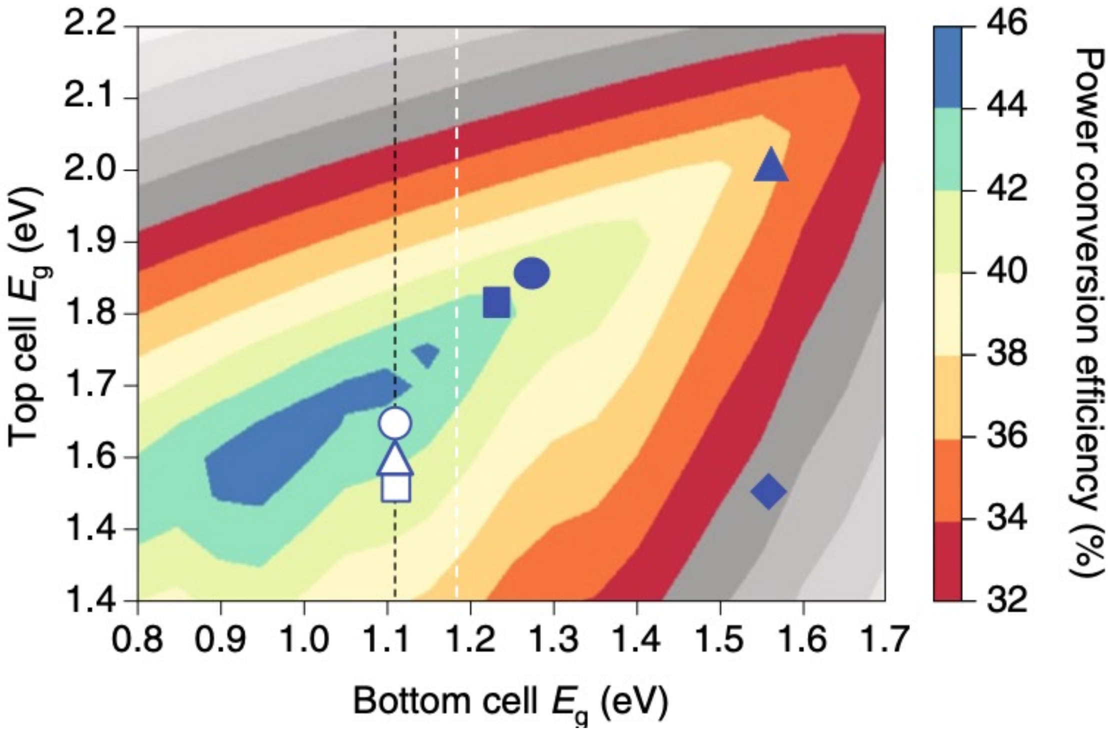
❑ Bandgap tunability

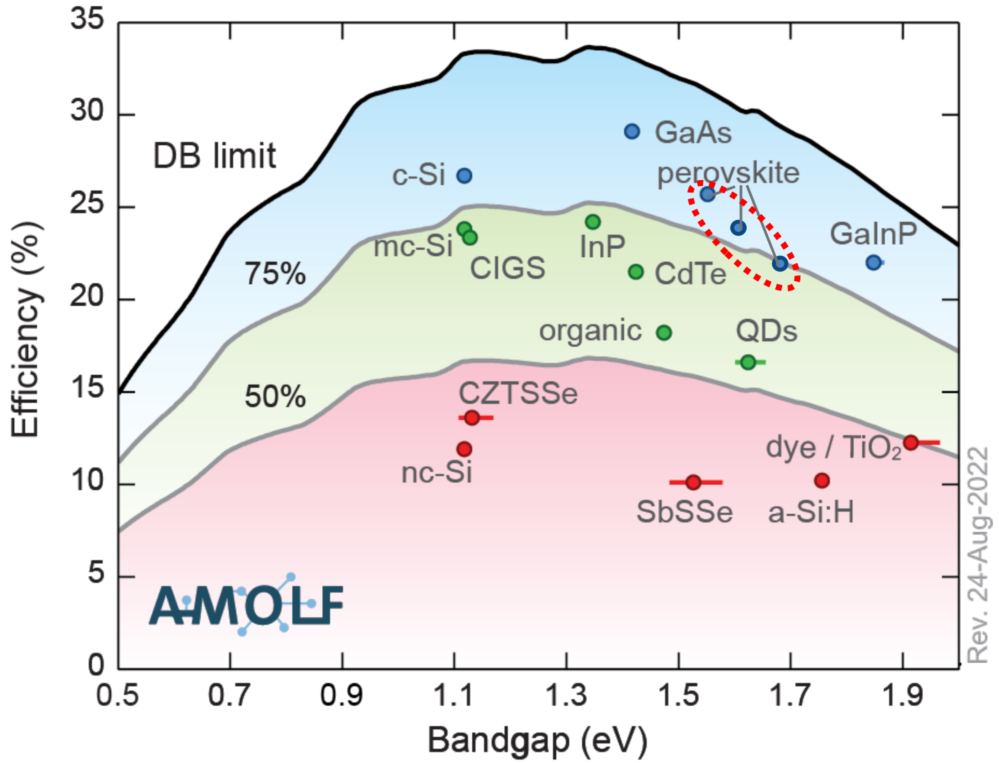


❑ Compatibility with vacuum and solution processing

Advanced Materials, 2106540 (2022); Nature Reviews Materials 3, 18017 (2018); Nature Reviews Materials 2, 16100 (2017)

Perovskites - efficient wide-bandgap absorbers



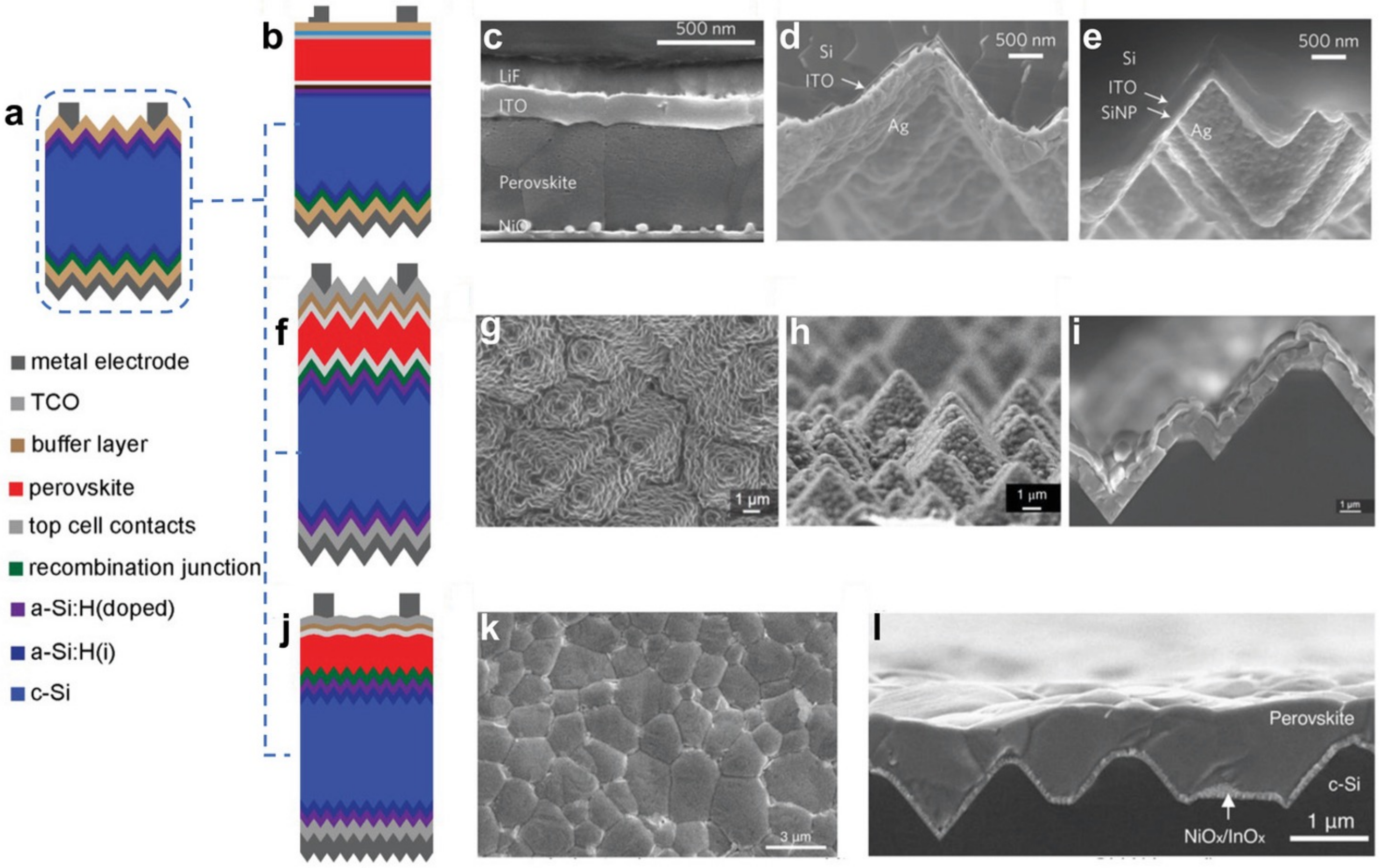


- Ideal tandem bandgaps: 1.0eV/1.6eV
  e.g., Si requires perovskite Bandgap >1.65 eV

- Efficient wide-bandgap absorbers

Nature Energy 3, 828 (2018)
https://www.lmpv.nl/db/

State-of-the art perovskite/Si tandem solar cell architecture evolution



✓ Solution processing
✗ Light management

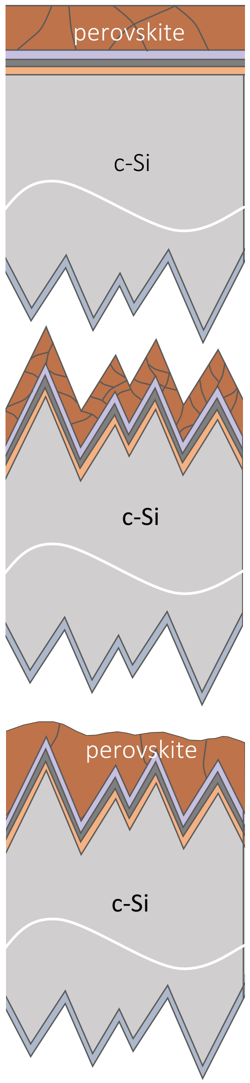
"one-step"
Certified PCE > 32%

✗ Solution processing
✓ Light management

"two-step"
Certified PCE > 31%

✓ Solution processing
✓ Light management

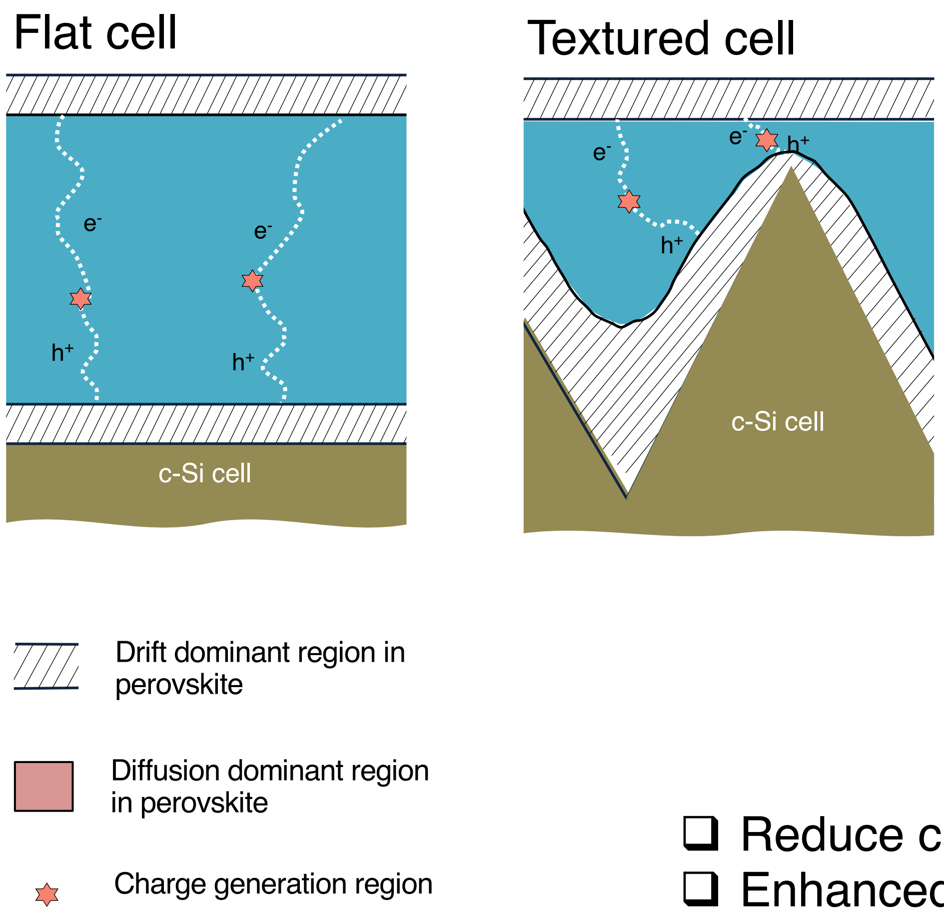
"one-step"
Certified PCE > 33%

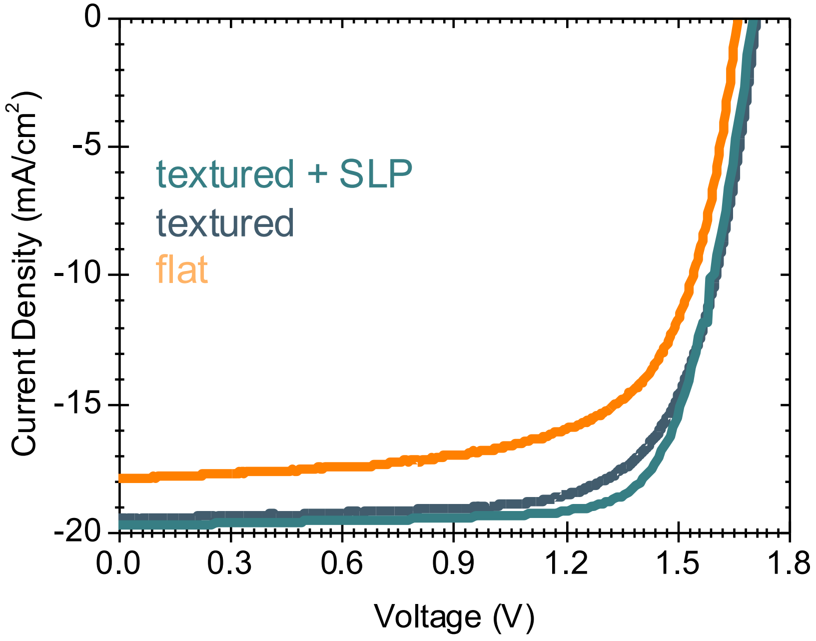


NUS National University of Singapore | Department of Chemical & Biomolecular Engineering
College of Design and Engineering

Fu, F.*; Ballif, C.; Hou, Y.* et al **Advanced Materials**, 2022, 2106540.
Hou, Y.; Aydin, E.; De Wolf, S.; Sargent, E. et al. **Science**, 2020, 367, 1135-1140

The depletion width correlates to the geometry factor





- ❑ Reduce carrier collection paths;
- ❑ Enhanced wetting of perovskite precursor;

Hou, Y.; Aydin, E.; De Wolf, S.; Sargent, E. et al. **Science**, 2020, 367, 1135-1140

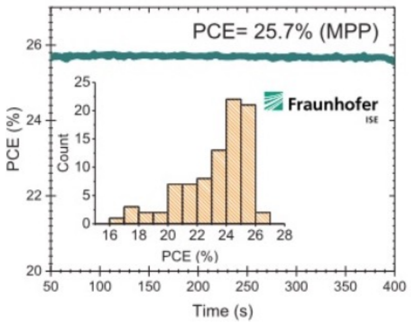
Perovskite/Si tandem performances evolution

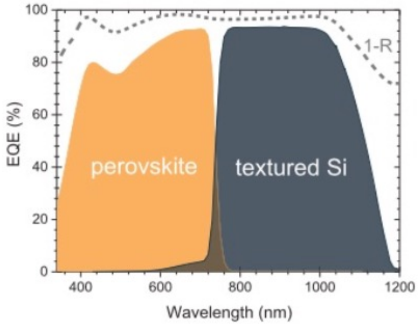

IN SCIENCE JOURNALS
Edited by Michael Funk
Science
AAAS

SOLAR CELLS
Growing perovskite on textured silicon

Wide–band gap perovskites could boost the efficiency of silicon solar cells by forming tandem cells, but usually the perovskite must be grown on a smoothed side of the silicon cell because the material grown on the rough light-trapping side often does not fully coat the silicon surface and its rough texture is prone to phase separation. Hou *et al.* grew thick films of a perovskite with a band gap of ~1.68 electron volts and used a passivant, 1-butanethiol, to limit its phase separation. The tandem cells had a certified power conversion efficiency of 25.7% and had negligible losses after 400 hours of operation. —PDS *Science*, this issue p. 1135

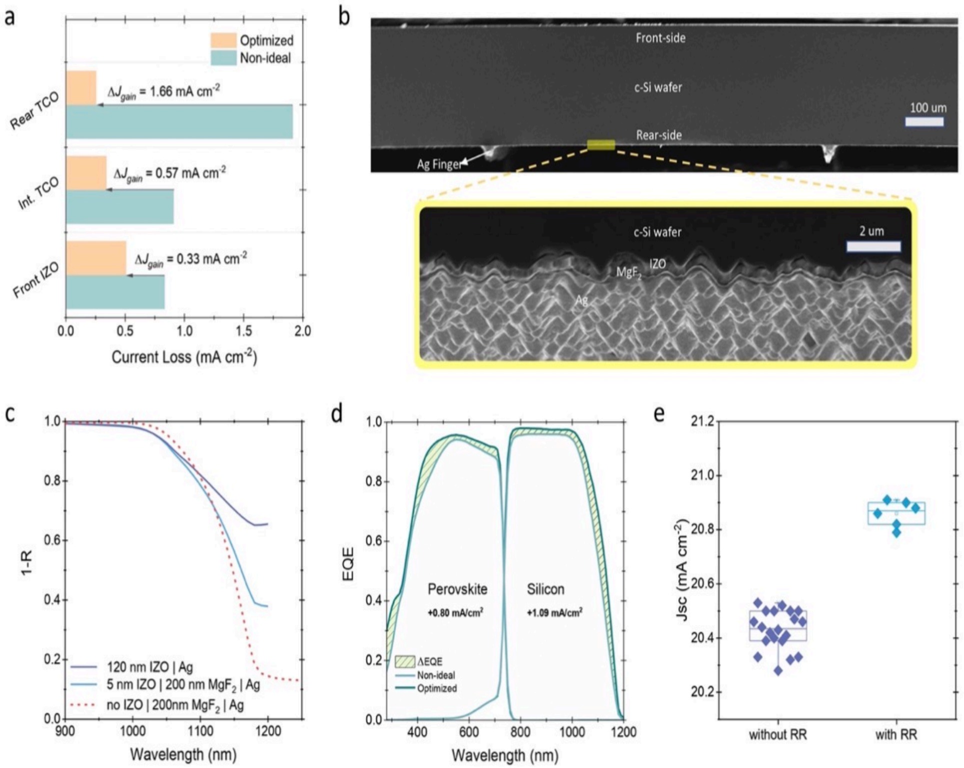
Cross-sectional scanning electron microscope image of textured crystalline silicon, which can form the bottom cell in perovskite-silicon tandem solar cells





Hou, Y.; Aydin, E.; De Wolf, S.; Sargent, E. et
Science, 367, 1135-1140 (**2020**)

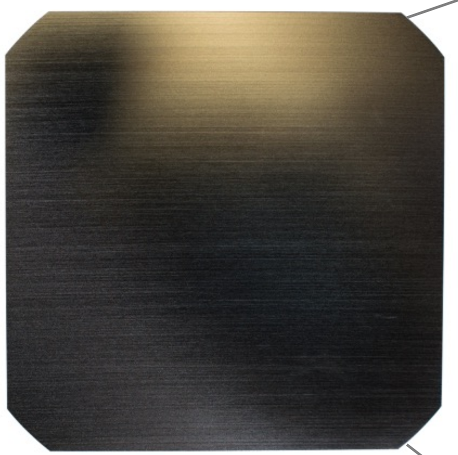
Aydin, E.; Wolf, S. D. *et al.*
Nature, DOI: 10.1038/s41586-023-06667-4 (**2023**)



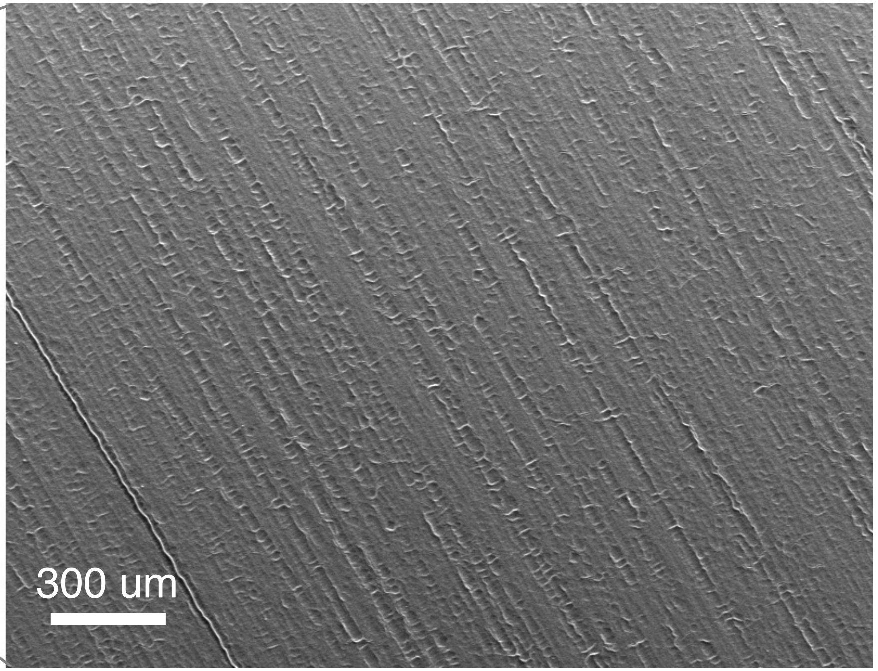
PCEs boost from 26% to 33%

1. Saw marks on Si surface

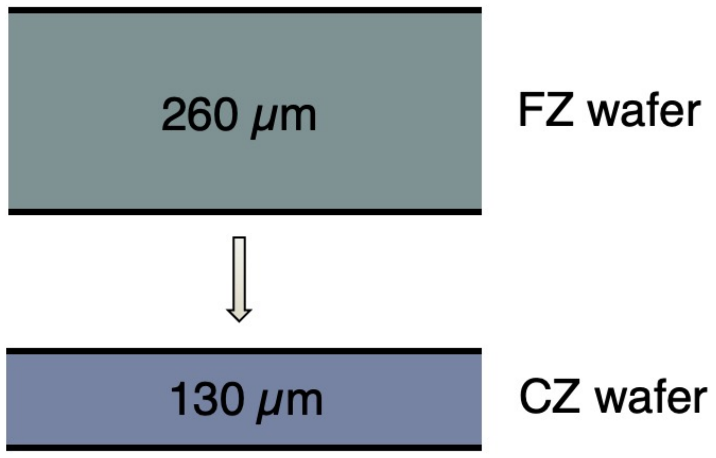
Float Zone (FZ)
Price: > 60 USD/piece

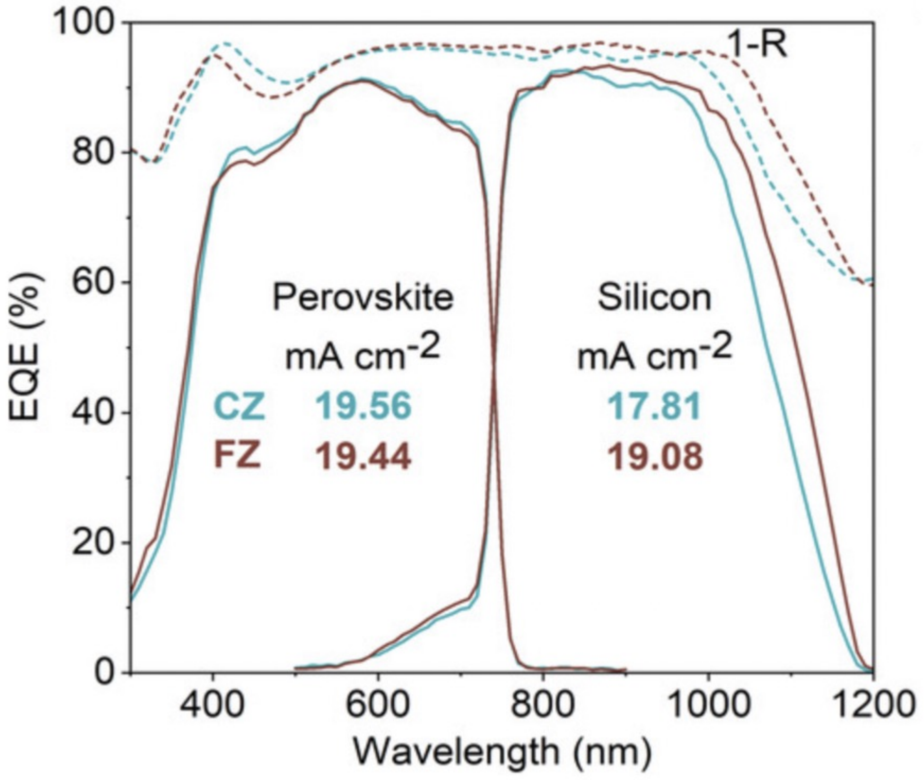


Czochralski (CZ)
Price: < 1 USD/piece



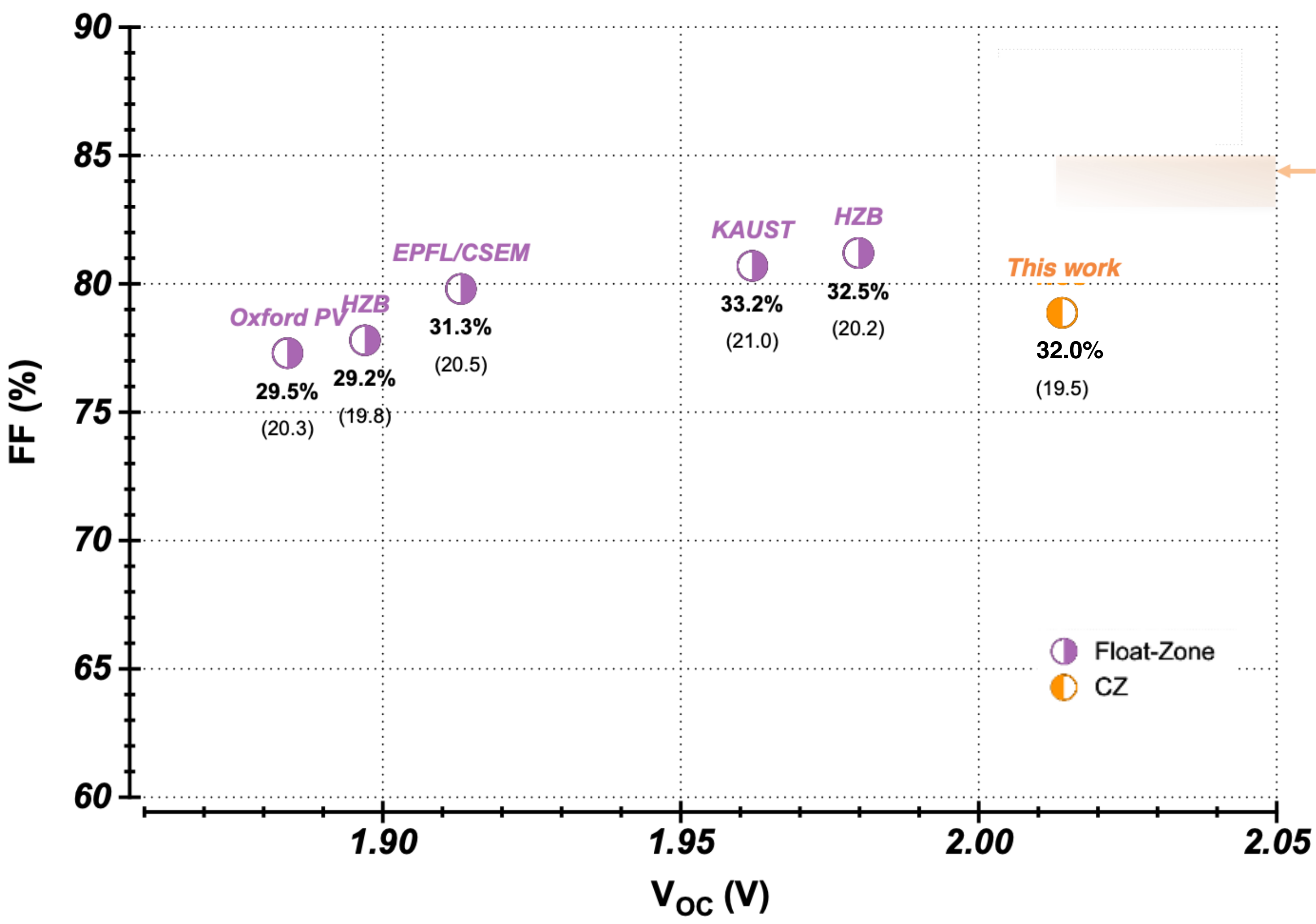
2. Lower absorption at NIR





Albrecht, S. et al. Solar RRL 5 (7), 2100244

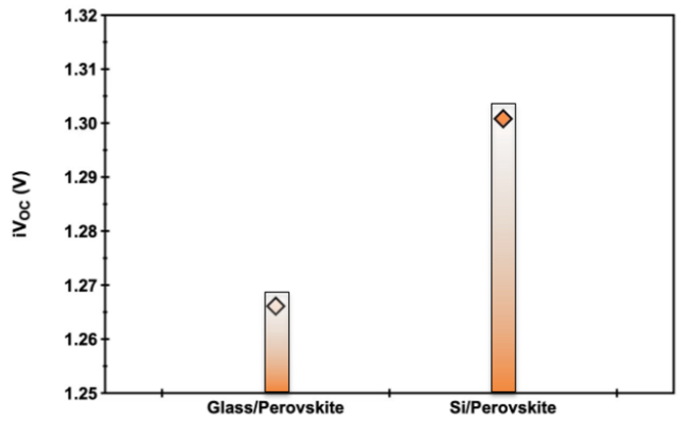
Where is the limit of perovskite/Si?



- Voc of perovskite: ~ 1.28 V
- Voc of shaded Si: ~ 0.72 V

Target zone

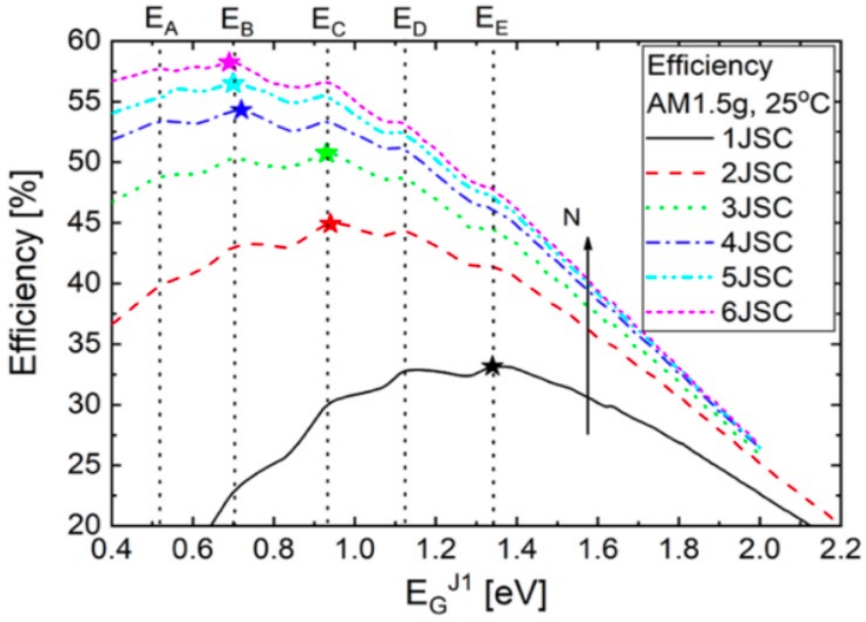
iVoc =1.30V (1.70 eV)

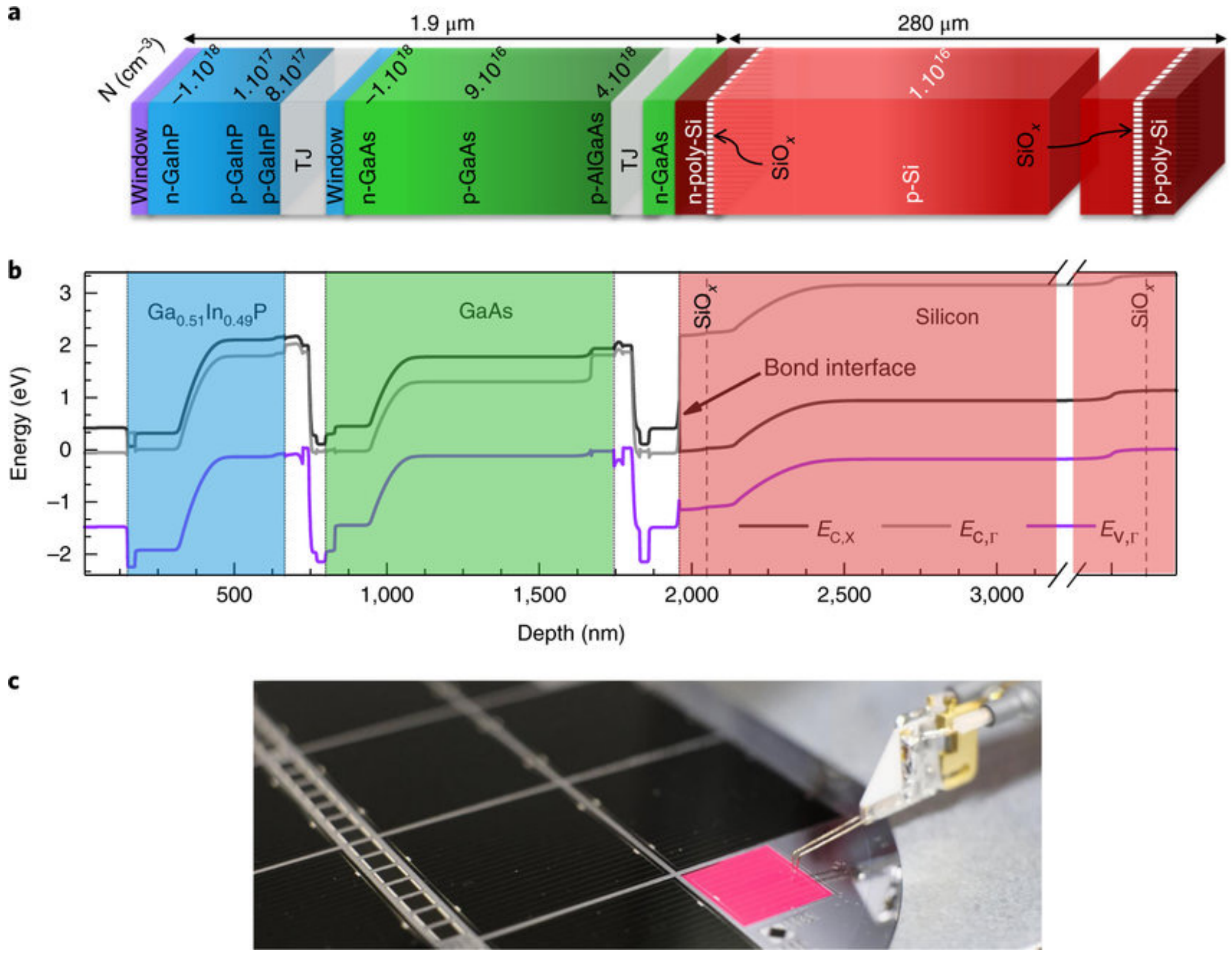


Achievable PCE:

2.05(Voc)*0.85(ff)*21(Jsc) = 36.5%(PCE)?

Triple-junction perovskite/perovskite/Si



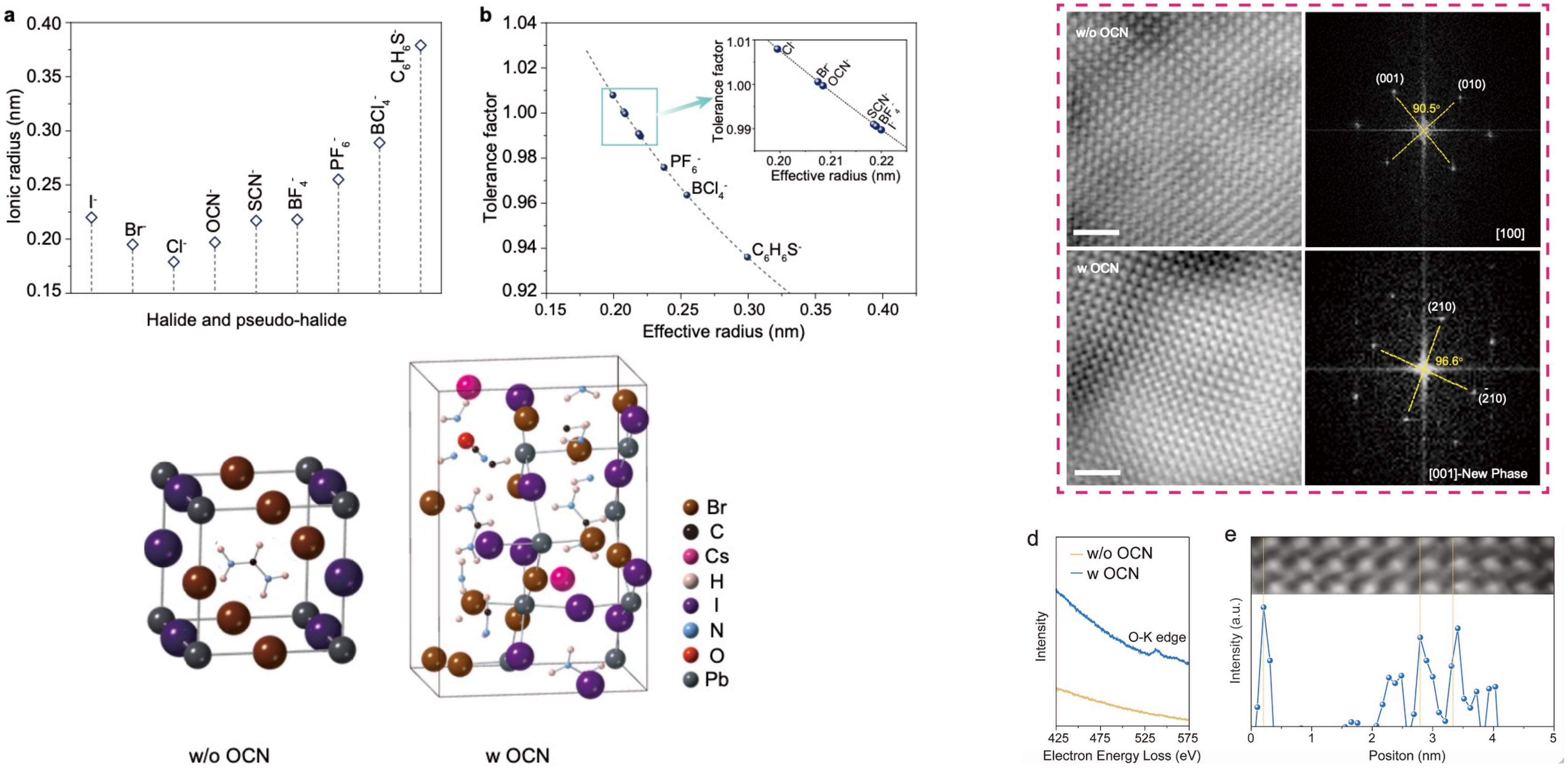


Perovskite/Si (1.7eV/1.1eV)

Perovskite/Perovskite/Si (1.9eV/1.5eV/1.1eV)

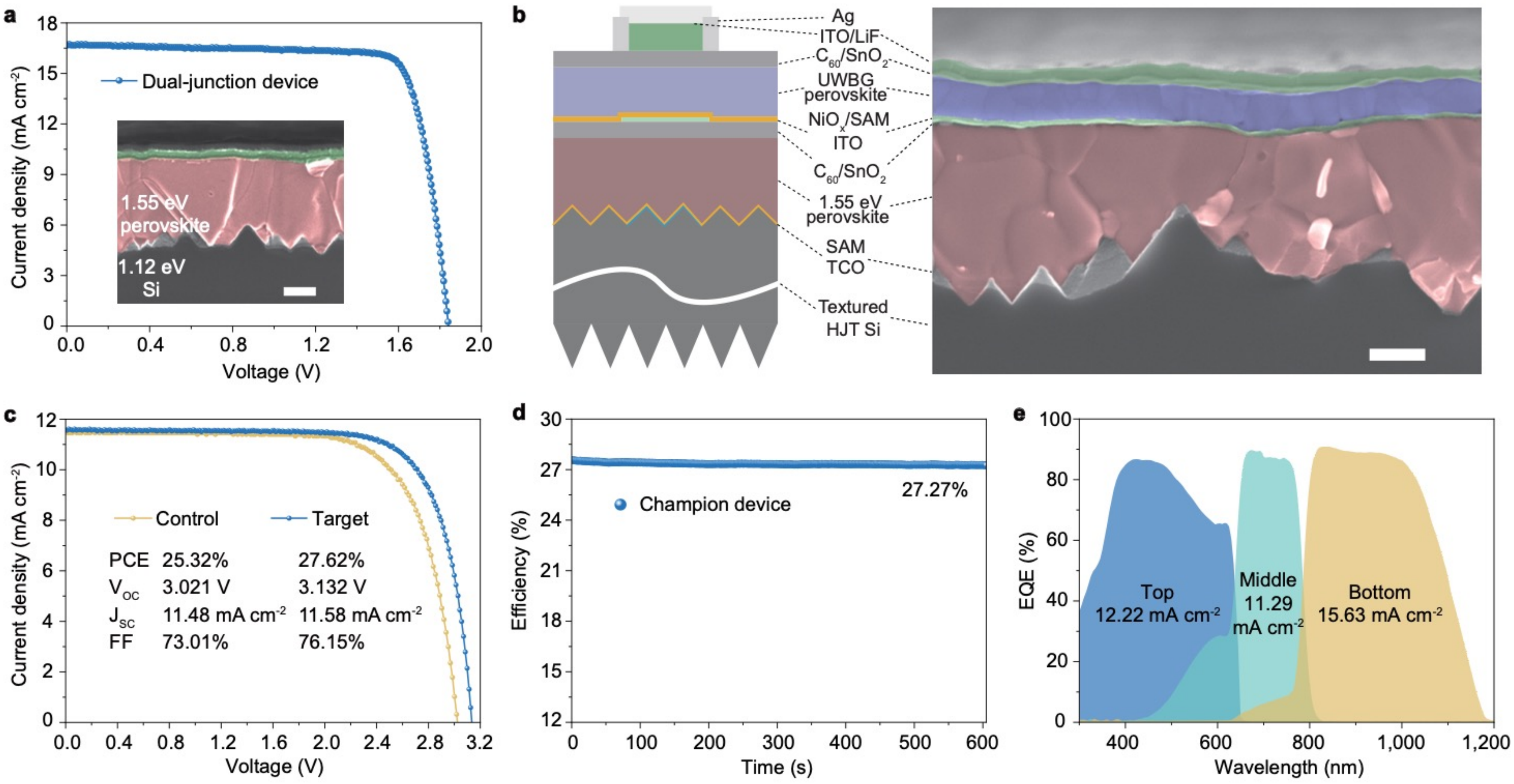
Liu, S., Lu, Y., ...Hou, Y. **Nature** (2024). DOI: 10.1038/s41586-024-07226-1

Triple-junction perovskite/perovskite/Si



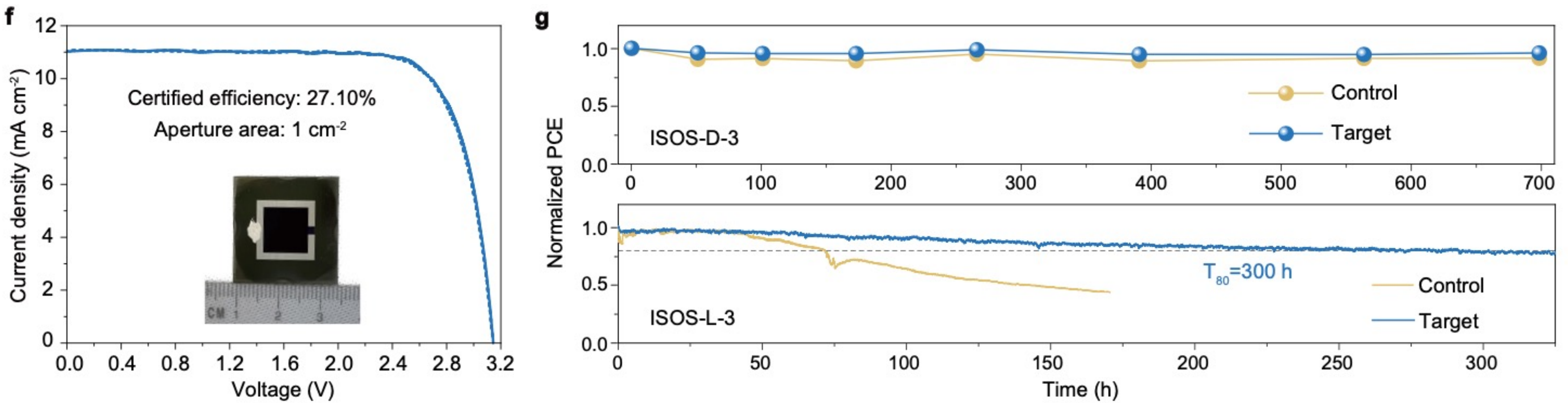
Liu, S., Lu, Y., ...Hou, Y. **Nature** (2024). DOI: 10.1038/s41586-024-07226-1

Triple-junction perovskite/perovskite/Si



Liu, S., Lu, Y., ...Hou, Y. **Nature** (2024). DOI: 10.1038/s41586-024-07226-1

Triple-junction perovskite/perovskite/Si

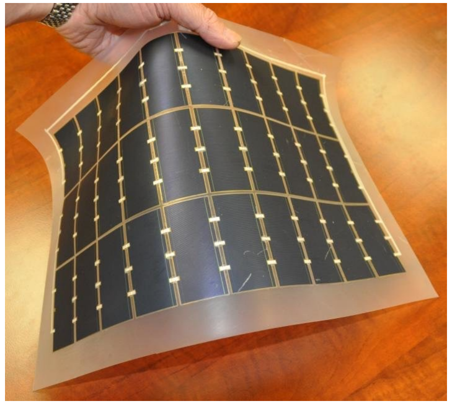


Liu, S., Lu, Y., ...Hou, Y. **Nature** (2024). DOI: 10.1038/s41586-024-07226-1

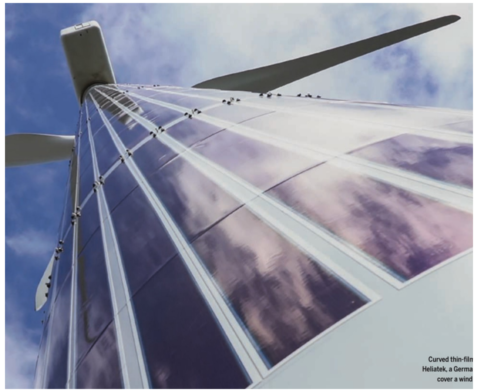
Centralized and decentralized PV

- *from PK/Si to PK-based thin-film tandems*

❑ III–V tandem (PCE = 30%)



❑ Organic tandem (PCE =10%)

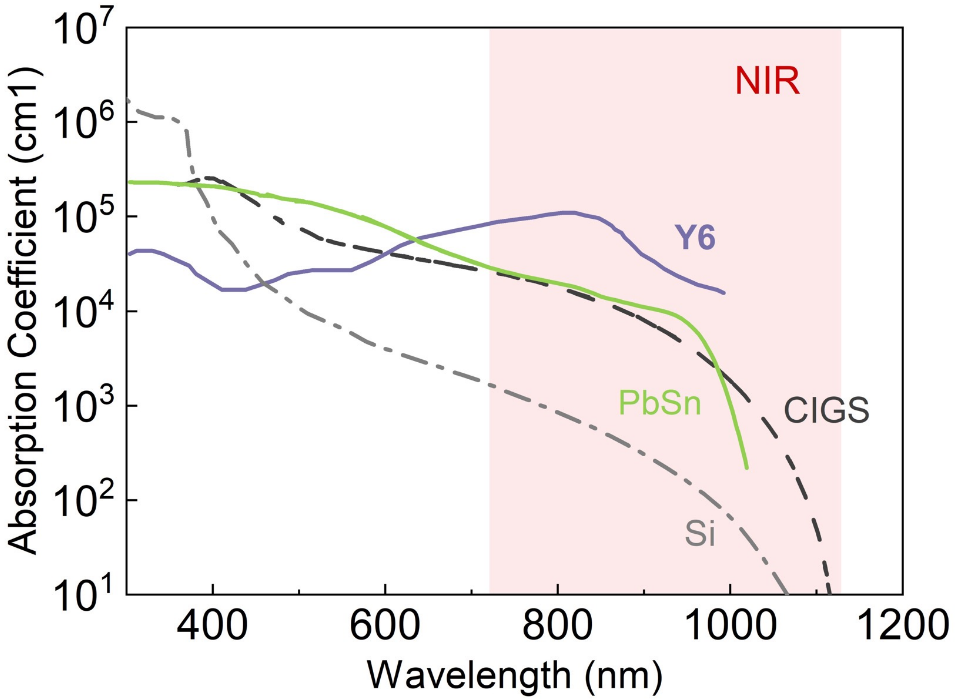


- ❑ Lightweight;
- ❑ Aesthetics;
- ❑ Efficient (>30%);
- ❑ Lifetime (~10 years)

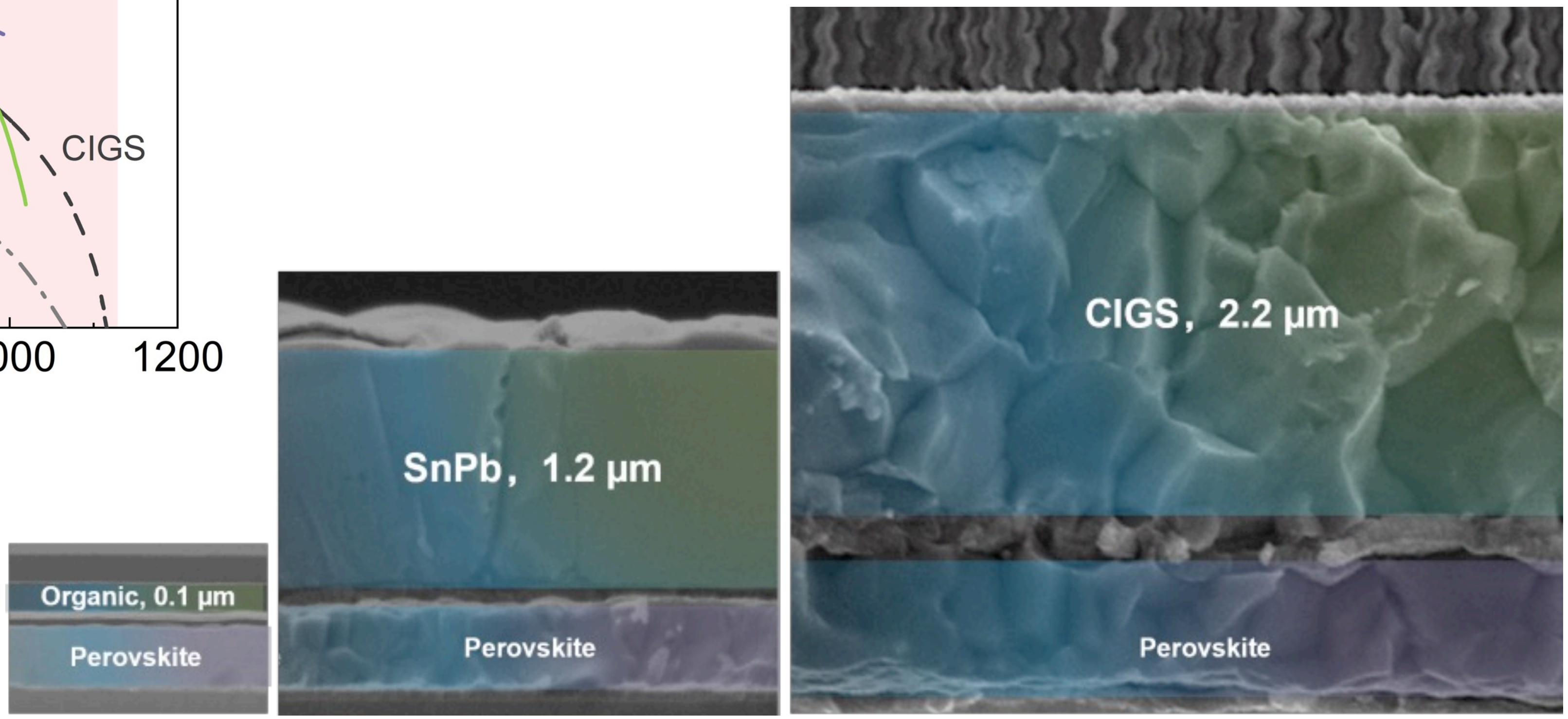
Thin-film-based tandem
(PCE = 30%)

Advanced Energy Materials, 11, 2002874 (2021); Energy Environ. Sci., 2014,7, 2925-2933

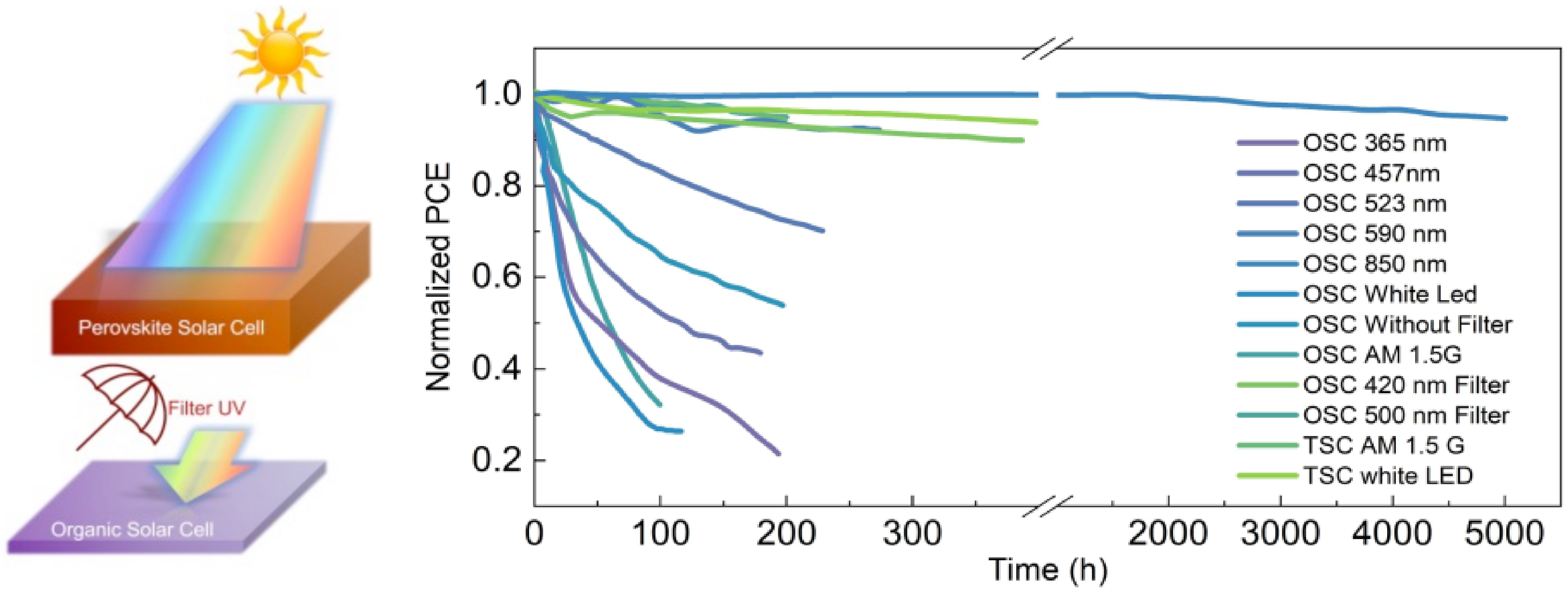
Integrating with other established thin-film PV technologies



- ❑ Organic materials are effective near-infrared (NIR) absorbers

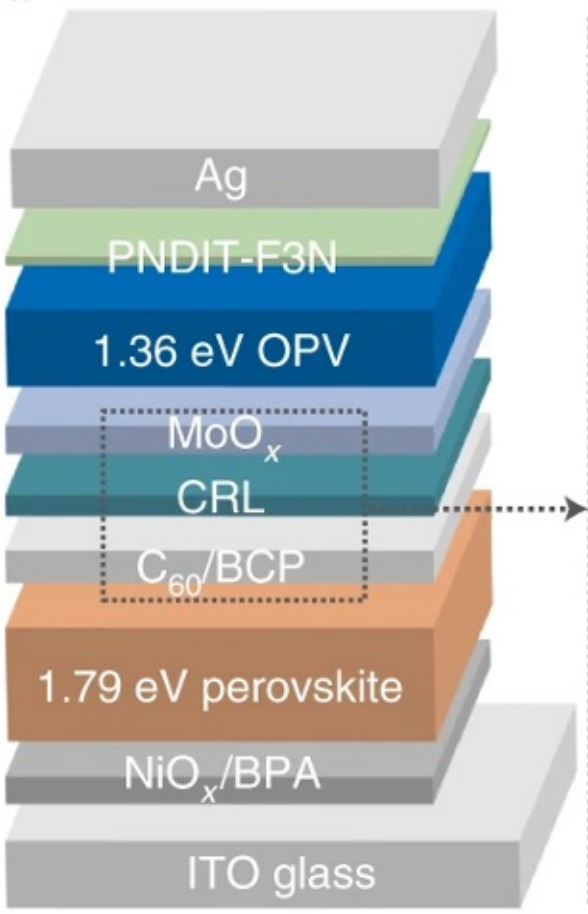


OPV becoming more stable in tandem configuration

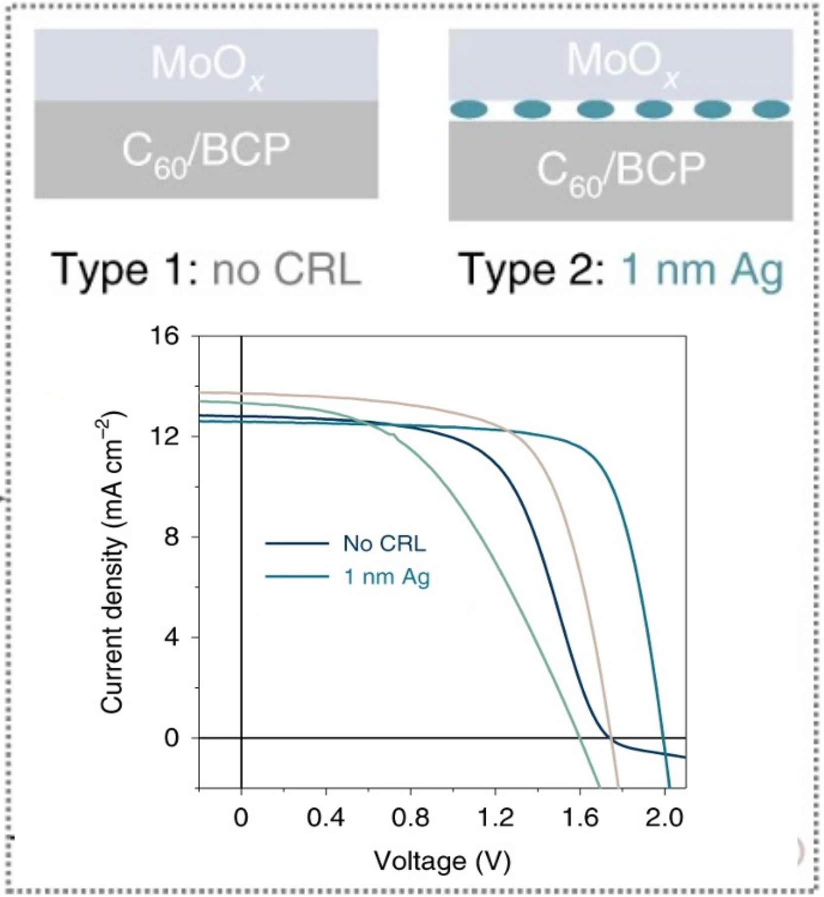


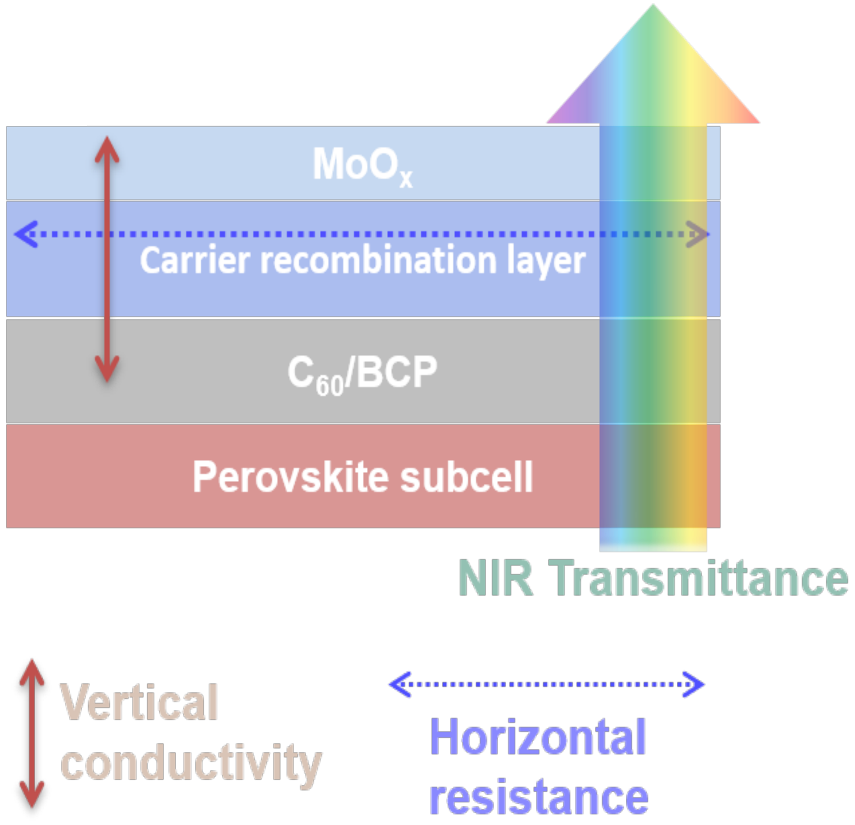
- ❑ Perovskite block all the high energy photons
- ❑ Organic materials are relatively stable under near-infrared light

First generation interconnecting layer (ICL)'s issues



First generation ICL

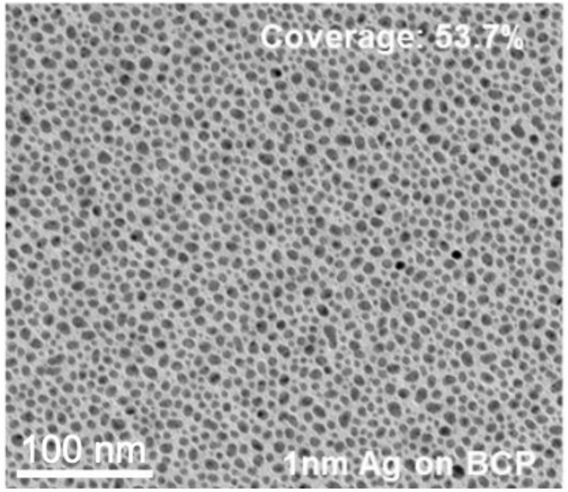


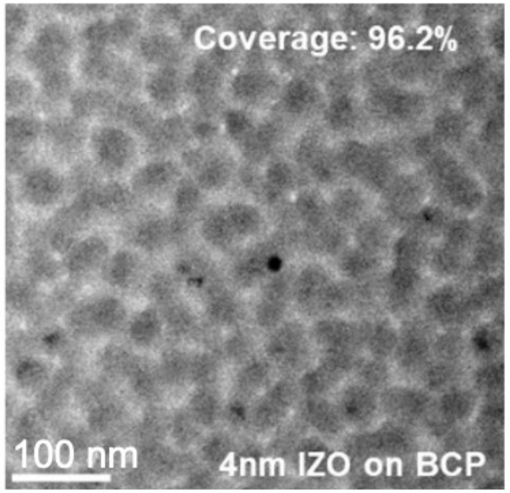


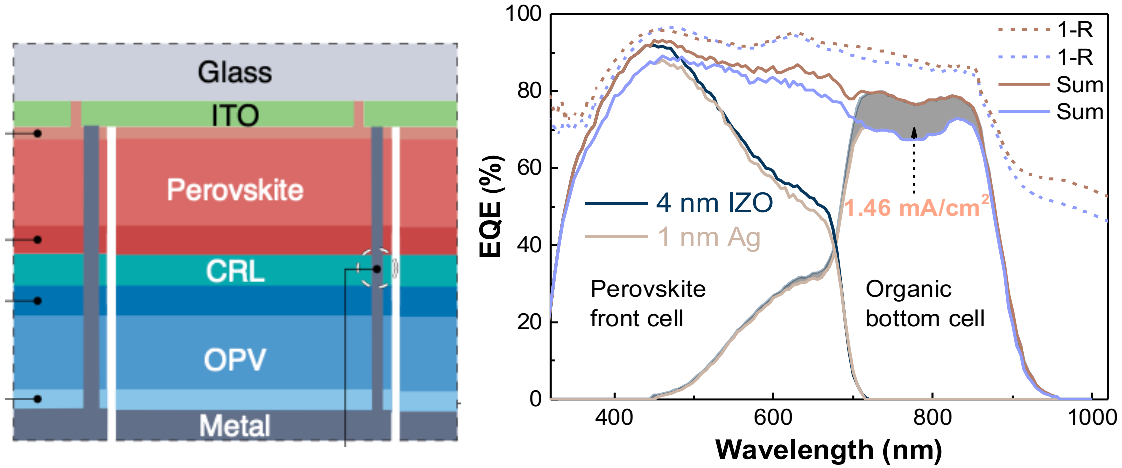
Chen, W...He, Z.;* Djurišić, A.;* Hou, Y.* **Nature Energy** 7, 229-237 (2022)

Second generation ICL – Ultrathin TCOs

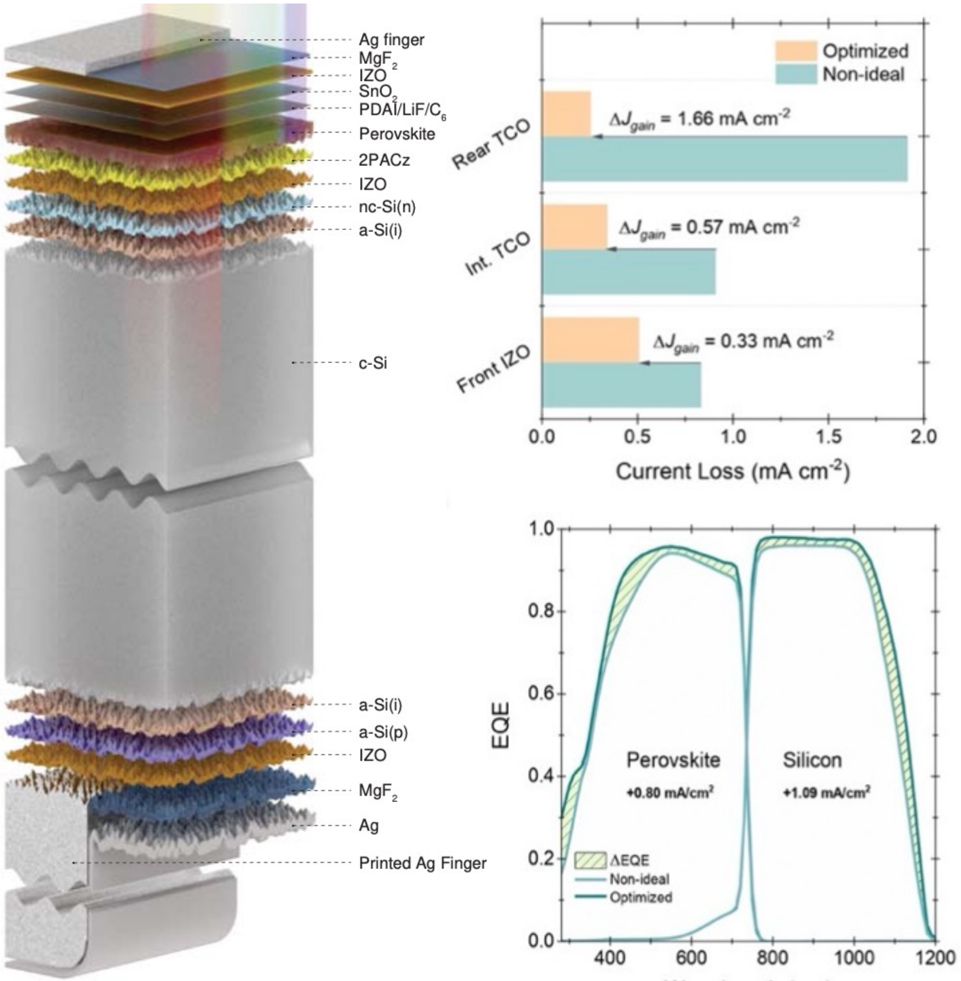
Perovskite/Organics







Perovskite/Si



Chen, W.; …He, Z.;* Djurišić, A.;* Hou, Y.* **Nature Energy** 7, 229-237 (2022)
Aydin, E.; Wolf, S. D. *et al.* **Nature**, DOI: 10.1038/s41586-023-06667-4 (2023)

Certified record efficient perovskite/organic tandem

Received: 12 May 2022 | Revised: 23 May 2022 | Accepted: 25 May 2022
DOI: 10.1002/pip.3595

SHORT COMMUNICATION

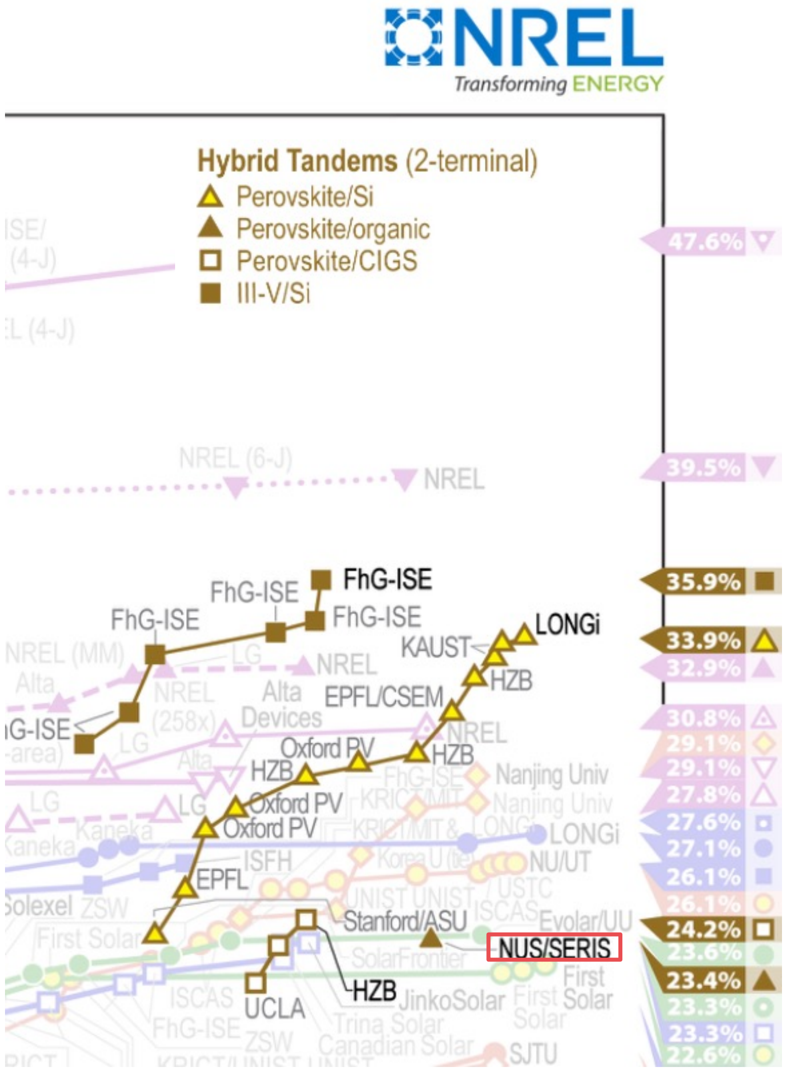
PROGRESS IN PHOTOVOLTAICS WILEY

Solar cell efficiency tables (Version 60)

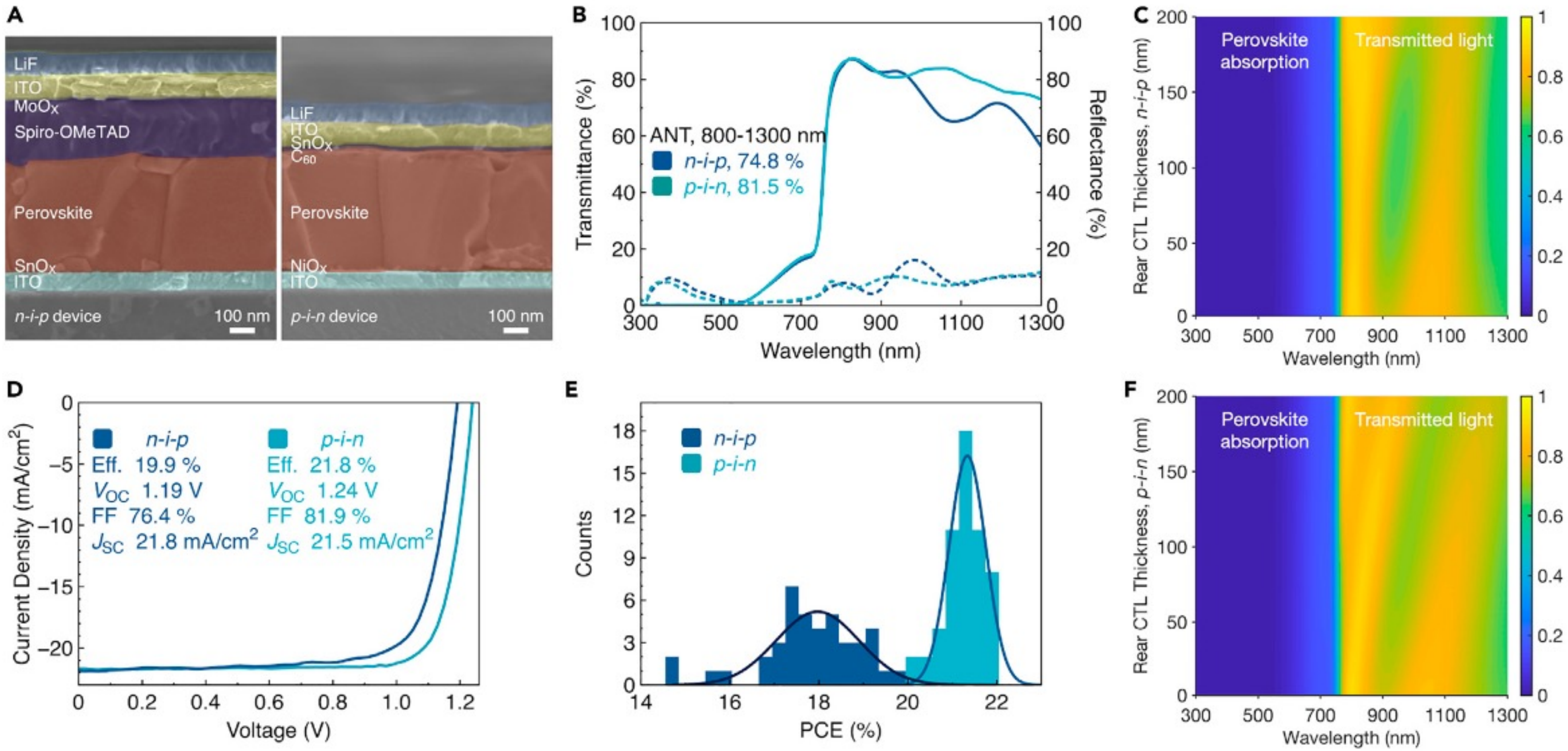
Martin A. Green[1] | Ewan D. Dunlop[2] | Jochen Hohl-Ebinger[3] | Masahiro Yoshita[4] | Nikos Kopidakis[5] | Karsten Bothe[6] | David Hinken[6] | Michael Rauer[3] | Xiaojing Hao[1]

TABLE 3 (Continued)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Perovskite/organic	23.4 ± 0.8[h]	0.0552 (da)	2.136	14.56[i]	75.6	JET (3/22)	NUS/SERIS, 2-term.[54]

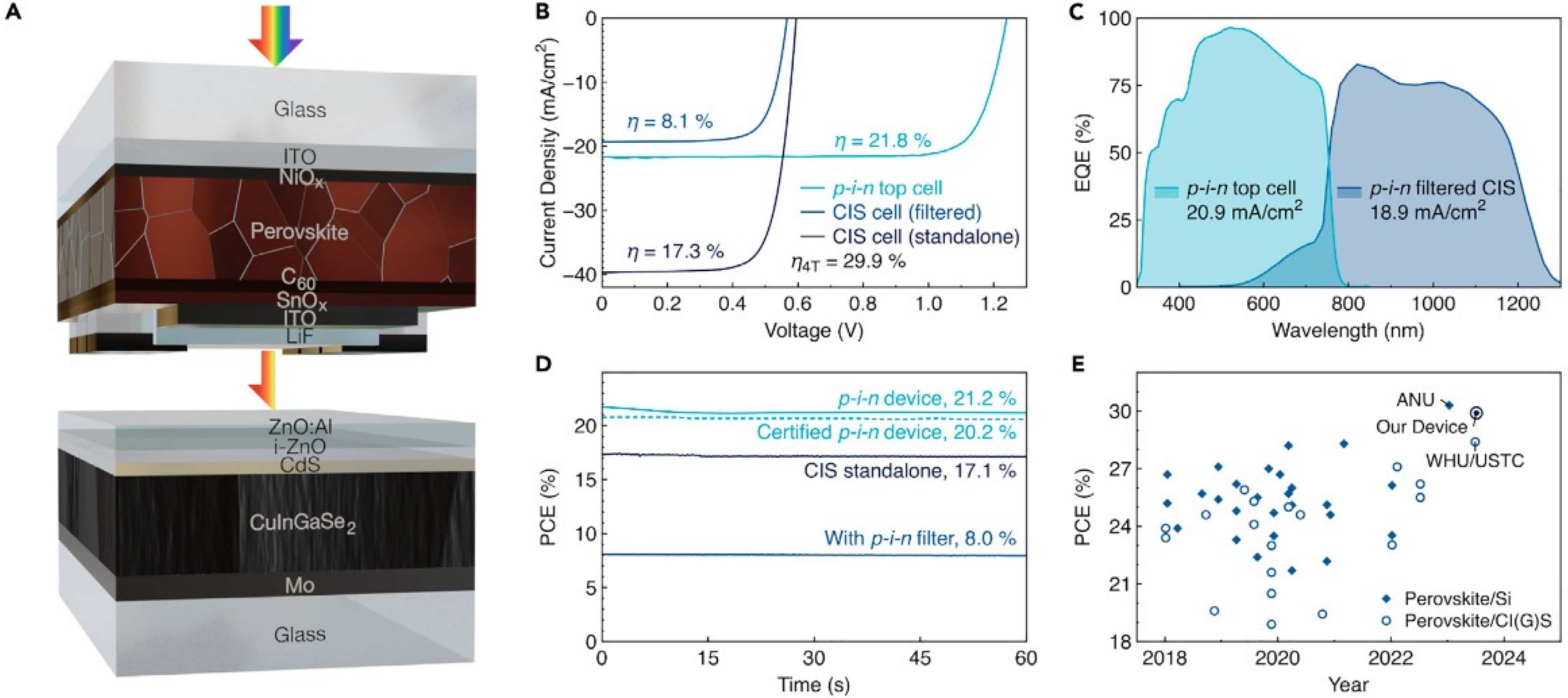


NIR light management by controlling interference spectrum



Liang, H.; … Fu, F.; Hou, Y. **Joule** 2023, 7, 1-14.

Performance of the perovskite/CIS tandem solar cell



Liang, H.; … Fu, F.; Hou, Y. **Joule** 2023, 7, 1-14.

NUS National University of Singapore | Department of Chemical & Biomolecular Engineering, College of Design and Engineering

NUS National University of Singapore | SERIS Solar Energy Research Institute of Singapore

Acknowledgment

Energy Market Authority
Smart Energy, Sustainable Future

EDB Singapore

Ministry of Education
SINGAPORE

National Research Foundation
Prime Minister's Office
Singapore

<u>Group members:</u>

Dr. Shunchang Liu
Dr. Zhenrong Jia
Dr. Xiuxiu Niu
Dr. Renjun Guo
Dr. Donny Lai
Dr. Wang Tao
Dr. Nengxu Li

Ezra Alvian (PhD student)
Haoming Liang (PhD student)
Zhuojie Shi (PhD student)
Xiao Guo (PhD student)
Xi Wang (PhD student)
Jinxi Chen (PhD student)
Yan Zhang (PhD student)
Ran Luo (PhD student)
Yuduan Wang (PhD student)
Zijing Dong (PhD student)
Qilin Zhou (PhD student)
Ling Kai Lee (PhD student)
Zhouyin Wei (PhD student)
Xin Meng (PhD student)
Xinyi Du (PhD student)
Xinyu Zhang (PhD student)