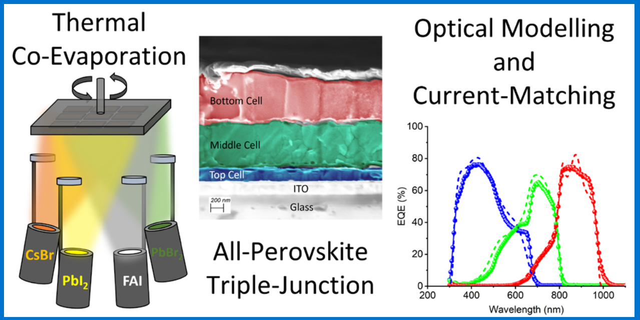
Thermal Co-evaporation for Multi-junction Perovskite Solar Cells



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Contents

Background

EDUCATION

University of New South Wales, Sydney, Australia
PhD in PV Eng.
JULY 2011 - JAN 2016
Doctoral Thesis: Transparent Conducting Aluminium Doped Zinc Oxide for Silicon Quantum Dot Solar Cell Devices in Third Generation Photovoltaics.
Joint Supervisors: Prof. Gavin Conibeer and Dr. Ivan Perez-Wurfl
Co-supervisor: Prof. Martin Green

University of New South Wales, Sydney, Australia
BEng (1st Class Hons.) in PV and Solar Energy Eng.
FEB 2007 - NOV 2010
Honours Thesis: 46% Efficient Split Spectrum Cells Project - Tandem Cell Spectral Response Characterization
Supervisor: Prof. Martin Green

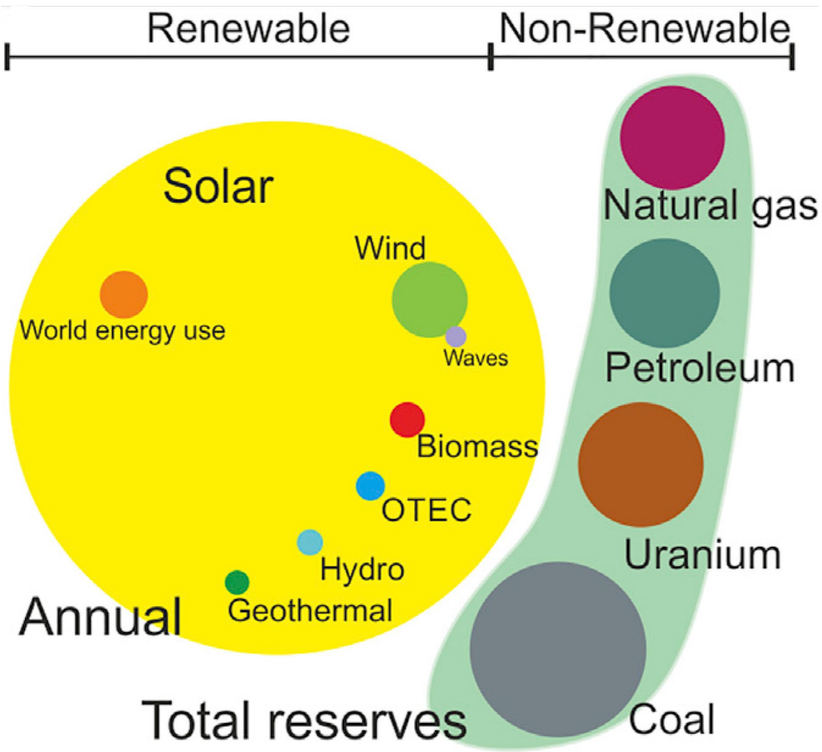
RESEARCH EXPERIENCE

University of Cambridge, Cambridge, UK
Marie Skłodowska-Curie Postdoctoral Fellow
JUL 2021 – JUN 2023
H2020 MSCA Postdoctoral Fellowship (2019). "Lightweight and Flexible All-Perovskite Triple-junction Solar Cells" (acronym PeTSoC). I was also the group manager at the lab (50+ researchers) which involved people management; supervision; running meetings; onboarding new researchers, visitors and students.
Supervisor: Prof. Sam Stranks

CSIRO Energy, Newcastle, Australia
Office of the Chief Executive (OCE) Postdoctoral Fellow
AUG 2019 – MAY 2021
Research and development of perovskite-silicon tandem solar cell technology.
Supervisors: Dr. Noel Duffy and Dr. Gregory Wilson

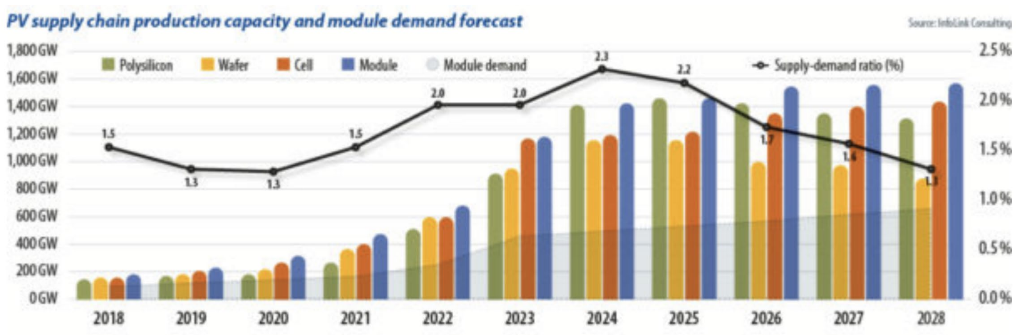
EPFL, Neuchâtel, Switzerland
Marie Skłodowska-Curie Postdoctoral Fellow
JUN 2017 – MAY 2019
H2020 MSCA Postdoctoral Fellowship (2016). "High Performance Wide Bandgap and Stable Perovskite-on-Silicon Tandem Solar Cells" (acronym POSITS).
Supervisors: Dr. Quentin Jeangros, Dr. Björn Niesen, and Prof. Christophe Ballif

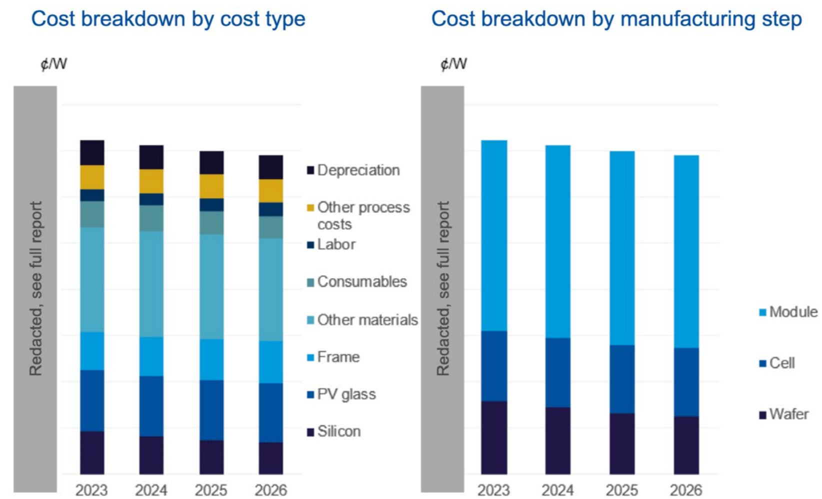
Solar Energy Production



- Anaya, M. *et al.* Joule, 1(4), 769–793 (2017)
- Adapted from Perez, R., and Perez, M. A fundamental look at supply side energy reserves for the planet. IEA/SHC Solar Update 62, 4–6 (2015).

Decrease in Silicon Solar Module Price





DATA: Exawatt. Based on a manufacturing integrated from ingot to module (i.e., manufacturing ingots, wafer, cells and modules in-house); assumes bifacial TOPCon, dual-glass, M10 wafers

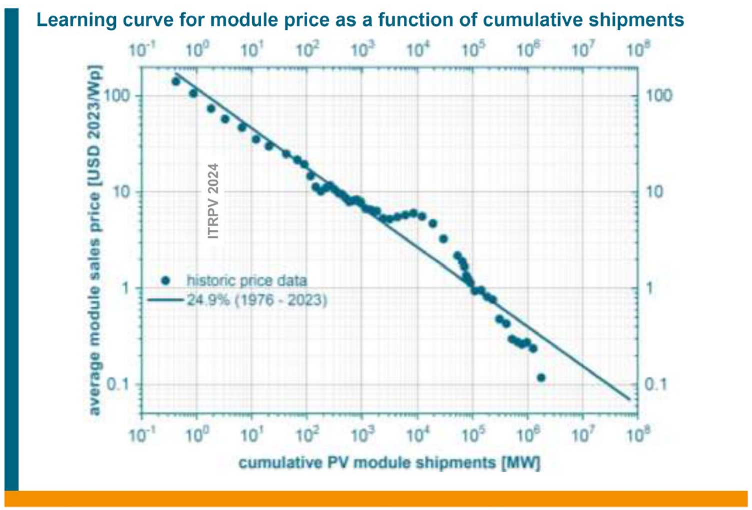


Fig. 1: Learning curve for module spot market price as a function of cumulative PV module shipments.

- Global PV module manufacturing capacity **1.49 TW** (1.19 TW China).
- Spot price of PV modules less than **$US 0.010 / W**
- Improve module area **efficiency** without dramatic increase in cost.

- Solar manufacturing slows in bid to balance supply and demand. (2025, March 05). Retrieved from https://www.pv-magazine-australia.com/2024/12/07/solar-manufacturing-slows-in-bid-to-balance-supply-and-demand
- VDMA - International Technology Roadmap for Photovoltaics (2024)
- 182*182-210mm Mono TOPCon Module (USD) https://www.infolink-group.com/spot-price/ Accessed: 10/02/2025
- 'Sustainable' module prices unlikely to fall further. (2025, March 05). Retrieved from https://www.pv-magazine.com/2024/02/20/sustainable-module-prices-unlikely-to-fall-further

Trends in Commercial PV Technology

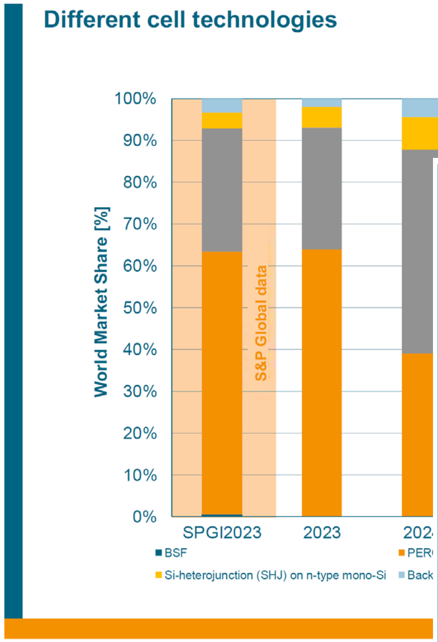


Fig. 37: Market shares for different cell technologies. S&P Glob

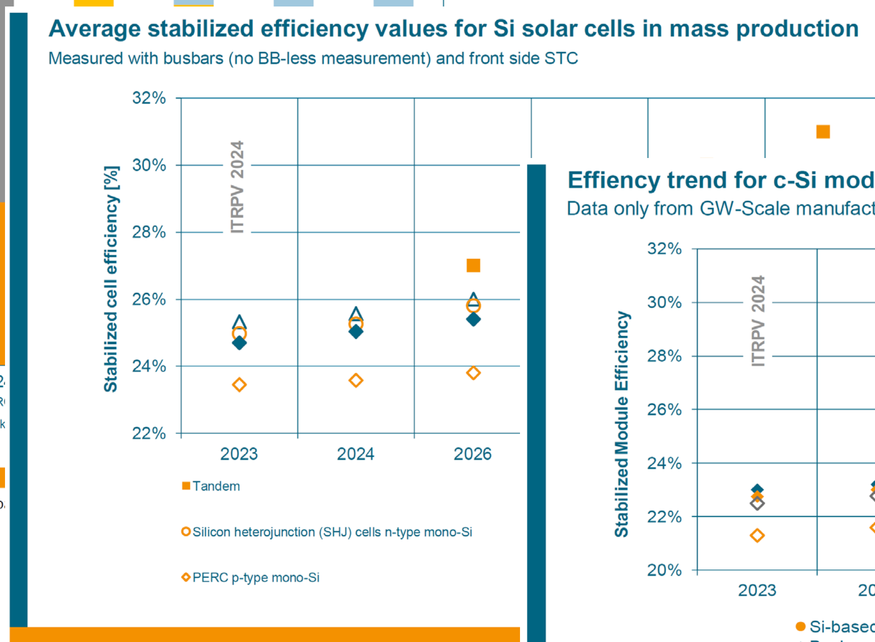


Fig. 40: Average stabilized efficiency values of c-Si solar cells in mass produ

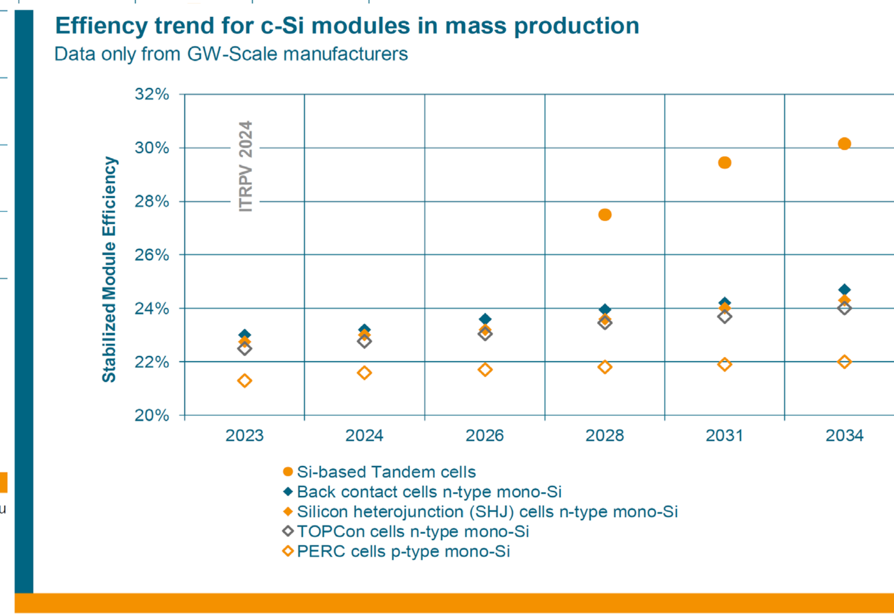


Fig. 59: Average module area efficiency in mass production for different c-Si solar cell technologies (Only data from GW-scale manufacturers).

Tandem or Multi-junction Solar Cells

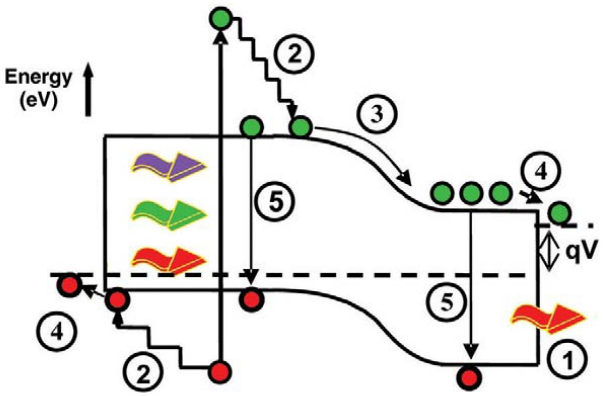
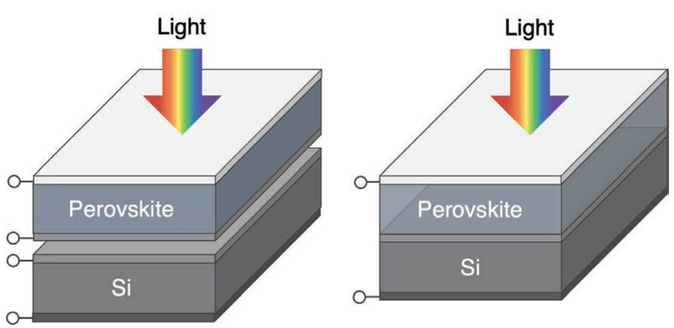


Fig. 2 Loss processes in a standard solar cell: (1) nonabsorption of below-bandgap photons; (2) lattice thermalization loss; (3) and (4) junction and contact voltage losses; (5) recombination loss (radiative recombination is unavoidable).

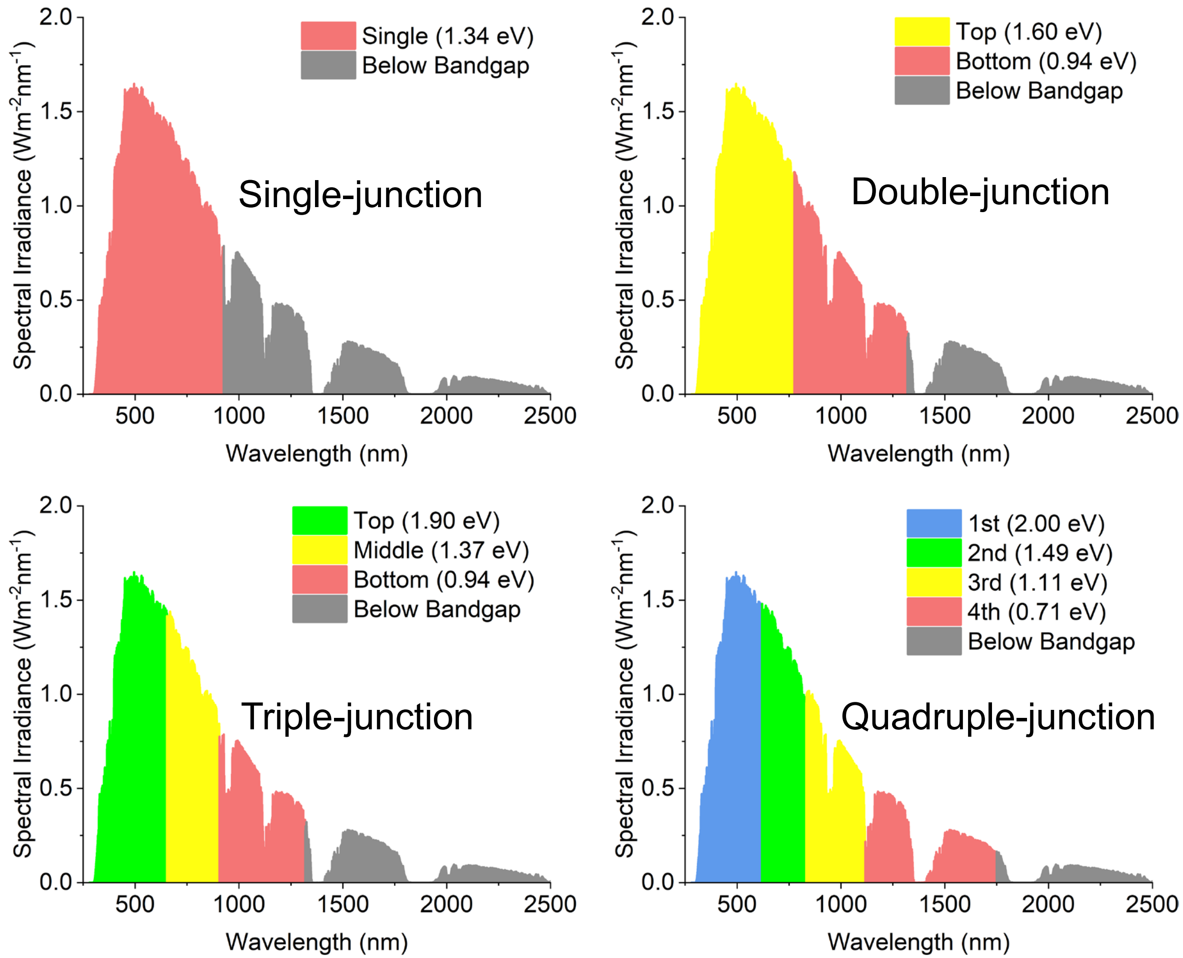


4-terminal

Mechanically stacked

2-terminal

Monolithic (series-connected)



- Conibeer, G. (2007). Third-generation photovoltaics. Mater. Today, 10(11), 42–50.
- Fu, F., Li, J., Yang, T. C.-J., Liang, H., Faes, A., Jeangros, Q., Ballif, C., Hou, Y., Monolithic Perovskite-Silicon Tandem Solar Cells: From the Lab to Fab?. Adv. Mater., 34, 2106540 (2022).

Efficiency Limit of 2T Monolithic Multi-junction Solar Cells

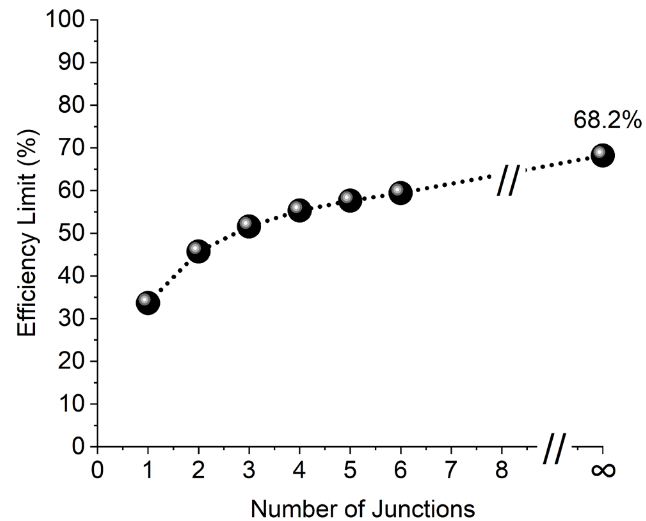
Table 5.1: Limiting efficiencies and optimal bandgaps for a range of tan(Marti and Araujo 1996; Brown 2002).

No. of Cells	Description	Optimal Bandgaps (eV)				
		E1	E2	E3	E4	E5
1	Diffuse	1.31				
	Direct	1.11				
2	Diffuse, series connected	0.97	1.70			
	Diffuse, unconstrained	0.98	1.87			
	Direct, series connected	0.77	1.55			
	Direct, unconstrained	0.77	1.70			
3	Diffuse, series connected	0.82	1.30	1.95		
	Diffuse, unconstrained	0.82	1.44	2.26		
	Direct, series connected	0.61	1.15	1.82		
	Direct, unconstrained	0.62	1.26	2.10		

Table 1. The optimal set of bandgaps in unconcentrated sunlight.

n	η (%)	E_{g1} (eV)	E_{g2} (eV)
1	30	1·3	—
2	42	1·9	1·0
3	49	2·3	1·4
4	53	2·6	1·8

Table 3



1 sun no angular restiction	No	–	–	–	–	69.9
Maximum concentration	Yes	–	–	–	–	86.8
Maximum concentration	No	–	–	–	–	86.8
M1.5 direct normal irradiance)						
1 sun, no angular restriction	Yes	1.13	–	–	–	32.5
1 sun no angular restiction	No	1.13	–	–	–	32.5
Maximum concentration	Yes	0.94	–	–	–	44.6
Maximum concentration	No	0.94	–	–	–	44.6
1 sun, no angular restriction	Yes	0.94	1.64	–	–	44.3
1 sun no angular restiction	No	0.94	1.64	–	–	44.1
Maximum concentration	Yes	0.71	1.41	–	–	59.7
Maximum concentration	No	0.71	1.41	–	–	59.4
1 sun, no angular restriction	Yes	0.71	1.16	1.83	–	50.1
1 sun no angular restiction	No	0.71	1.16	1.83	–	49.7
Maximum concentration	Yes	0.69	1.16	1.84	–	67.0
Maximum concentration	No	0.69	1.16	1.83	–	66.6
1 sun, no angular restriction	Yes	0.71	1.13	1.55	2.13	54.0
1 sun no angular restiction	No	0.71	1.13	1.55	2.13	53.6
Maximum concentration	Yes	0.53	1.13	1.55	2.13	71.0
Maximum concentration	No	0.53	1.13	1.55	2.13	70.7
1 sun, no angular restriction	Yes	–	–	–	–	65.4
1 sun no angular restiction	No	–	–	–	–	65.4
Maximum concentration	Yes	–	–	–	–	85.0
Maximum concentration	No	–	–	–	–	85.0

Table I. Summary of results for constrained and unconstrained solar cell stacks under the AM1.5G spectrum for 1x concentration and under maximum concentration. T band gap values shown correspond to the optimum combinations for the 1x AM1.5G case.

E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	η (%)	E_1	E_2	E_3	E_4	E_5	E_6	E_7	E_8	η (%)
Unconstrained AM1.5G Spectrum									*Constrained AM1.5G spectrum*								
1.34	—	—	—	—	—	—	—	33.68	1.34	—	—	—	—	—	—	—	33.68
0.94	1.73	—	—	—	—	—	—	46.06	0.94	1.60	—	—	—	—	—	—	45.71
0.93	1.40	2.05	—	—	—	—	—	51.94	0.94	1.37	1.90	—	—	—	—	—	51.58
0.70	1.13	1.64	2.23	—	—	—	—	55.91	0.71	1.11	1.49	2.00	—	—	—	—	55.31
0.69	0.98	1.38	1.81	2.40	—	—	—	58.37	0.70	1.01	1.33	1.67	2.14	—	—	—	57.61
0.69	0.94	1.19	1.53	1.92	2.45	—	—	59.93	0.69	0.96	1.20	1.47	1.79	2.24	—	—	59.41
0.69	0.94	1.15	1.41	1.72	2.11	2.57	—	61.36	0.69	0.93	1.14	1.37	1.60	1.90	2.33	—	60.78
0.51	0.70	0.94	1.15	1.41	1.73	2.11	2.57	62.34	0.51	0.75	0.98	1.18	1.40	1.63	1.92	2.35	61.42
Unconstrained maximum concentration									*Constrained maximum concentration*								
1.11	—	—	—	—	—	—	—	40.74	1.11	—	—	—	—	—	—	—	40.74
0.77	1.70	—	—	—	—	—	—	55.80	0.76	1.54	—	—	—	—	—	—	55.47
0.62	1.26	2.10	—	—	—	—	—	63.75	0.60	1.14	1.82	—	—	—	—	—	63.15
0.52	1.03	1.61	2.41	—	—	—	—	68.67	0.49	0.93	1.38	2.01	—	—	—	—	67.85
0.45	0.88	1.34	1.88	2.65	—	—	—	72.00	0.44	0.81	1.17	1.58	2.18	—	—	—	71.02
0.40	0.78	1.17	1.60	2.12	2.87	—	—	74.41	0.38	0.71	1.01	1.33	1.72	2.30	—	—	73.33
0.36	0.70	1.04	1.40	1.81	2.32	3.06	—	76.22	0.37	0.66	0.92	1.18	1.48	1.85	2.42	—	75.09
0.33	0.64	0.94	1.25	1.59	1.98	2.47	3.20	77.63	0.30	0.60	0.83	1.06	1.29	1.57	1.96	2.50	76.19

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- Brown, A. S., & Green, M. A. Limiting efficiency for current-constrained two-terminal tandem cell stacks. Prog. Photovoltaics Res. Appl., 10(5) (2002).
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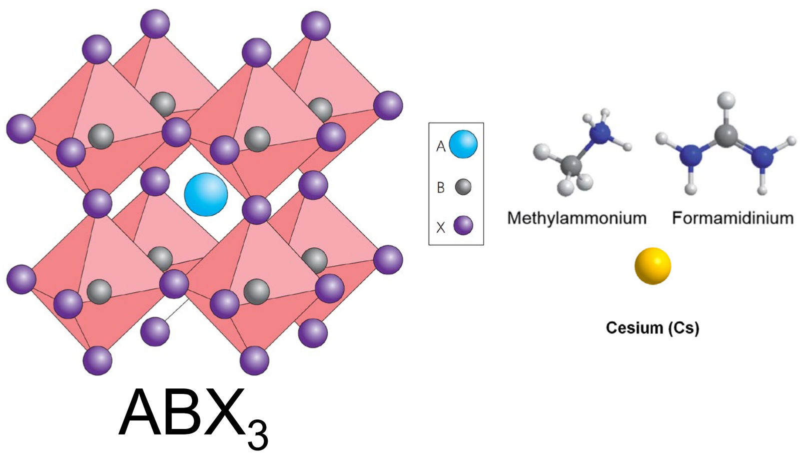
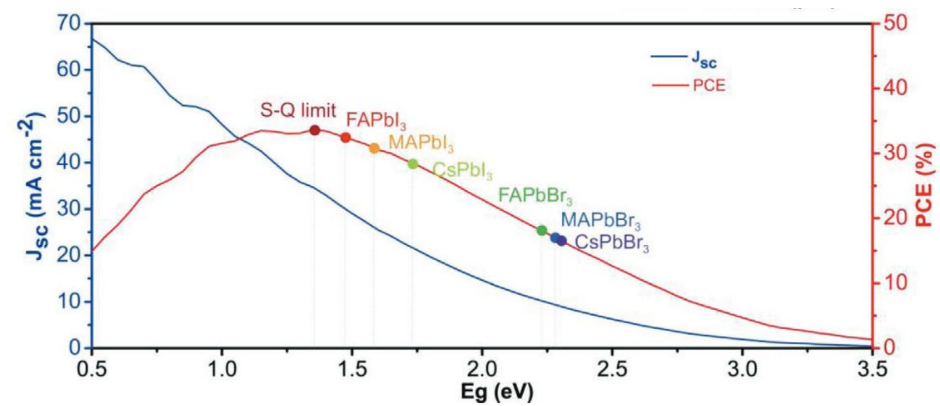
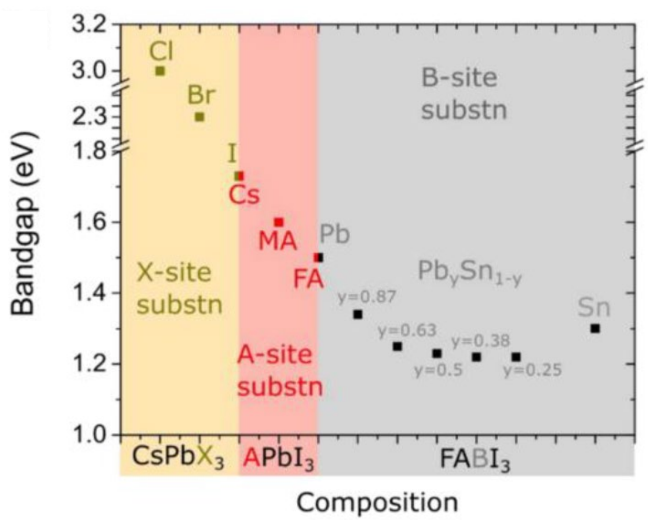
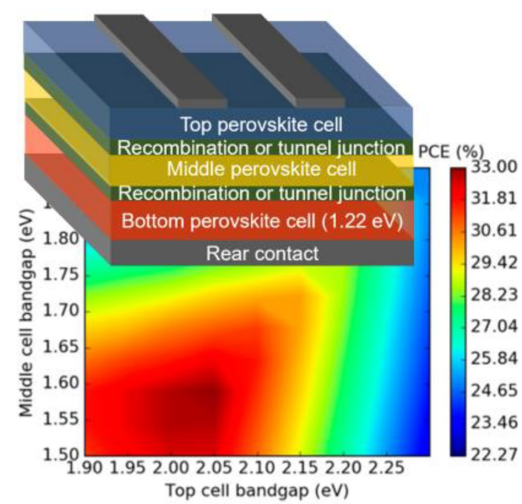
- Bremner, S. P., Levy, M. Y., & Honsberg, C. B. Prog. Photovoltaics Res. Appl., 16(3), 225–233 (2008)

Bandgap Tunability of Perovskites









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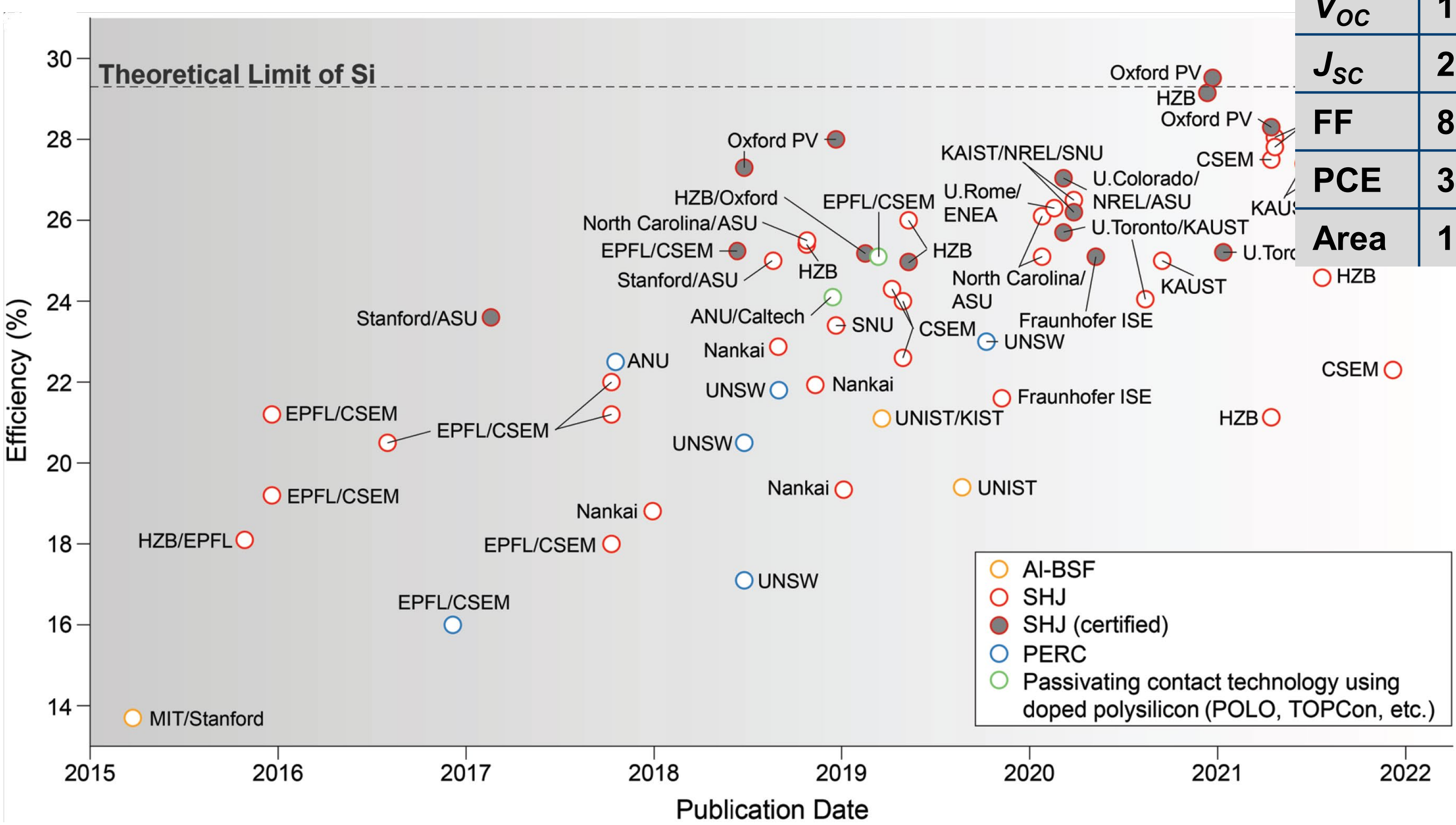
- Eperon, G.E., Hörantner, M.T., & Snaith, H.J. Nat. Rev. Chem., 1(0095), 1–18 (2017)
- Yang, T.C.J. MSCA Actions PeTSoC-891205 (2020)
- Adapted from Hörantner, M. T. et al. ACS Energy Lett., 2(10), 2506–2513 (2017).

Review of Monolithic Perovskite-Silicon Tandems

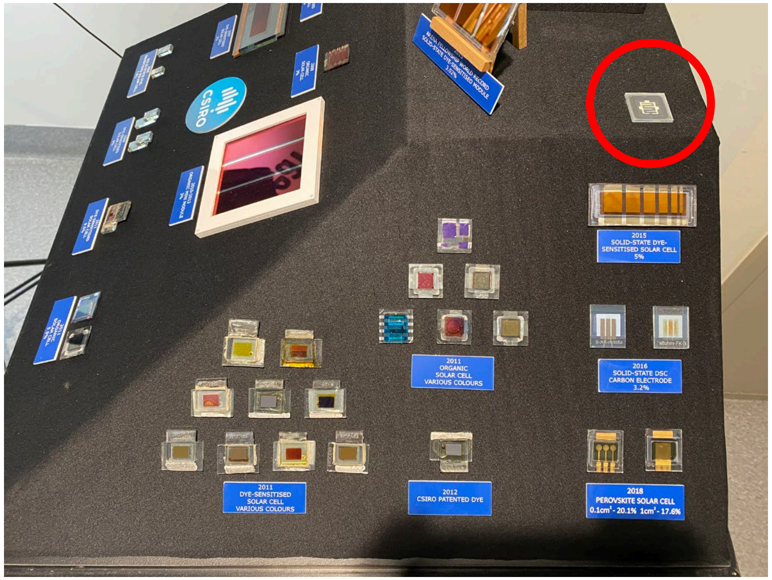
Longi

V_{OC}	1.996 V
J_{SC}	20.7 mA/cm²
FF	83.6%
PCE	34.6%
Area	1.004 cm²



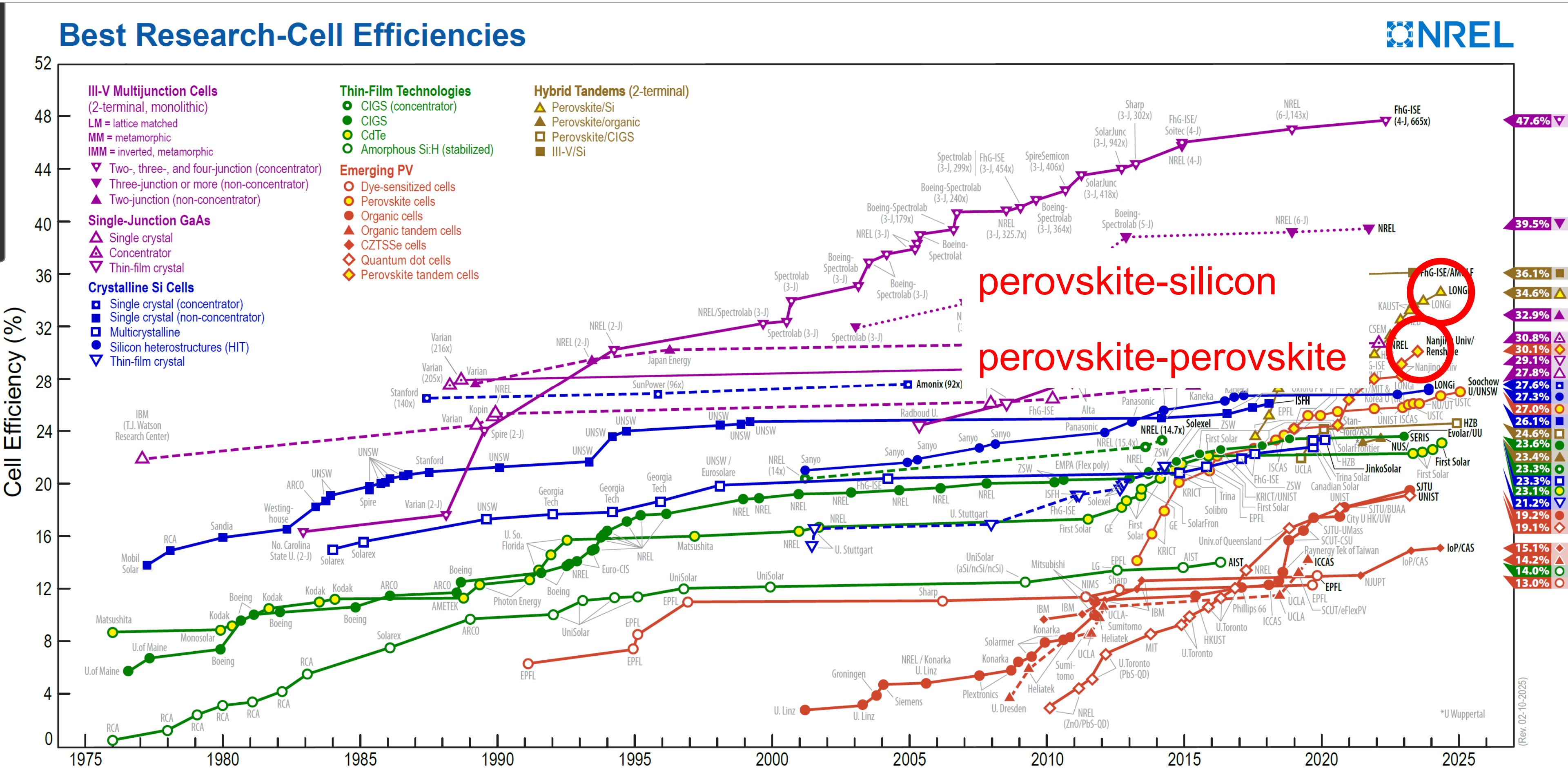
- Fu, F., Li, J., Yang, T. C.-J., Liang, H., Faes, A., Jeangros, Q., Ballif, C., Hou, Y., Monolithic Perovskite-Silicon Tandem Solar Cells: From the Lab to Fab?. Adv. Mater., 34, 2106540 (2022).

CSIRO Perovskite-Silicon Tandems



CSIRO’s first Perovskite-PERC Tandem Solar Cells (2020)

NREL Solar Cell Efficiency Chart



- NREL Best Research-Cell Efficiencies Chart (Downloaded 02/03/2025) https://www.nrel.gov/pv/cell-efficiency.html

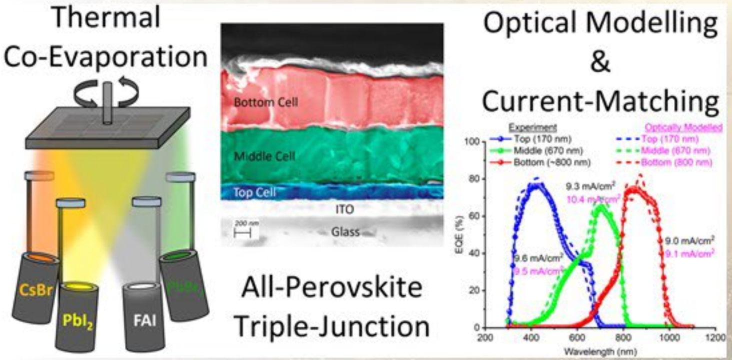
Recent Work on Triple-junction Perovskites

Incorporating thermal co-evaporation in current-matched all-perovskite triple-junction solar cells

Terry Chien-Jen Yang, Taeheon Kang, Melissa Fitzsimmons, Guadalupe Vega, Yang Lu, Leo Rosado, Alberto Jiménez-Solano, Linfeng Pan, Szymon J. Zelewski, Jordi Ferrer Orri, Yu-Hsien Chiang, Dengyang Guo, Zher Ying Ooi, Yutong Han, Weidong Xu, Bart Roose, Caterina Ducati, Sol Carretero Palacios, Miguel Anaya and Samuel D. Stranks

EES Sol., 2025, Advance Article. DOI: 10.1039/D4EL00012A

Featured in
EES Solar



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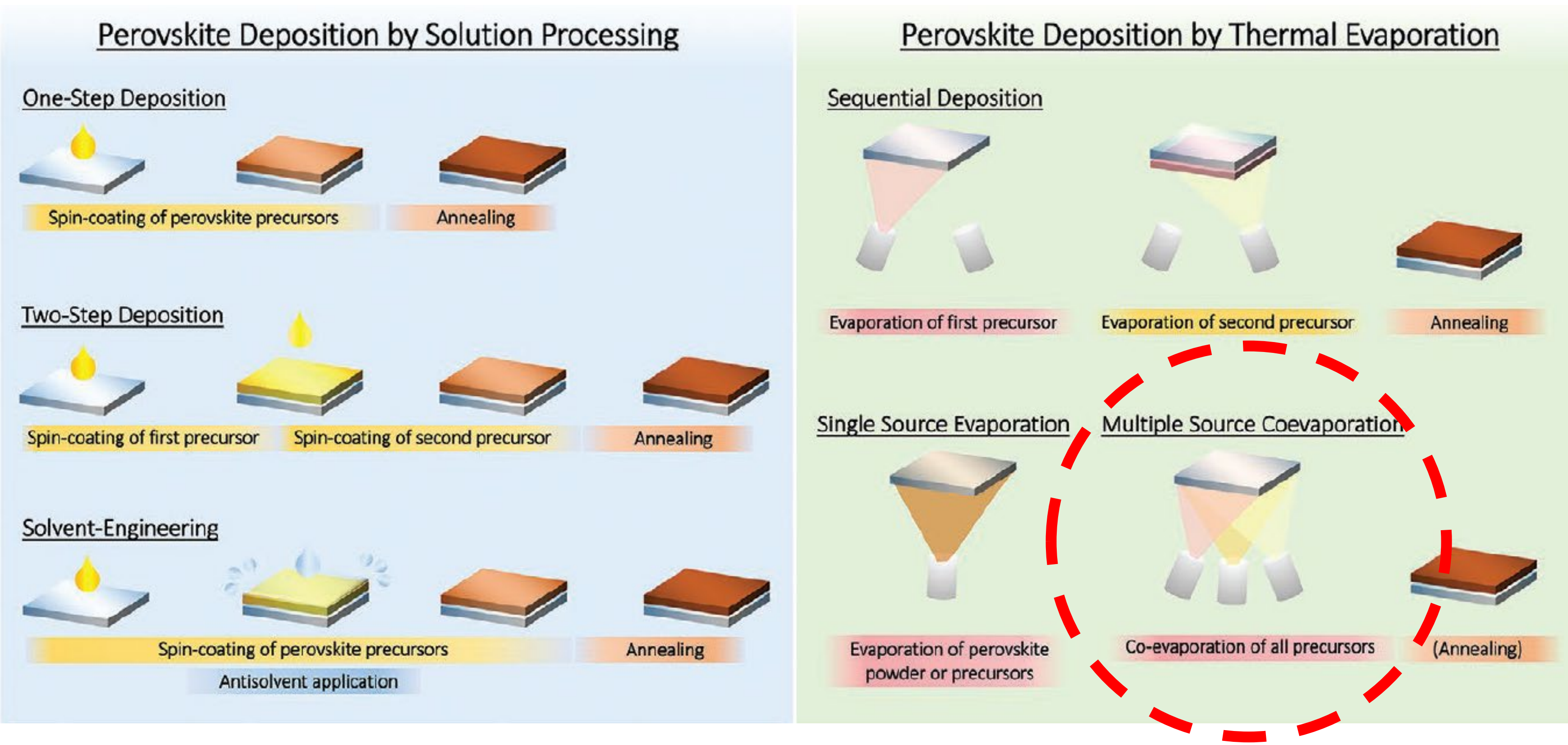
Perovskite Deposition by Solution vs Thermal Evaporation



- Vaynzof, Y., *Adv. Energy Mater.* 10, 2003073 (2020)

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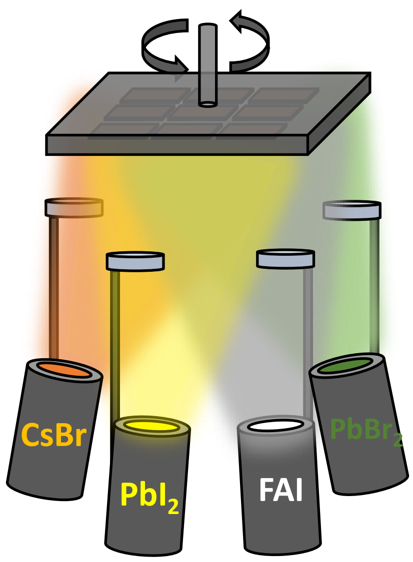
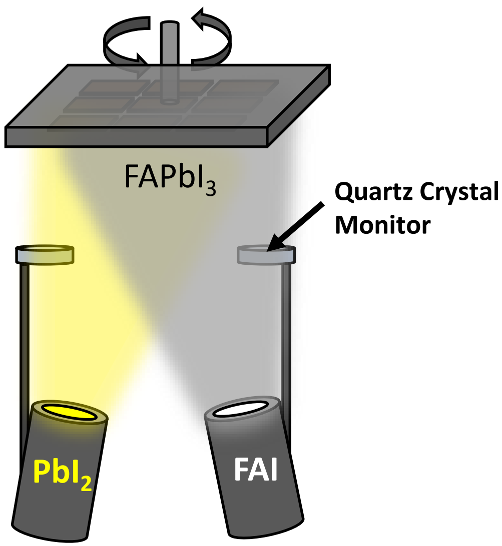
The Three Perovskite Active Layers in the Triple-junction Solar Cell

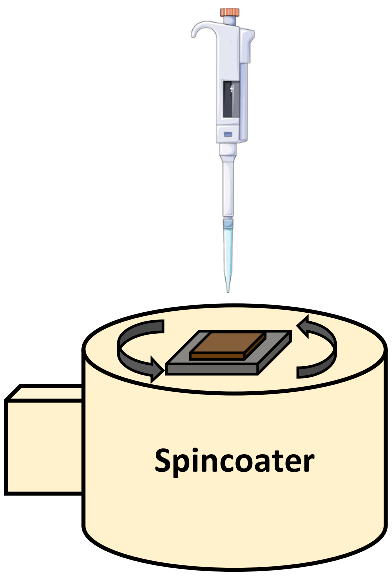
Top Subcell
$Cs_{0.3}FA_{0.7}Pb(I_{0.56}Br_{0.44})_3$



Middle Subcell
$FAPbI_3$

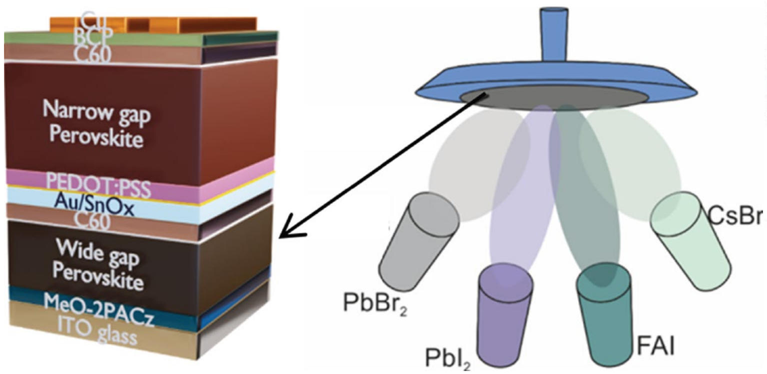


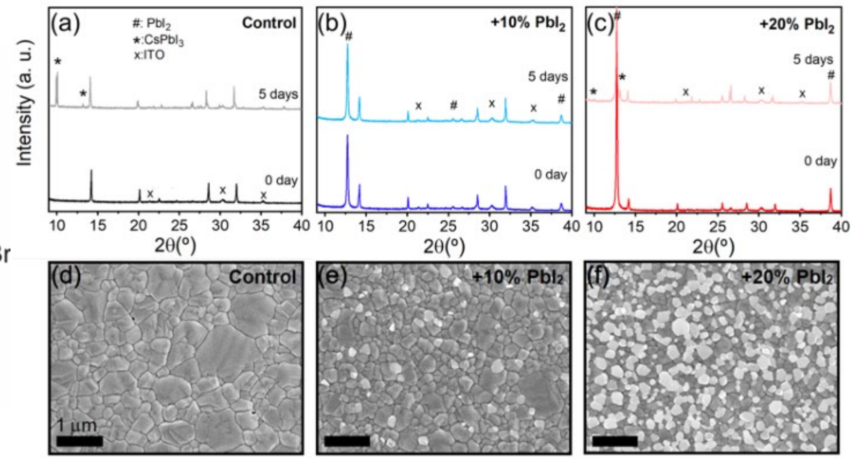
Bottom Subcell
$Cs_{0.25}FA_{0.75}Pb_{0.5}Sn_{0.5}I_3$



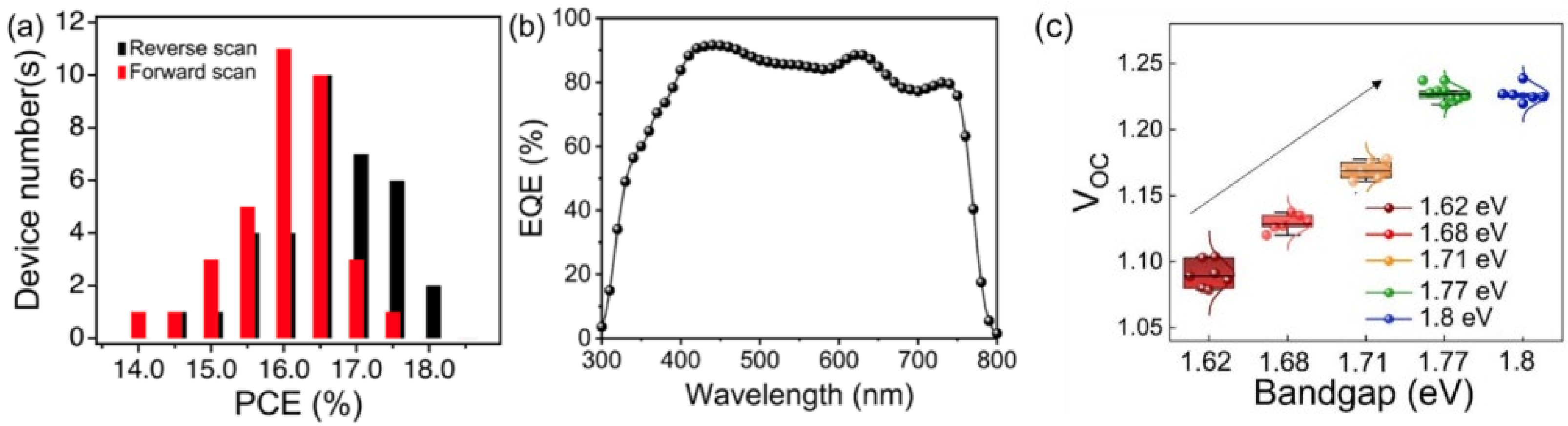
Yang, T. C.-J., Kang, T., Stranks, S. D. et al. Incorporating thermal co-evaporation in current-matched all-perovskite triple-junction solar cells. *EES Sol.* (2025) https://doi.org/10.1039/D4EL00012A

Co-evaporated $Cs_{0.3}FA_{0.7}Pb(Br_{0.1}I_{0.9})_3$ Perovskite Solar Cells





Dr. Y.H. Chiang



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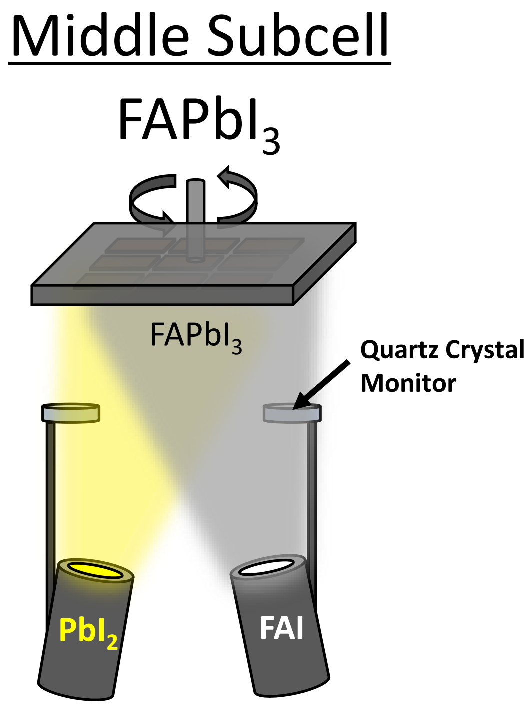
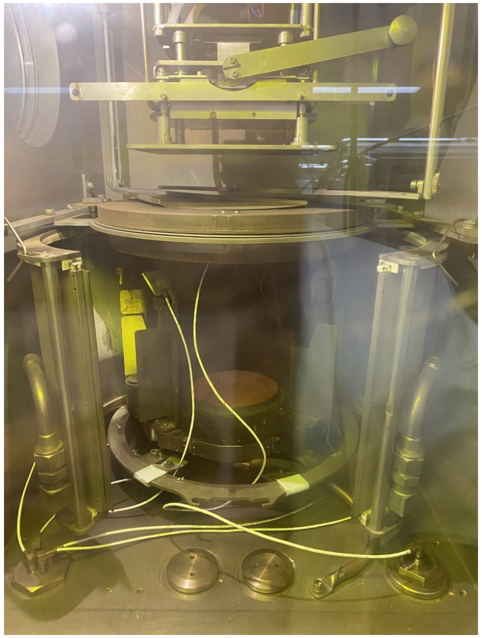
- Chiang, Y.-H. et al.. ACS Energy Lett., 8(6), 2728–2737 (2023)

$FAPbI_3$ Co-evaporation

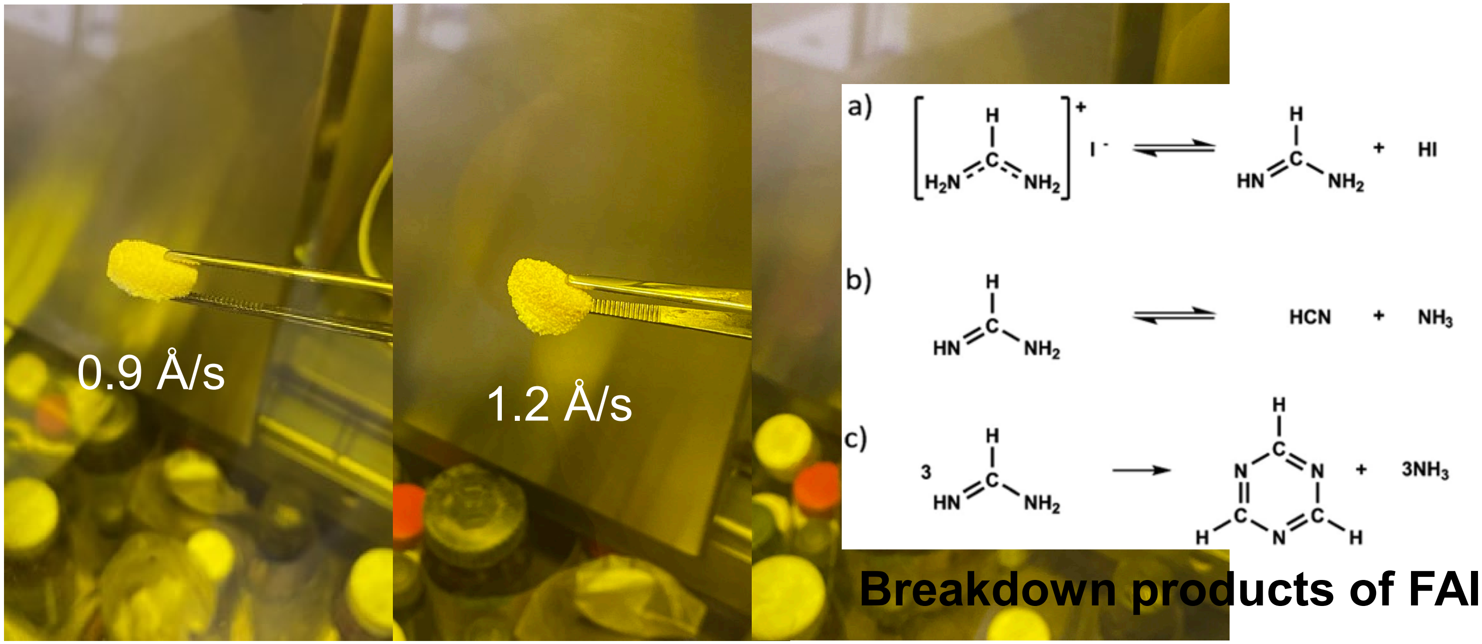




Thermal co-evaporator

Yang, T. C.-J., Kang, T., Stranks, S. D. et al. Incorporating thermal co-evaporation in current-matched all-perovskite triple-junction solar cells. *EES Sol.* (2025) https://doi.org/10.1039/D4EL00012A

Issues with FAI Decomposition

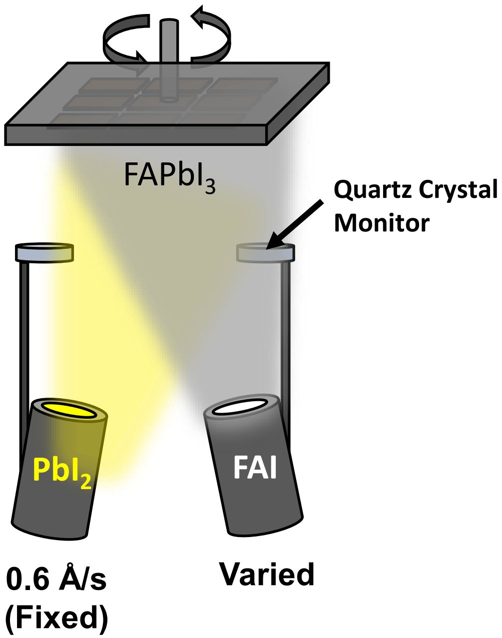


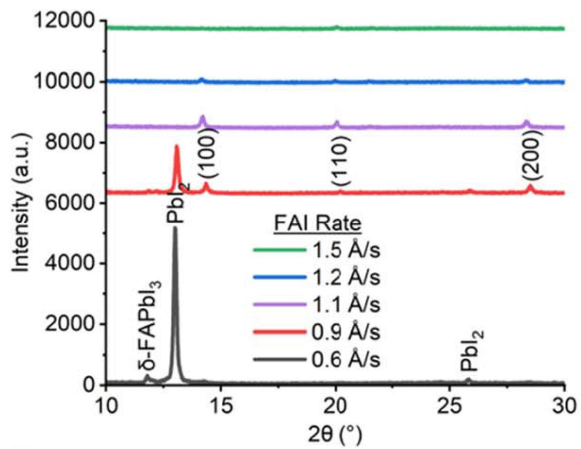
Breakdown products of FAI

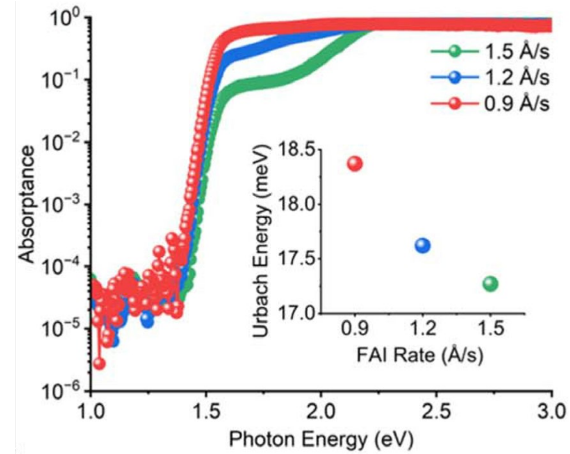
FAI powder after evaporation

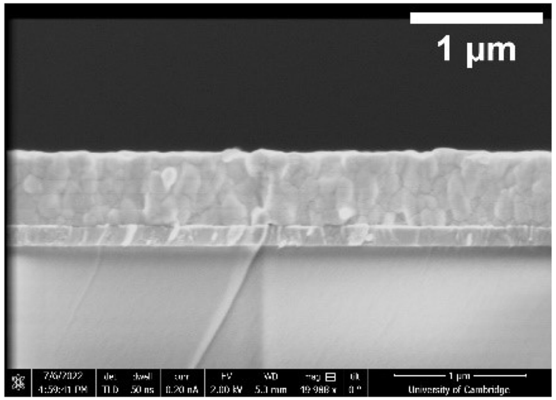
- Kroll, *et al. Sustainable Energy Fuels*, 2022,6, 3230-3239

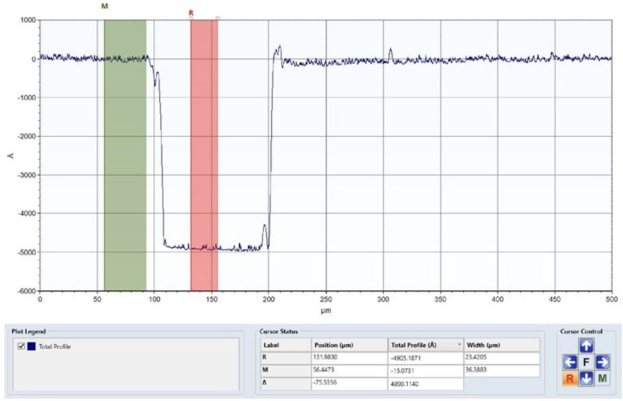
FAI Rate on $FAPbI_3$ Material Quality











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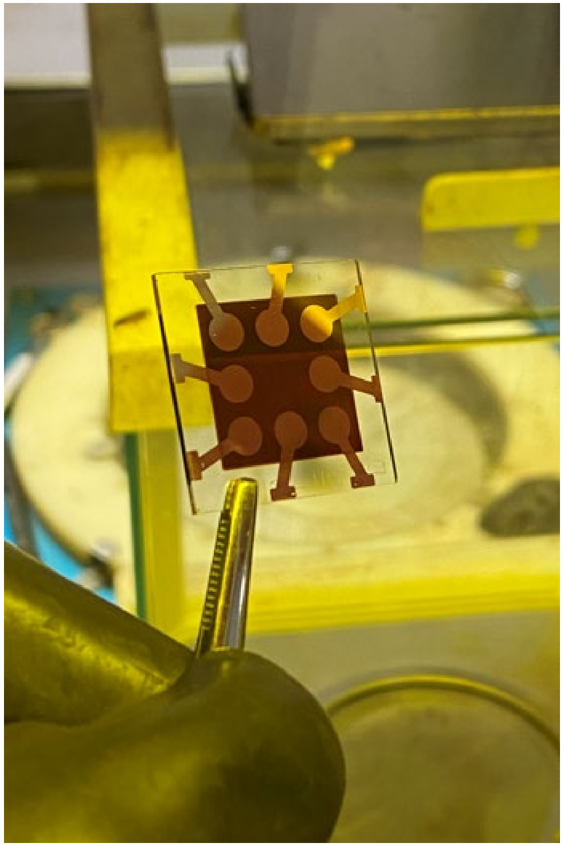
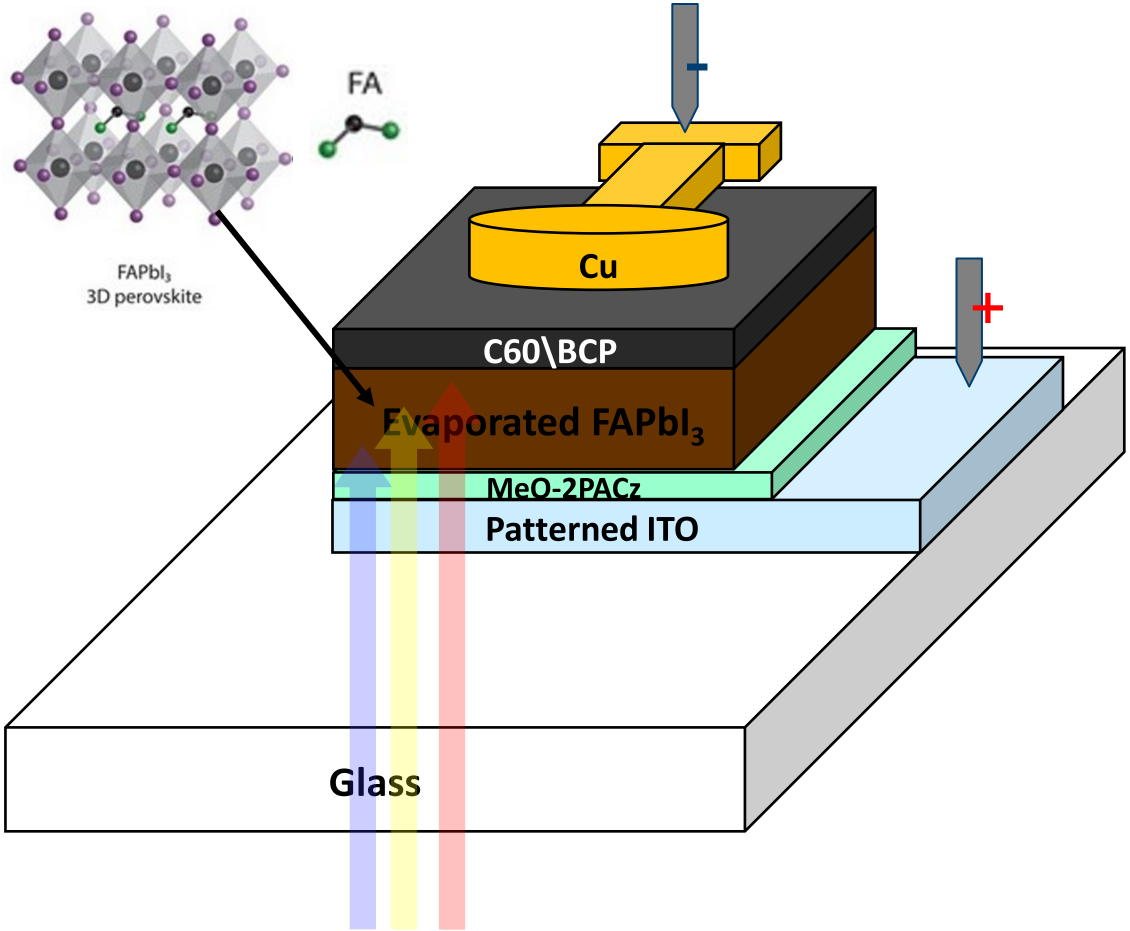
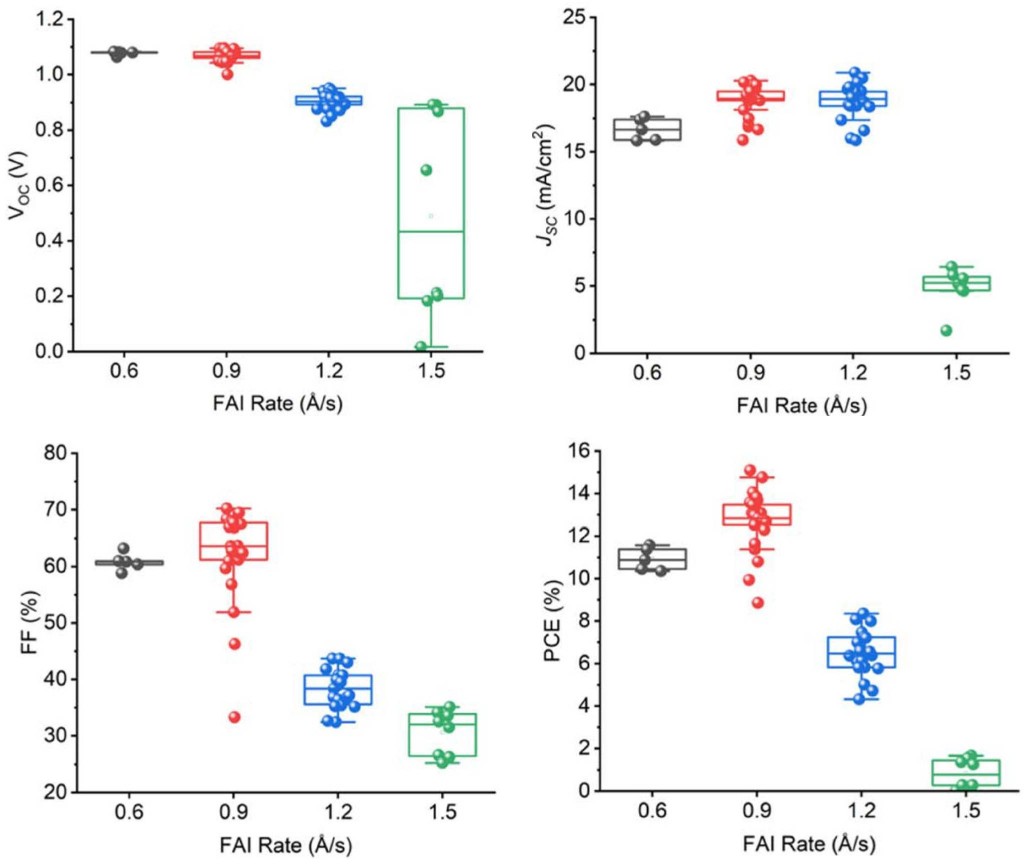
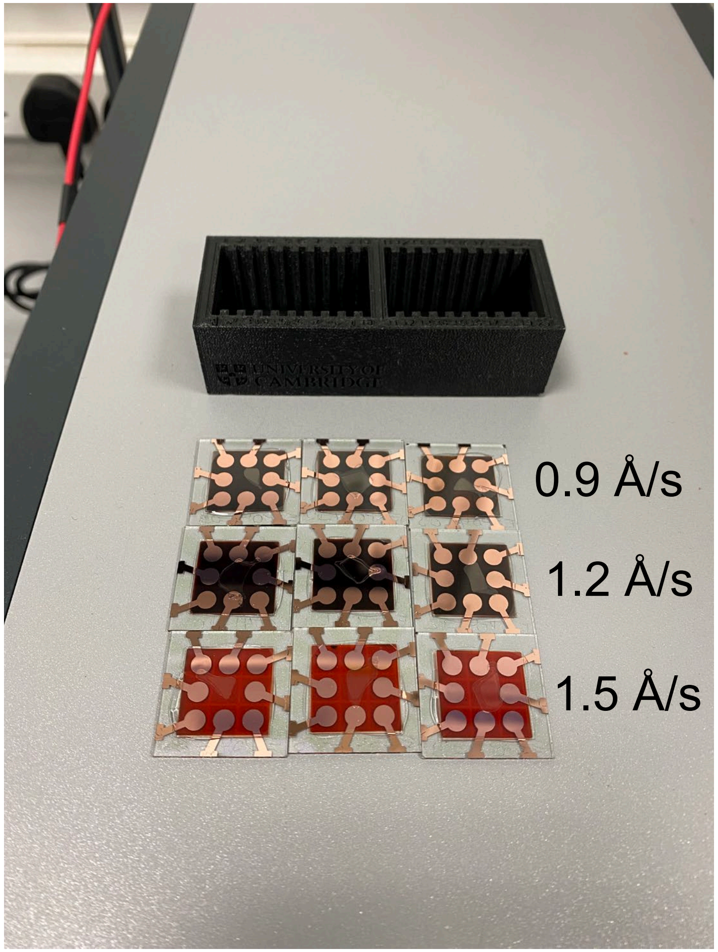
$FAPbI_3$ Perovskite Solar Cells





PbI_2:FAI Rate Dependence





PbI_2 rate fixed at **0.6 Å/s** FAI rate variable

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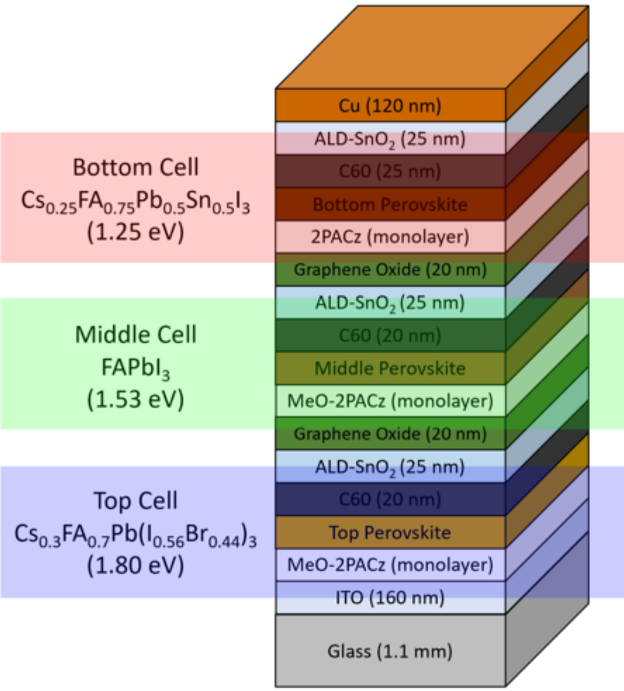
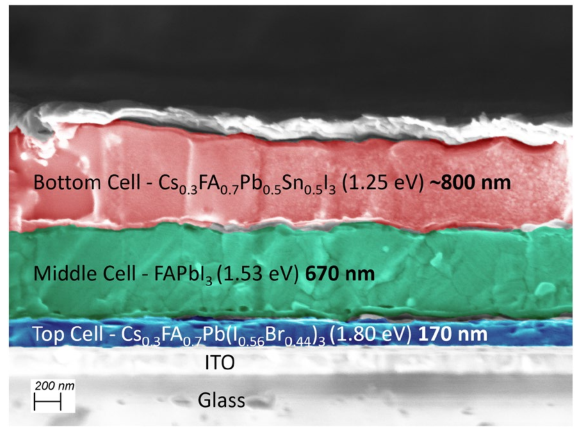
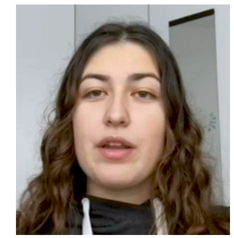
Monolithic Triple-junction All-Perovskite Solar Cell Design with Optical Modelling Thickness Optimization

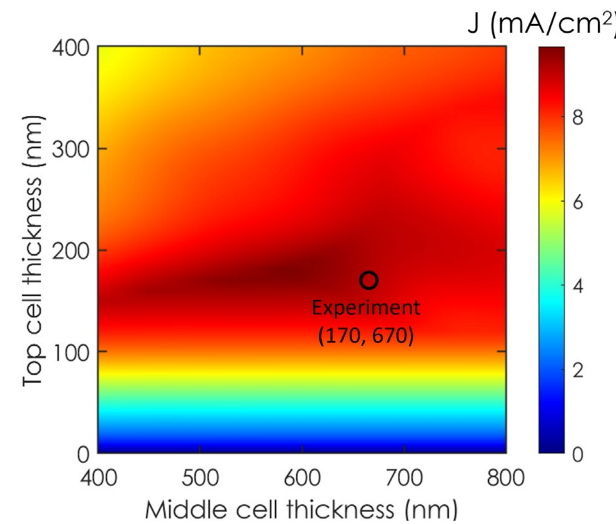






G. Vega

M. Anaya



T. Kang

M. Fitzsimmons

Yang, T. C.-J., Kang, T., Stranks, S. D. et al. Incorporating thermal co-evaporation in current-matched all-perovskite triple-junction solar cells. *EES Sol. 1 41-55* (2025) https://doi.org/10.1039/D4EL00012A

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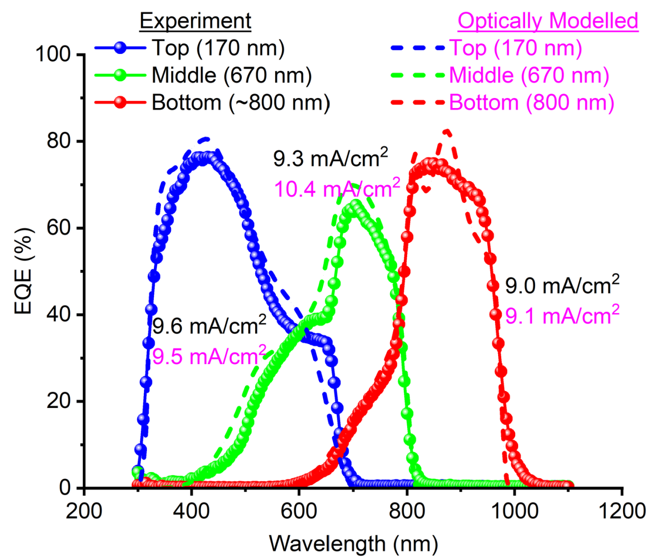
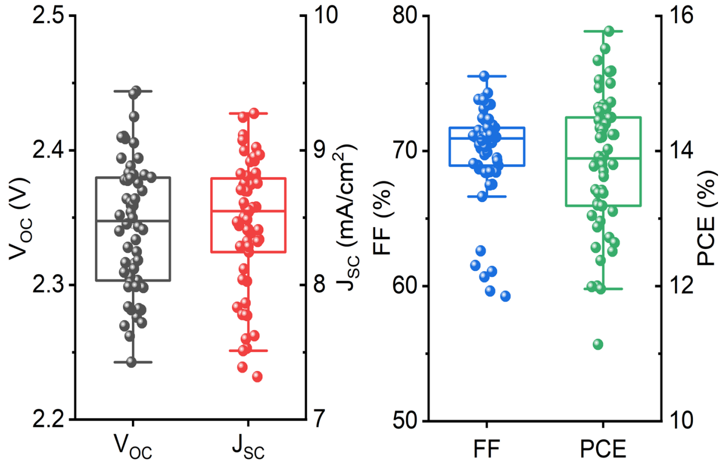
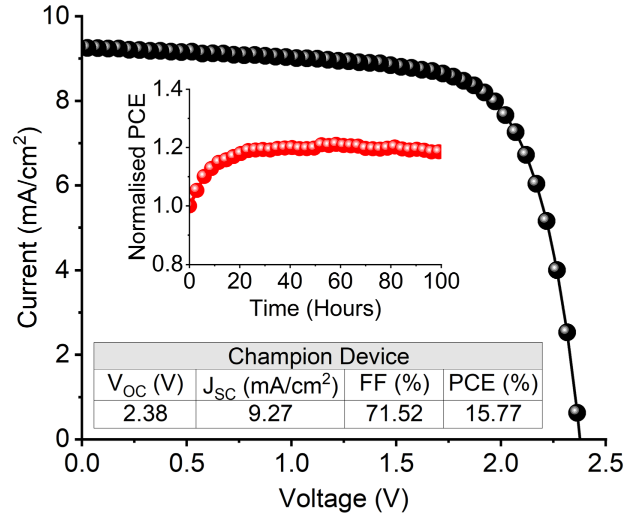
Device PV Parameters

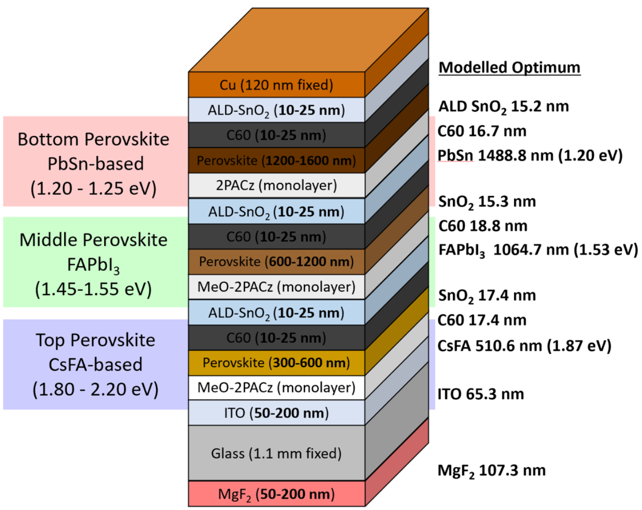


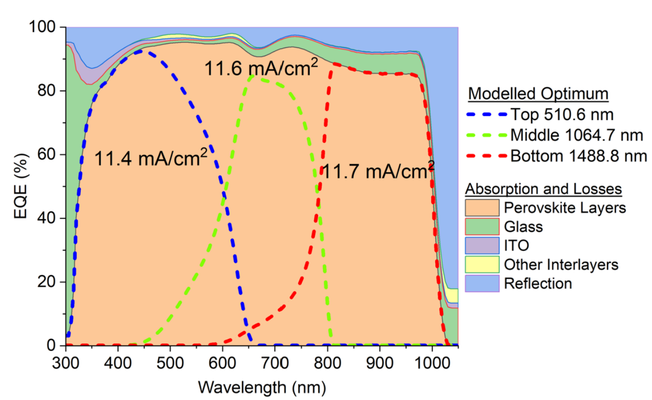


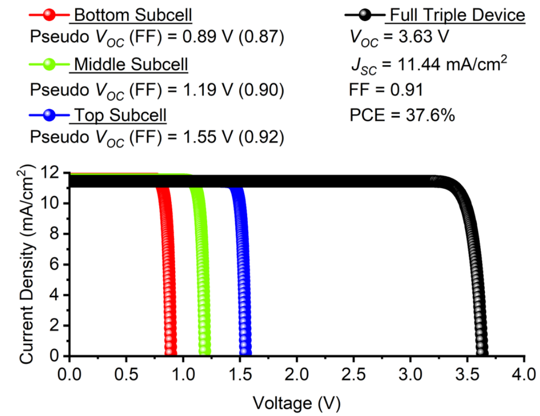


Champion Device			
V_{OC} (V)	J_{SC} (mA/cm^2)	FF (%)	PCE (%)
2.38	9.27	71.52	15.77

Future Design Improvements and Practical Efficiency Limit







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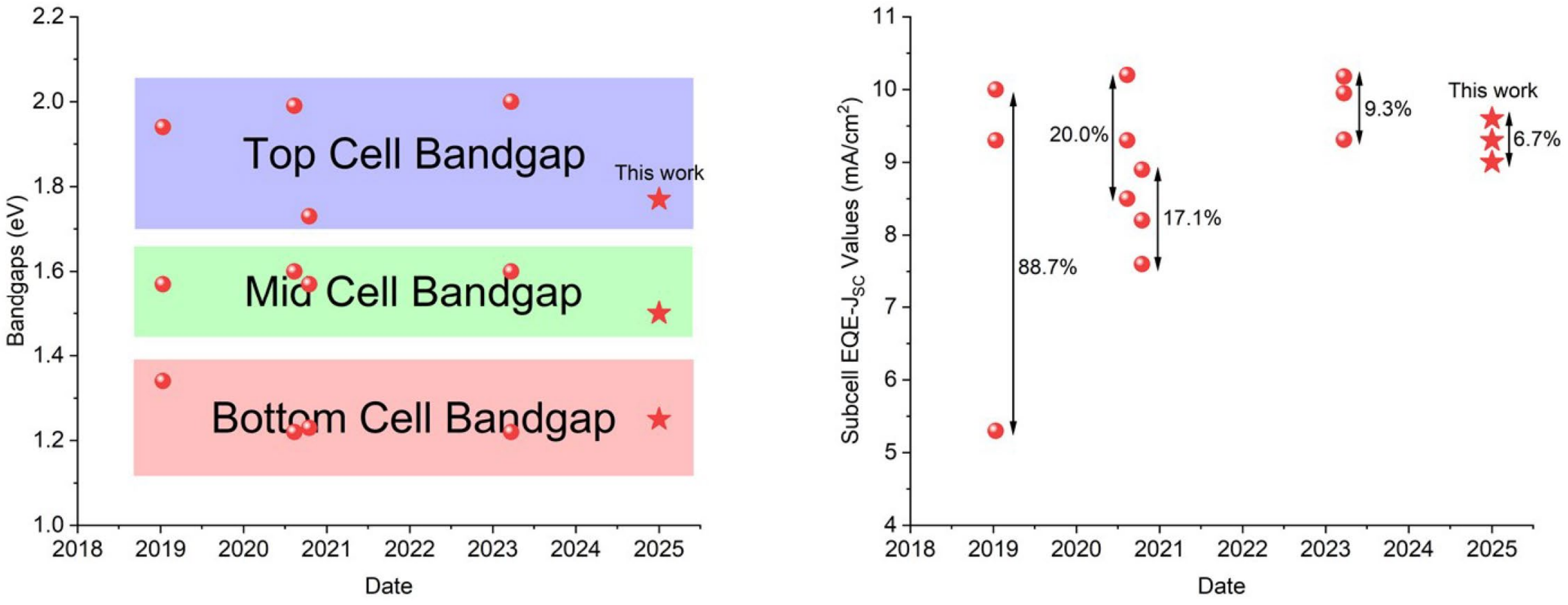
Literature Review of Existing All-Perov Triple-junctions



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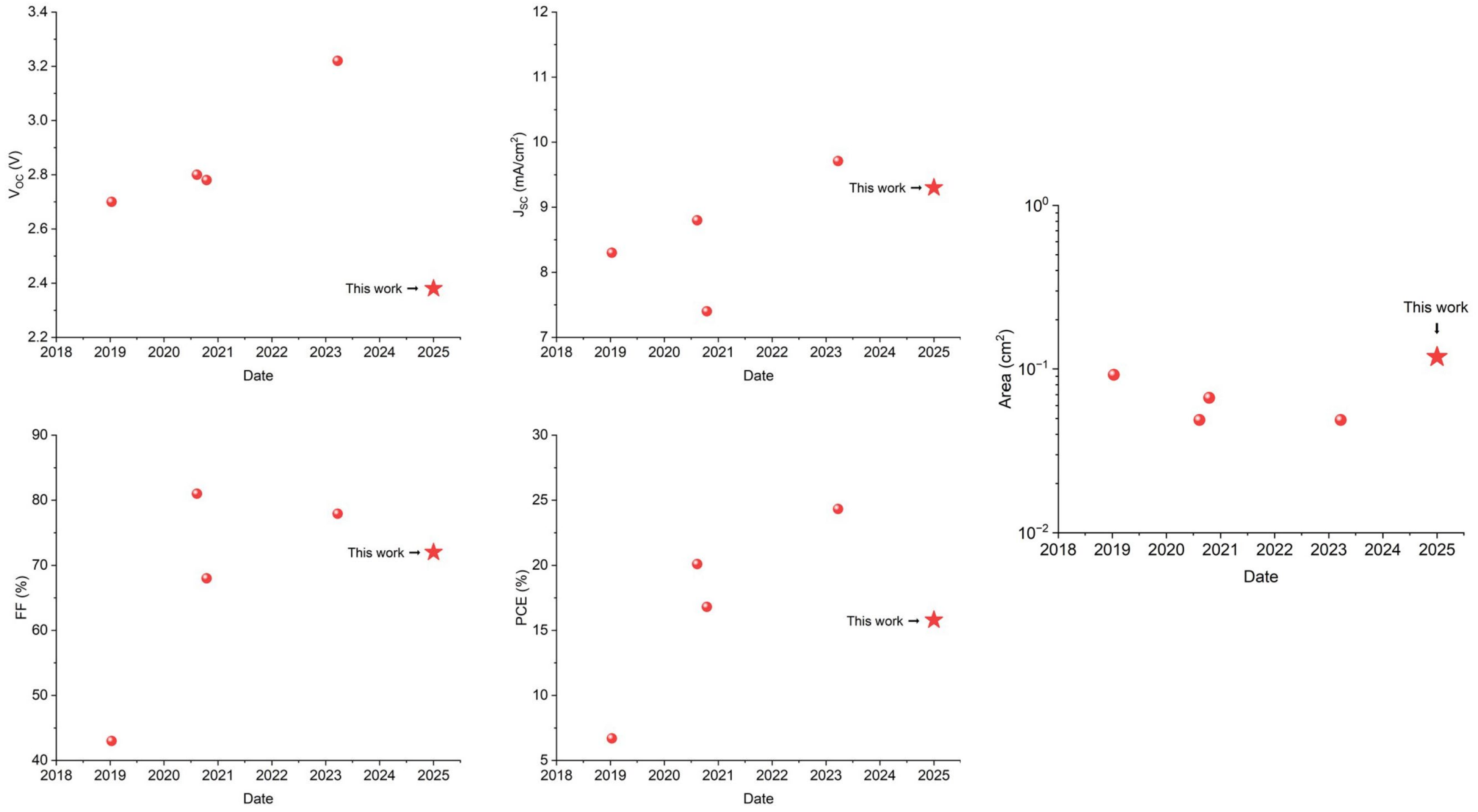
Literature Review of All-Perov Triple-junction PV Parameters

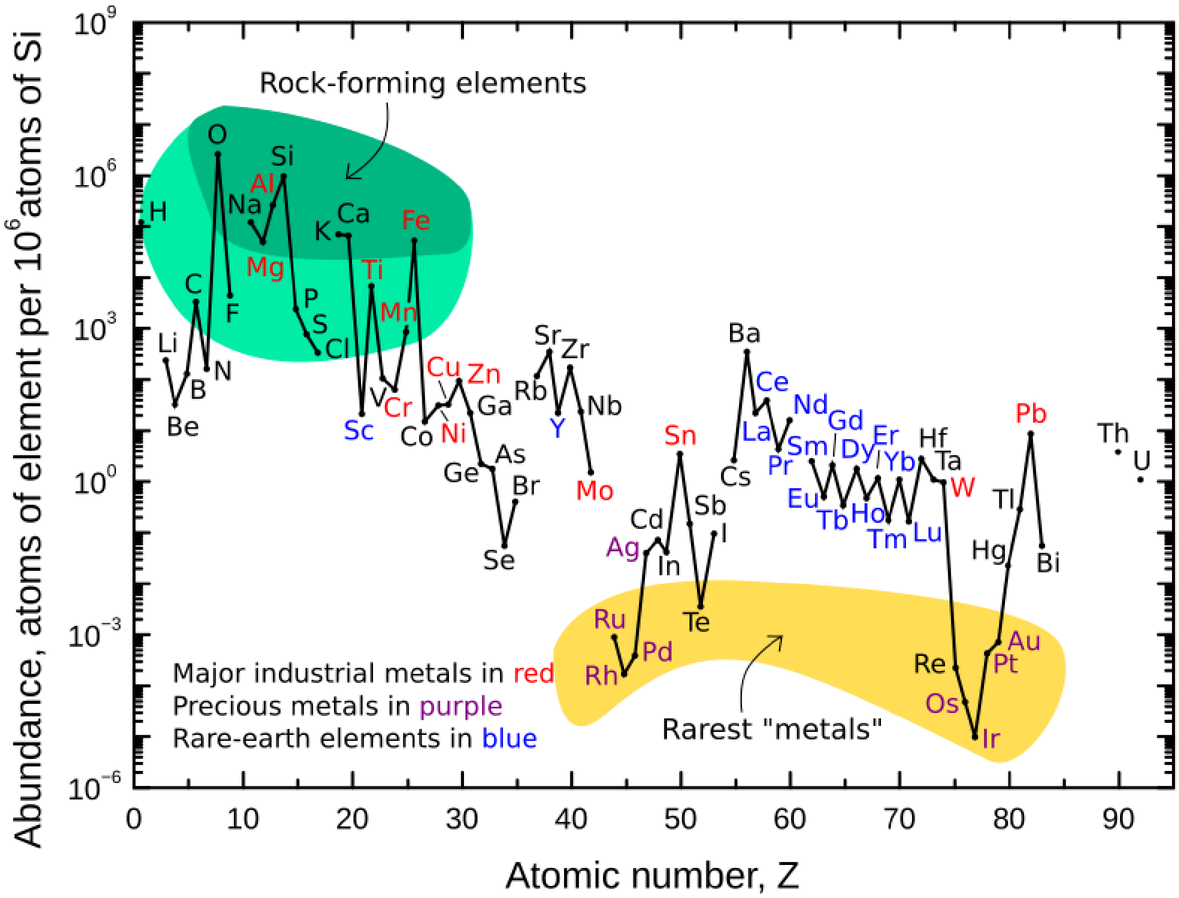


Next Solar Photovoltaic Material – Future Outlook

Semiconductor Material	Efficient (>20%)	Elemental Abundance	Fabrication Cost	Stable (>20 years)	Non-toxic
c-Si	✓	✓	✓	✓	✓
a-Si	×	✓	✓	✓	✓
Si NC/QDs	×	✓	✓	✓	✓
III-V Multi-junctions	✓	×	×	✓	×
Perovskites	✓	✓	✓	?	×
Organics	✓	✓	✓	×	✓
DSSCs	×	✓	✓	×	✓
II-VI CdTe	✓	×	✓	✓	×
II-VI CIGS	✓	×	✓	✓	✓
II-VI CZTS	?	✓	✓	✓	✓

• Anderson, Don L.; 'Chemical Composition of the Mantle' in *Theory of the Earth*, pp. 147–175 ISBN 0865421234

Elemental Abundance in the Earth Crust



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Questions