Materials Science That Breaks the Efficiency, Lightweight, Reliability Trade: Efficient Multijunction Solar Cells on Flexible Substrates

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Outline—Markets and U.S. Department of Defense (DoD) Use Cases

- Thin-Film Solar-Cell Applications
  - DoD Mission and User Requirements
  - Case Studies—Warfighter and Long-Endurance Drones

- Photovoltaic (PV) Research and Development Background and Thin-Film Manufacturing
  - Importance of DoD Funding for Perovskite Solar Cells (PSCs) Development

- New Developments in PSC

- Liquid-Processed (Ink) Solar Cells Based on Perovskite Materials
  - Advantage of PSCs Over Conventional Thin-Film Solar Cells
  - Outlook/Roadmap to Reliability and Manufacturability Needed for Real Impact at Scale

DoD User Requirements

- Efficiency
  - Higher Efficiency
  - Higher Energy: Weight Ratio
  - Higher Energy: Volume Ratio (Energy Density)

- Operation
  - Larger Operating Temperature Range
  - Easily Stowable/Transportable (Rollable)
  - Surface Conformable (Wing, Wall)
  - Rugged (Air Deployable)
  - Easy Retrieval (Rollup) or Disposable

- Logistics
  - Lower Cost, Less Push for Return to Inventory
  - Easily Stored
  - Less Transport and Storage Volume and Weight

U.S. Army Releases Its Climate Strategy/Article/The U.S. Army

Potential DoD Applications

- Individual or squad
  - Powering the Remote Warfighter: Reducing Weight
- Forward Base or Equipment
  - Air-Dropped Tubes of Large PV Rolls
  - Truck-Deployed, Large PV Rolls for Auxiliary Power (e.g., High Altitude, Low Temperature)
- Smart Battlefield
  - Persistent Internet of Things
  - Powering 5G Communications Local Network (e.g., Local System for Global Positioning System Denied)
  - Aircraft
  - Long-Duration Aircraft (e.g., Wing-Conformable PV)
- Aerospace
  - Space-Based or Space-Launched Devices
  - Low-Temperature, Very Large, Self-Deployable Array (e.g., Micrometeor-Resistant
- Marine)
  - Autonomous Surface Vessels (e.g., Vertical Walls of Surface Craft)
  - Floating Array for Long-Duration Aquatic Sensors (e.g., Sonobuoy)

Case Study—Powering the Warfighter

- Warfighter Today Has to Carry ~2 kg of Batteries
  - Existing solar cells are not sufficiently lightweight, flexible, and energy efficient.[1]

- Previous Developments in Flexible PV: Konarka Funded by the Defense Advanced Research Projects Agency in 2004 to Produce Flexible PV for "Battery Charging on the Battlefield, Remote Power for Soldiers and Unmanned Vehicles, and Solar-Powered Sensor Networks"[2]
  - Problem: had only 6% efficiency, although predicted 20% efficiency.[3]

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[1]www.benning.army.mil/Infantry/Magazine/issues/2013/Jul-Sep/Meredith.html
[2]www.renewableenergyworld.com/solar/konarka-contracted-for-hybrid-solar-pv-cells-10552/#gref
[3]www.renewableenergyworld.com/solar/konarka-contracted-for-hybrid-solar-pv-cells-10552/#gref

Case Study—Long-Duration Aircraft

- Helios—Prototype in 1999
- Current Record Over 2 Months: Zephyr—Long-Term Recon[1]
- Chinese Interest[2]
- Perovskites Excellent Match for HAPS[3]

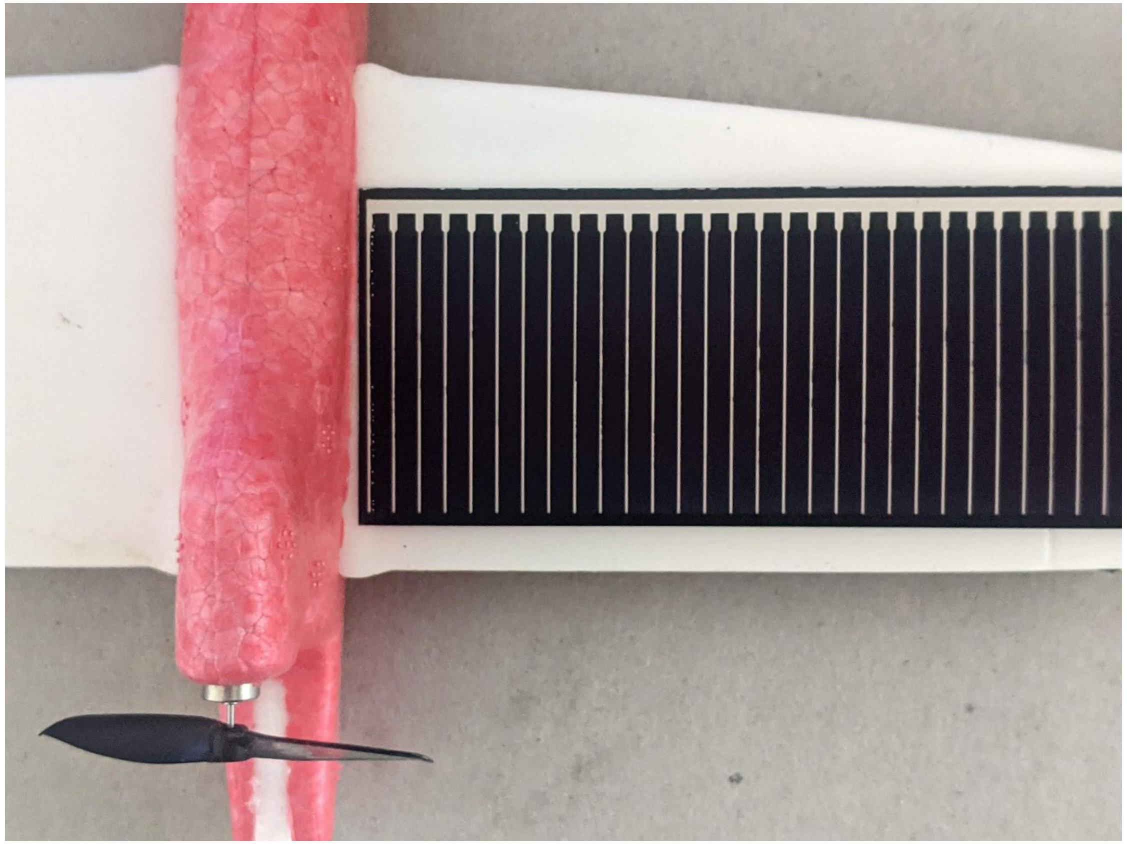

Photo Courtesy of Charles Brumlik. (Used With Permission)

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[1]www.airbus.com/en/products-services/defence/uas/uas-solutions/zephyr
[2]https://onlinelibrary.wiley.com/doi/full/10.1002/cjoc.202200481
[3]https://pubs.rsc.org/en/content/articlelanding/2020/tc/c9tc04984c/unauth

Background of Solar Cells

- Solar cells have to accomplish two tasks:
  1. Capture photons
  2. Convert the photon to an electron and transport it externally

- Silicon was chosen initially because of work on microchips.
  - The physics of how holes and electrons were transported was well understood.
  - However, silicon is a lousy photon absorber!
  - Thick pieces of silicon are required, and capture efficiency falls off when the photon strikes the surface at less than 90°.

- Many other materials are better photon absorbers than silicon but can be much harder to extract the electron.
  - Better photon absorbers allow thin-film solar cells with no loss of capture efficiency and improvements at lower angles of incidence.
  - A 1-m^2 panel with 20% efficiency can generate close to 300 W.
  - Schockley-Quesser Theoretical Limit (single junction) has 33% efficiency at 1.34 eV.

Comparison of Thin-Film PV Technologies

Properties	PSC	CIGS	OPV	IMM
PCE	>28%	~23%	~18%	>30%
Robust	Yes	Yes	Yes	Yes
Longevity	~3,000 hr	>10,000 hr	>10,000 hr	>10,000 hr
Temperature Range	Broad	Medium	Medium	Broad
Radiation tolerance	High	High	Low	High
Flexibility	Good	Good	High	Acceptable
Cost	<c-Si	< c-Si	<c-Si	High
Cell to module losses >5%	Yes	Yes	Yes	Yes
TRL (1-9)	5	8	5	7
Critical Materials	No	Yes	No	Yes
Environmental Concerns	Yes (contains lead)	Limited	Limited	Limited

PSC: perovskite solar cells
CIGS: copper indium gallium selenide
PCE: power-conversion efficiency

OPV: organic photovoltaics
IMM: inverted metamorphic (III-V solar cells)
TRL: technology readiness level

Importance of Military Applications to PSC Development

Current PV Supply Is Dominated by c-Si Manufactured in China

- Global PV trade was >$40B in 2021 with 80% tied to China.
- PSC offers a way to leapfrog China's dominance of the PV industry!
- It has a much lower cost manufacture and different supply chain.
- There is neither existing capital nor knowledge base critical to manufacture of PSC.

Challenges for PSC

- Stability
- Scale-Up to larger sizes

Stability Issue Precludes Widespread Commercial Applications

- Current PSC ~3,000-hr lifetime compared with c-Si with 30,000-hr lifetimes. However, 3,000 hr is sufficient for many defense applications.
- PSC needs a first customer!

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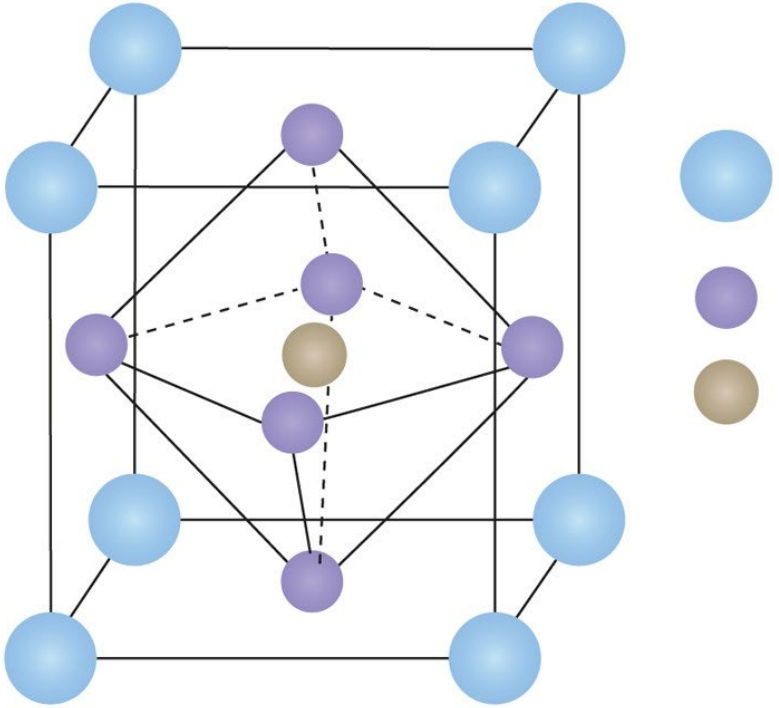
www.iea.org/reports/solar-pv-global-supply-chains/executive-summary

The Rise of Perovskite Materials



ABX_3

Ca2+ (A site)

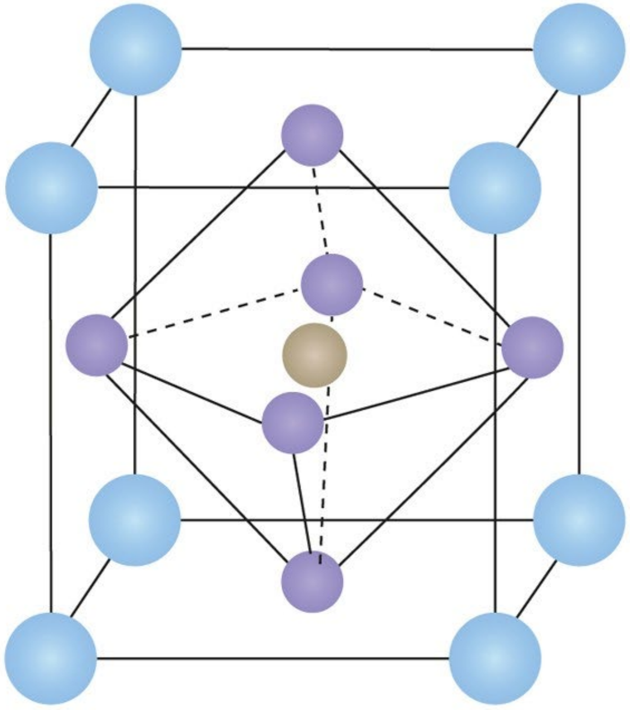
O2- (X site)

Ti4+ (B site)

Lev Perovski (1792–1856)

The Rise of Perovskite Materials (cont.)

Combines the Advantages of Inorganic and Organic Semiconductors



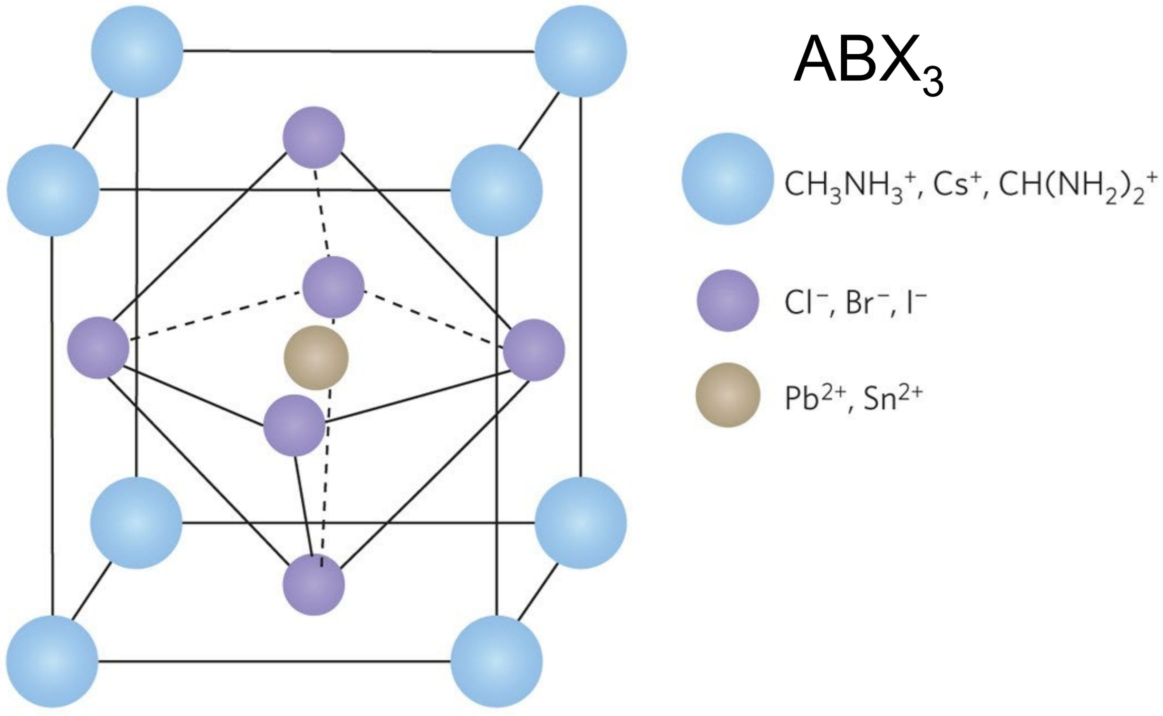
ABX_3

- (blue sphere) $CH_3NH_3^+$, Cs^+, $CH(NH_2)_2^+$
- (purple sphere) Cl^-, Br^-, I^-
- (tan sphere) Pb^{2+}, Sn^{2+}

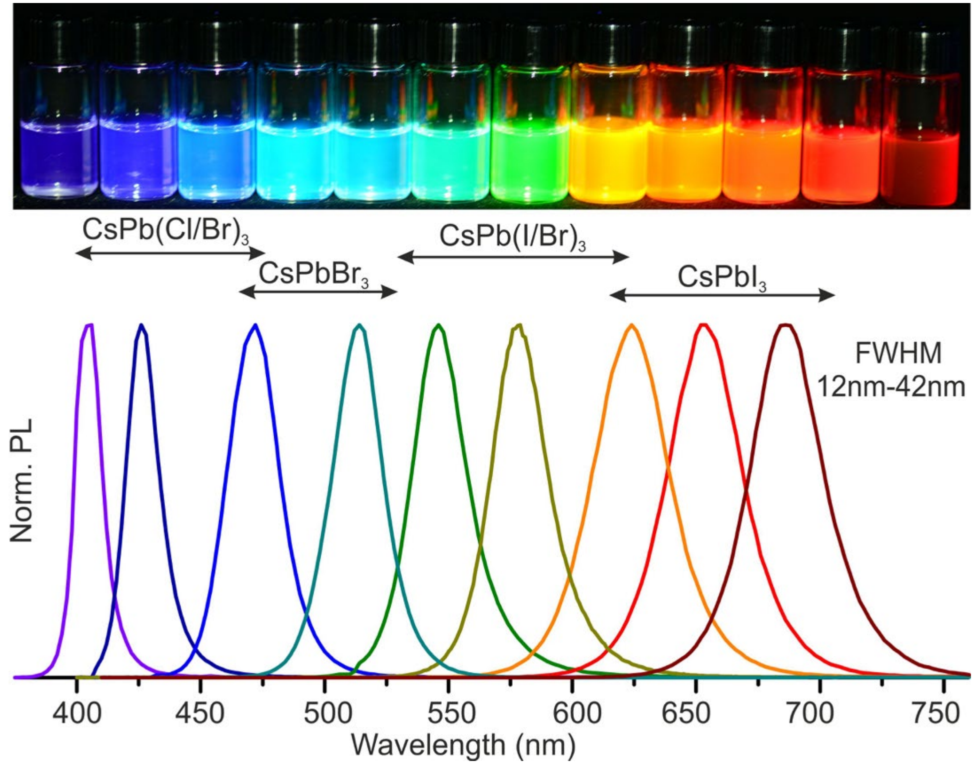
Lev Perovski (1792–1856)

The Rise of Perovskite Materials (cont.)

Combines the Advantages of Inorganic and Organic Semiconductors

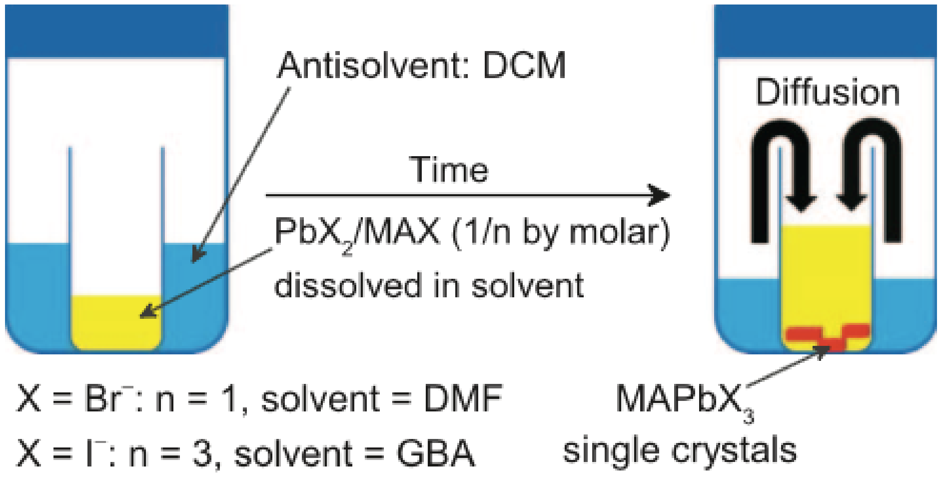


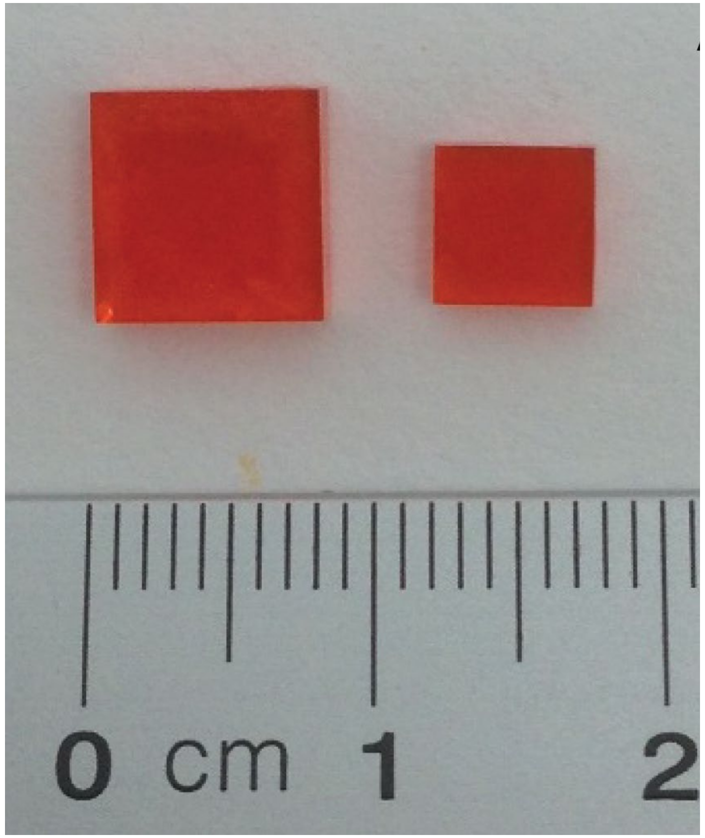
Bandgap Tuning Through Composition



Protesescu, L. , S. Yakunin, M. I. Bodnarchuk, F. Krieg, R. Caputo, C. H. Hendon, R. X. Yang, A. Walsh, and M. V. Kovalenko. "Nanocrystals of Cesium Lead Halide Perovskites ($CsPbX_3$, X = Cl, Br, and I): Novel Optoelectronic Materials Showing Bright Emission With Wide Color Gamut." *Nano Lett.*, vol. 15, no. 6, pp. 3692–3696, 2015. (Open Access)

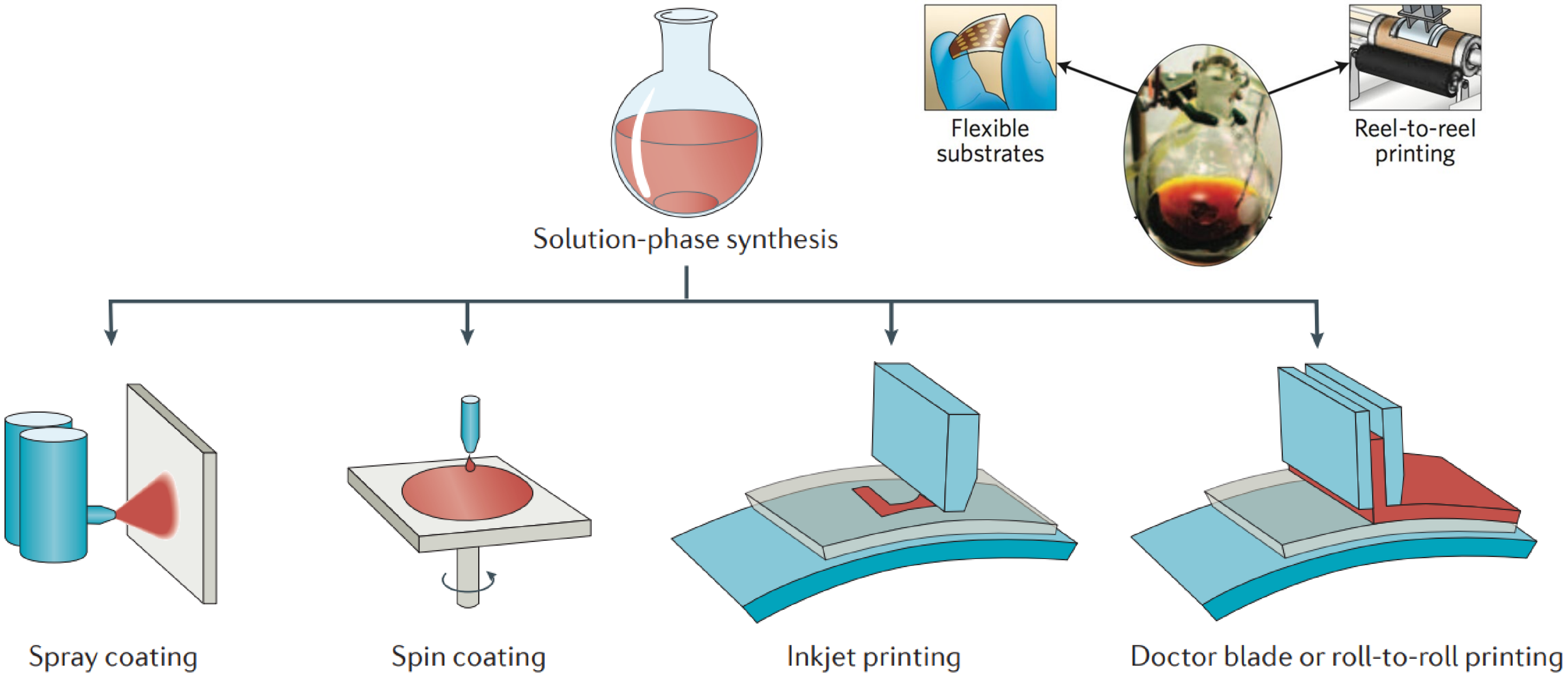
The Rise of Perovskite Materials (cont.)





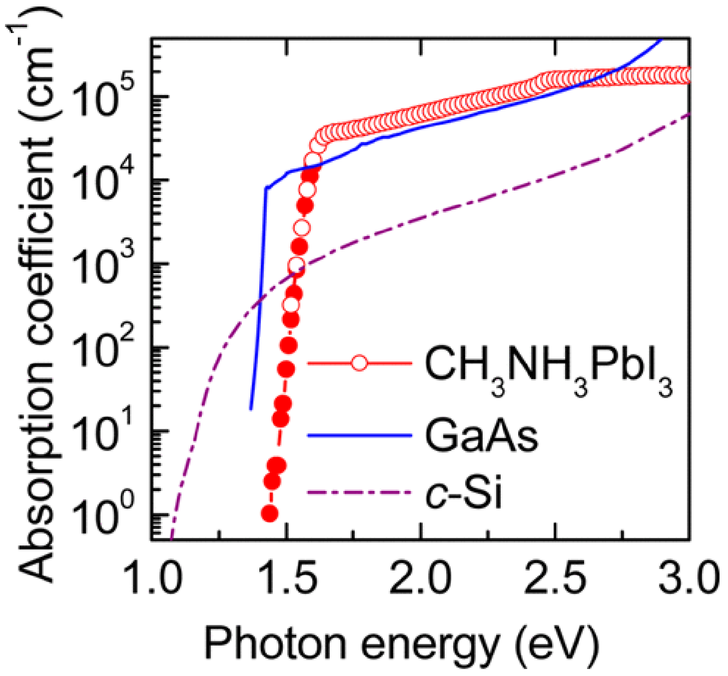
Shi, D., V. Adinolfi, R. Comin, M. Yuan, E. Alarousu, A. Buin, Y. Chen, S. Hoogland, A. Rothenberger, K. Katsiev, Y. Losovyj, X. Zhang, P. A. Dowben, O. F. Mohammed, E. H. Sargent, and O. M. Bakr. "Solar Cells. Low Trap-State Density and Long Carrier Diffusion in Organolead Trihalide Perovskite Single Crystals." *Science*, vol. 347, no. 6221, pp. 519–522, 30 January 2015.

Solution-Processed Materials



Sargent, E.H. *Nature Photonics*, 2013.

Perovskites as High-Quality Semiconductors



ADVANCED MATERIALS

Progress Report

Halide Perovskites: Poor Man's High-Performance Semiconductors

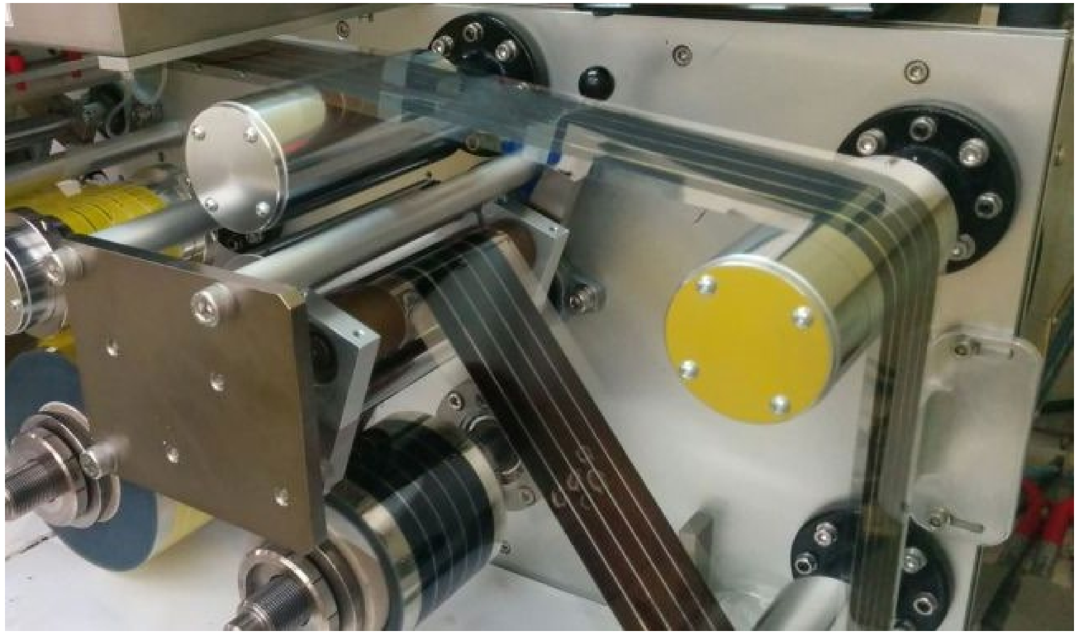
Constantinos C. Stoumpos, Mercouri G. Kanatzidis

First published: 13 May 2016 | https://doi.org/10.1002/adma.201600265 | Citations: 291

De Wolf, S., J. Holovsky, S.-J. Moon, P. Löper, B. Niesen, M. Lidensky, F,J. Haug, J.-H. Yum, and C. Ballif. "Organometallic Halide Perovskites: Sharp Optical Absorption Edge and Its Relation to Photovoltaic Performance." *J. Phys. Chem. Lett.*, vol. 5, no. 6. pp. 1035–1039, 5 March 2014. (Copyright 2014 American Chemical Society, used with permission)

Flexible and Lightweight

Perovskites Cells Are 99% Thinner Than Silicon Cells



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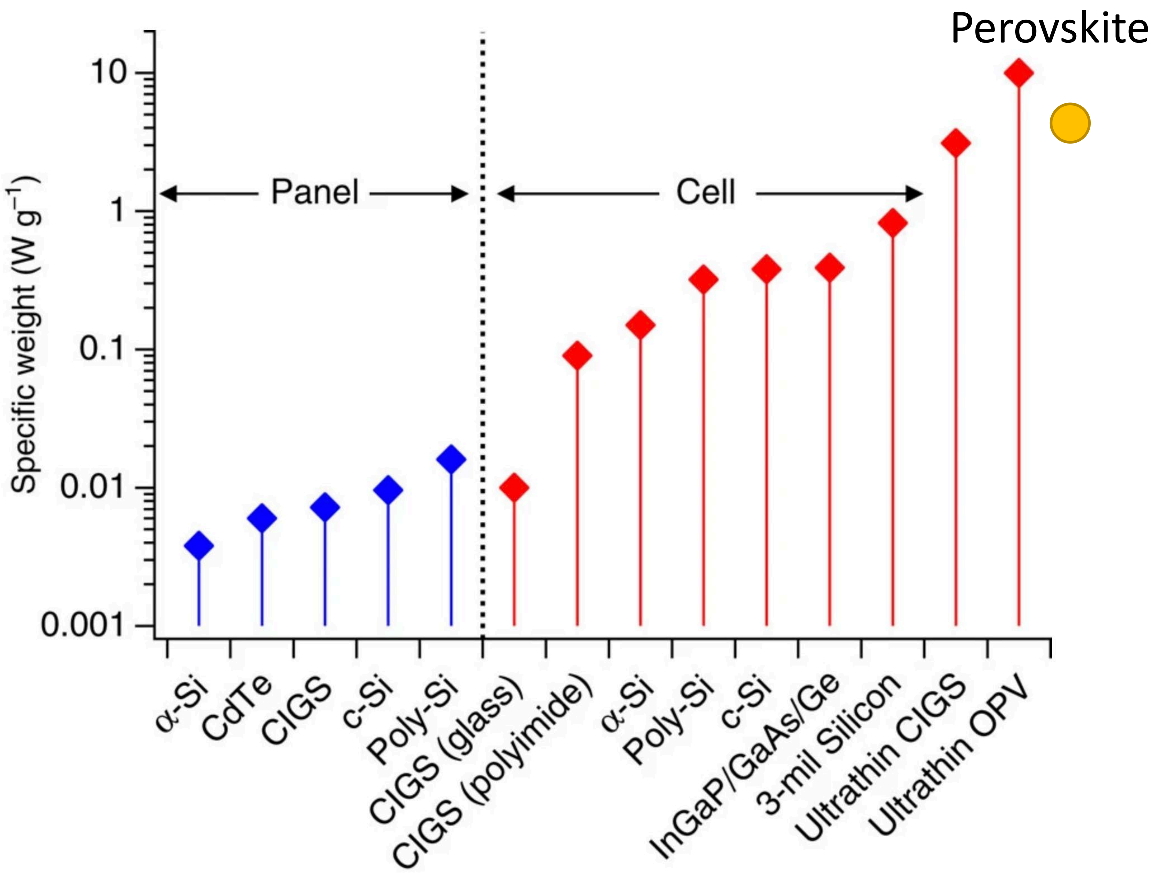

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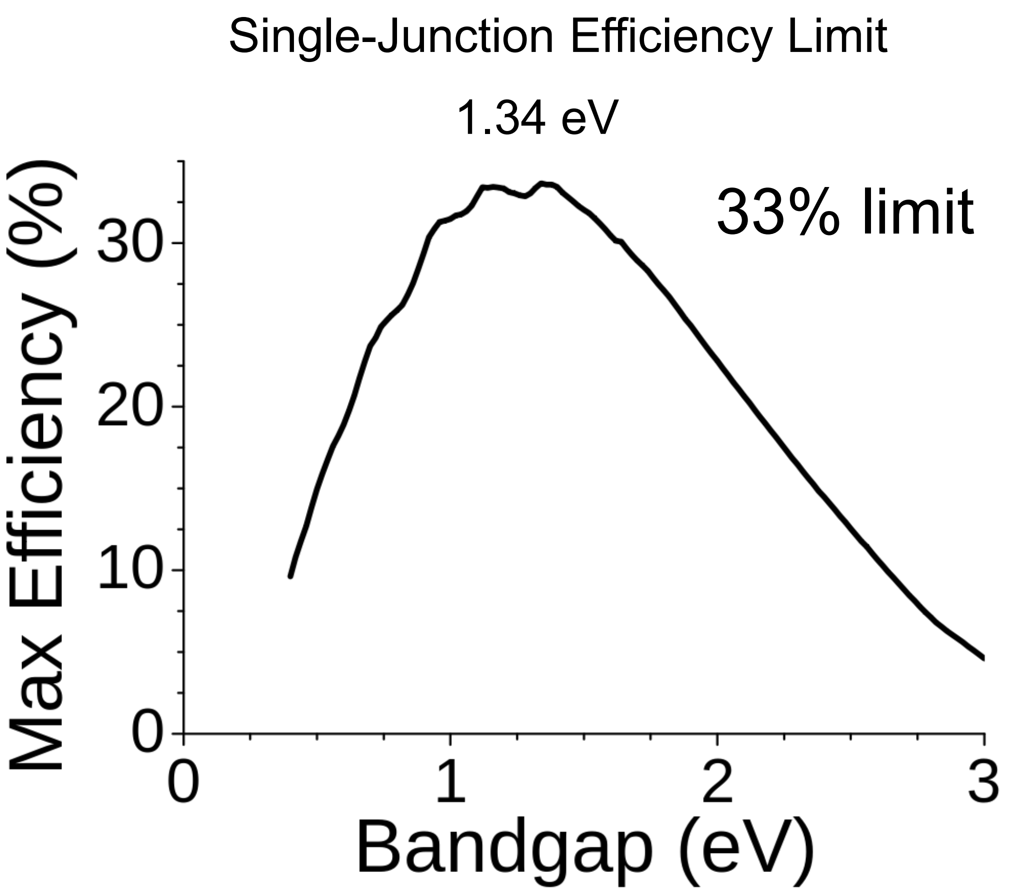
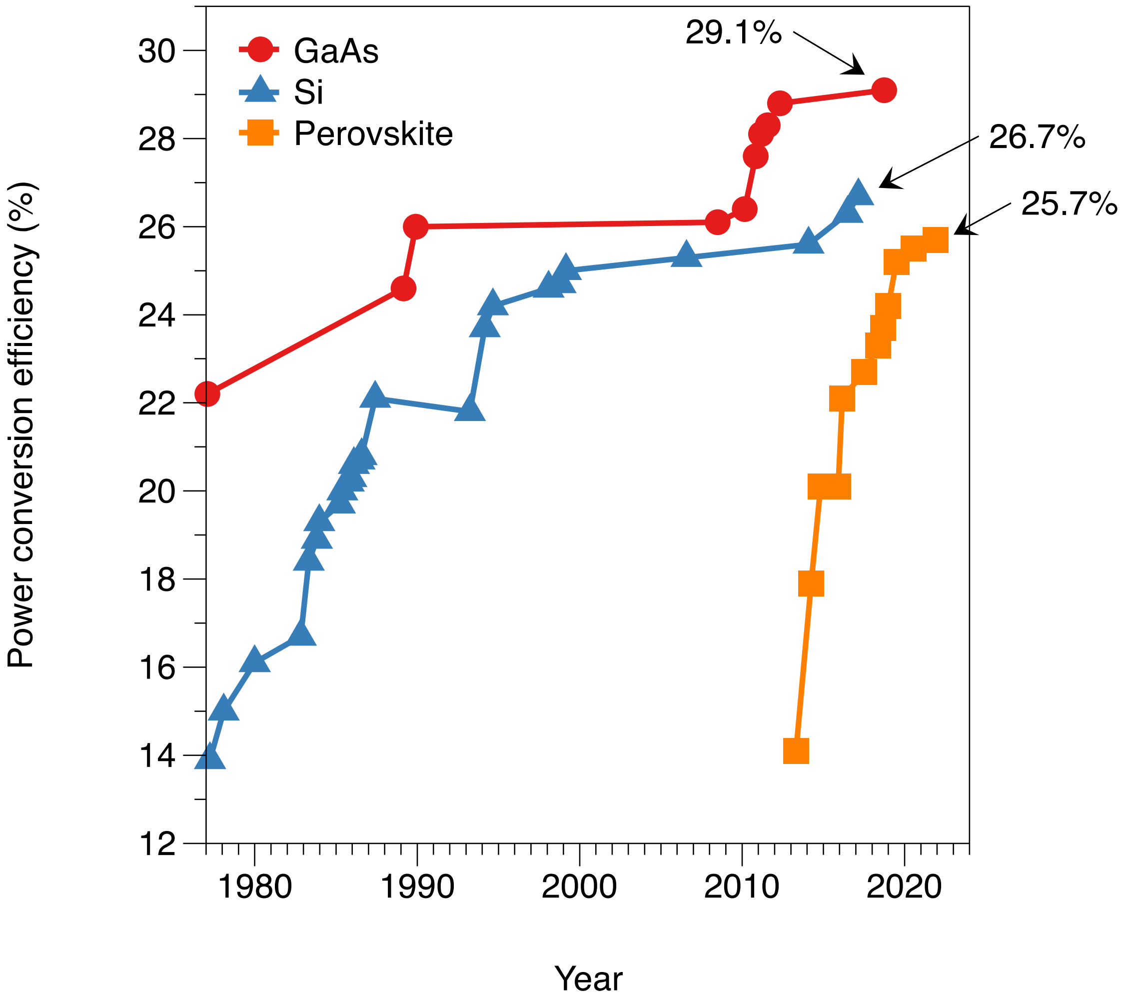
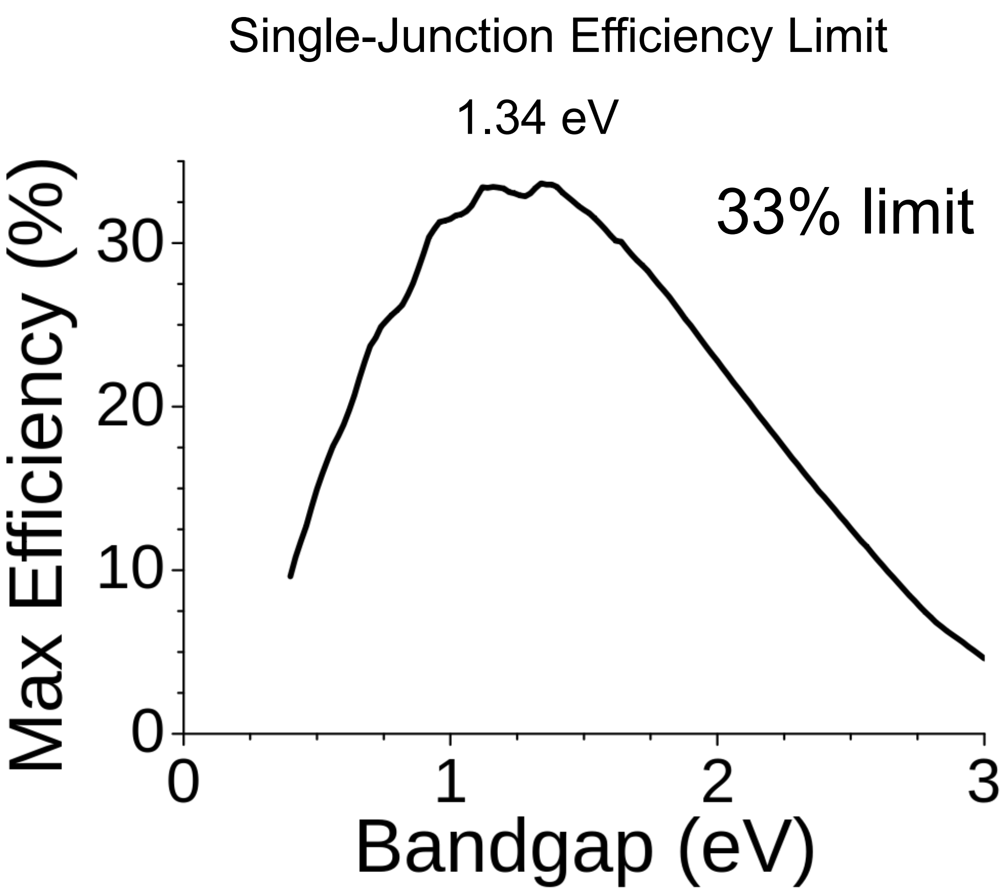
Single-Junction Limitation

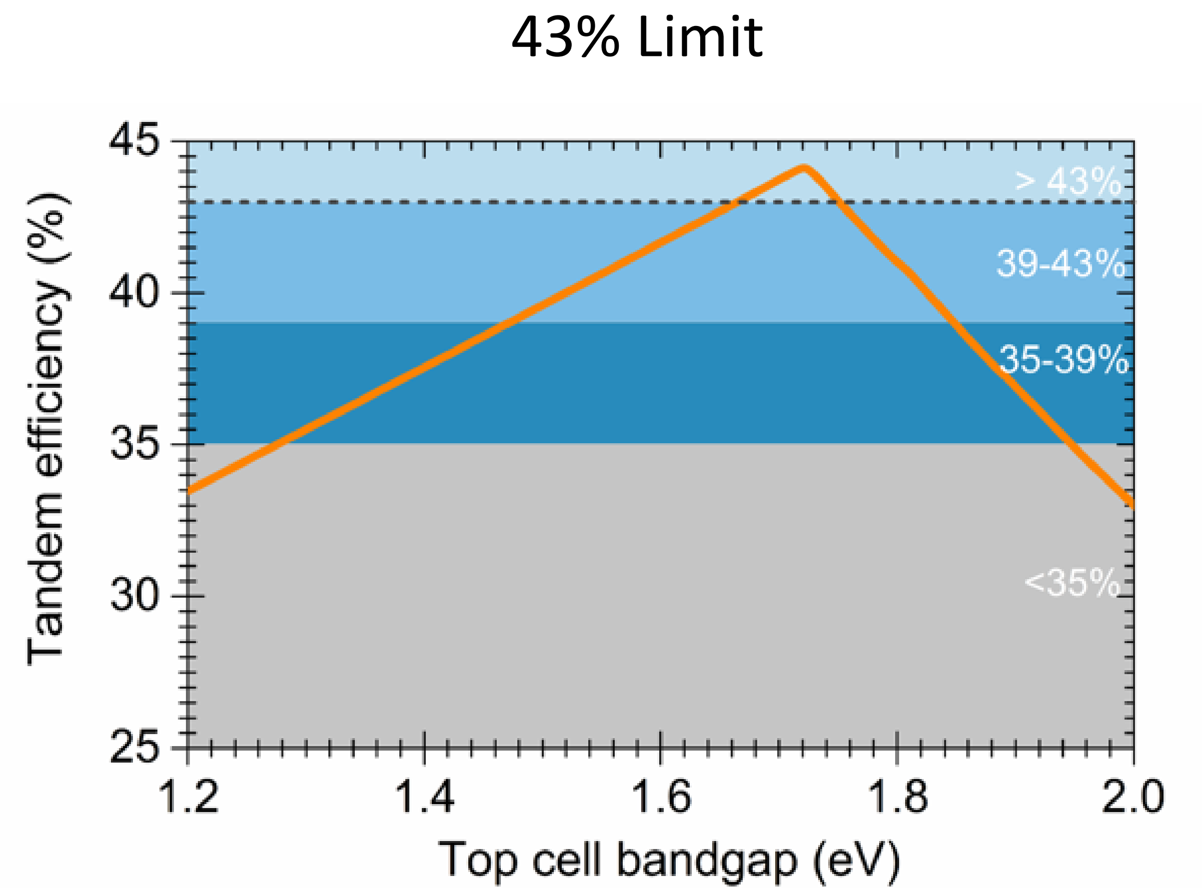




This plot is courtesy of the National Renewable Energy Laboratory (NREL), Golden, CO.

High-Efficiency Tandems





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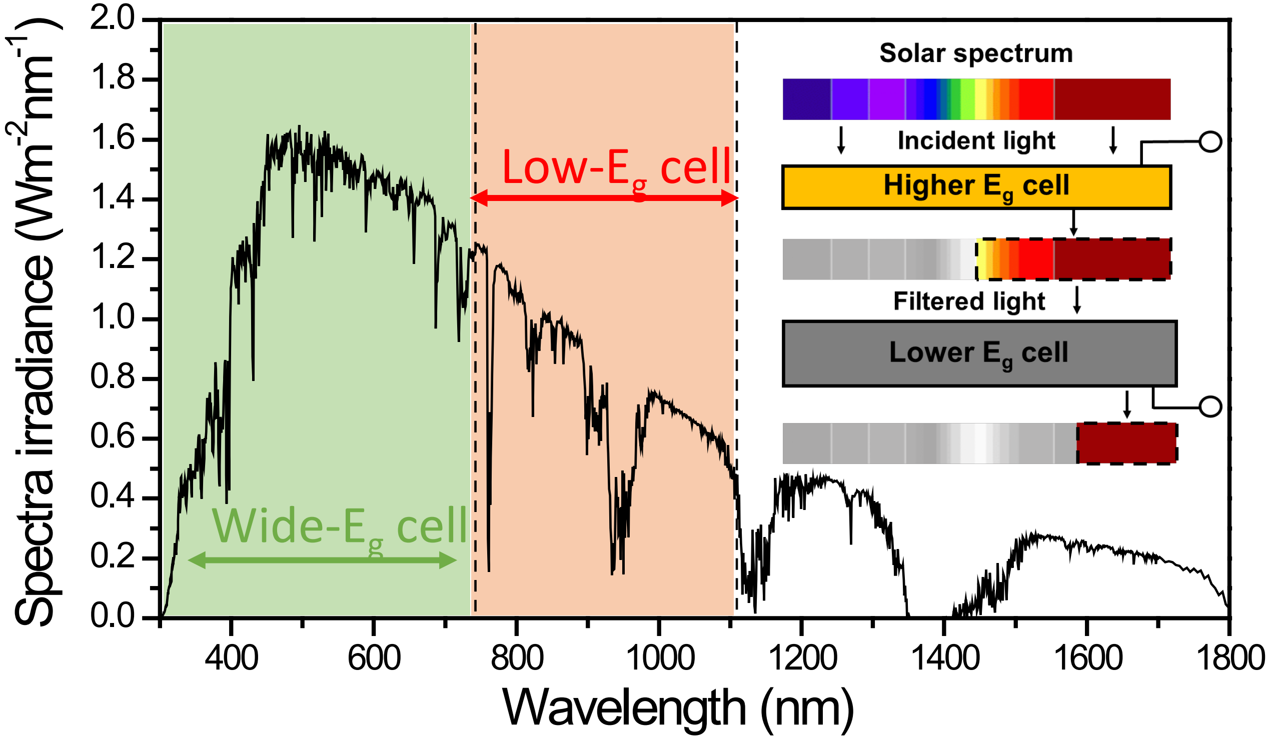
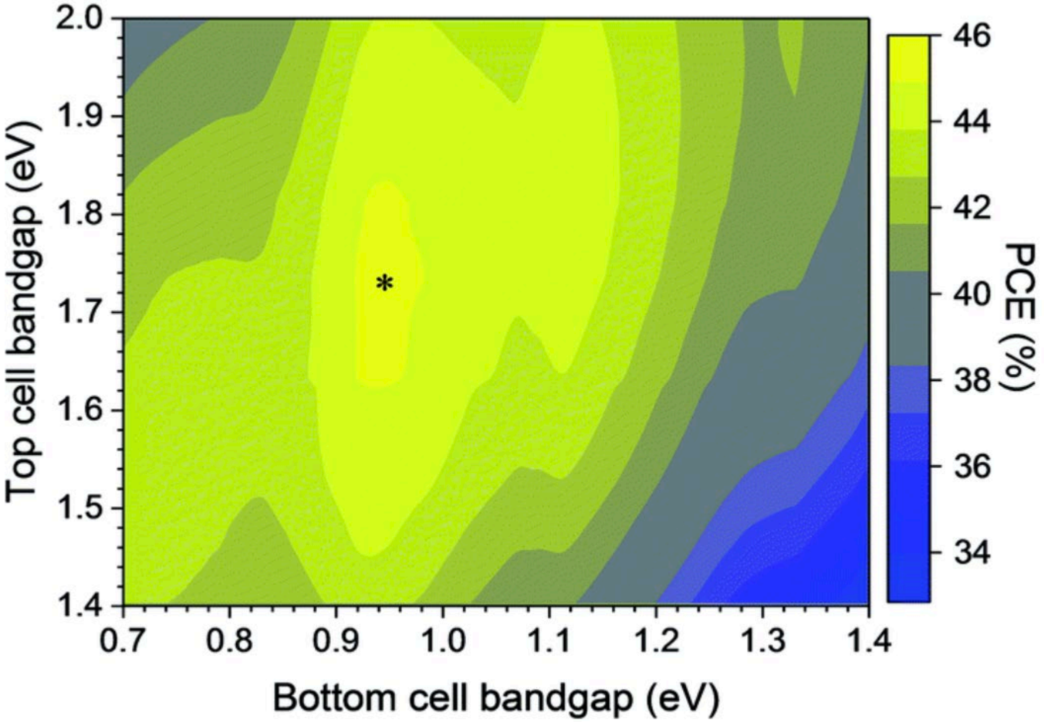
Perovskites: Flexible Bandgaps





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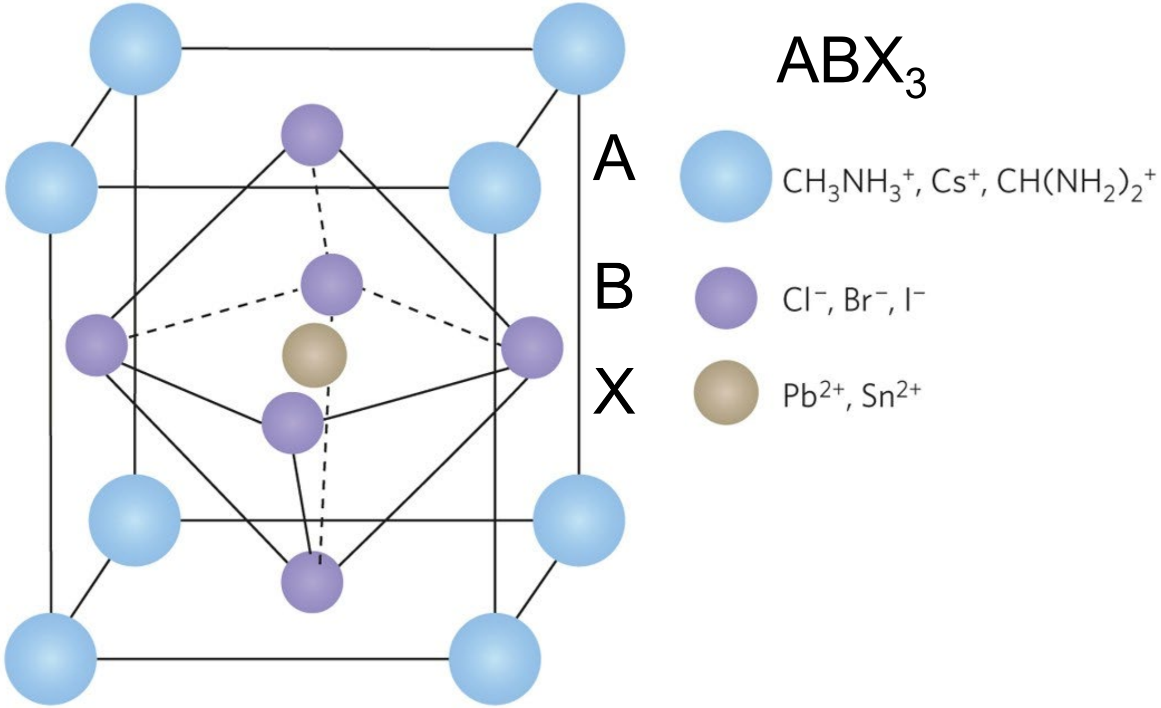
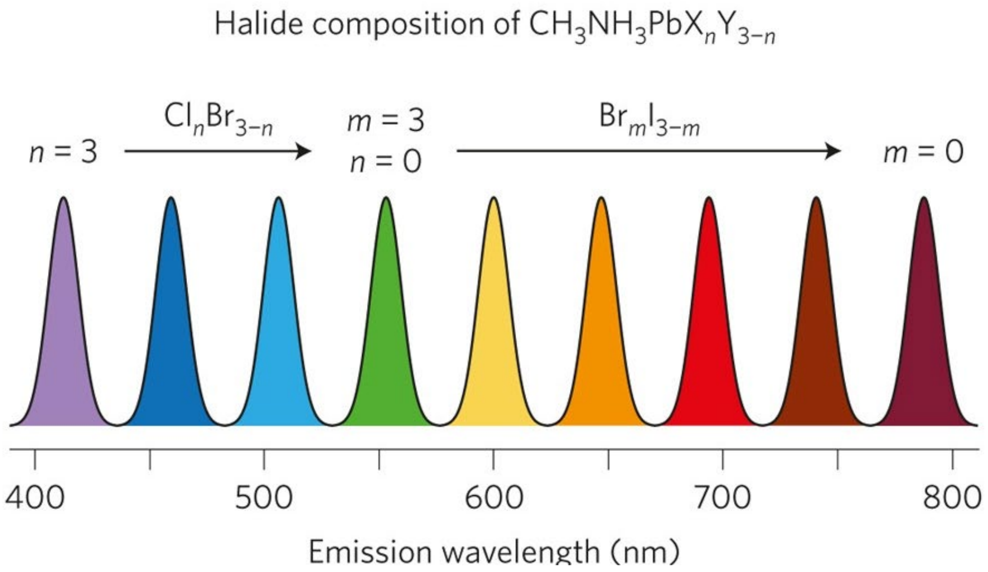
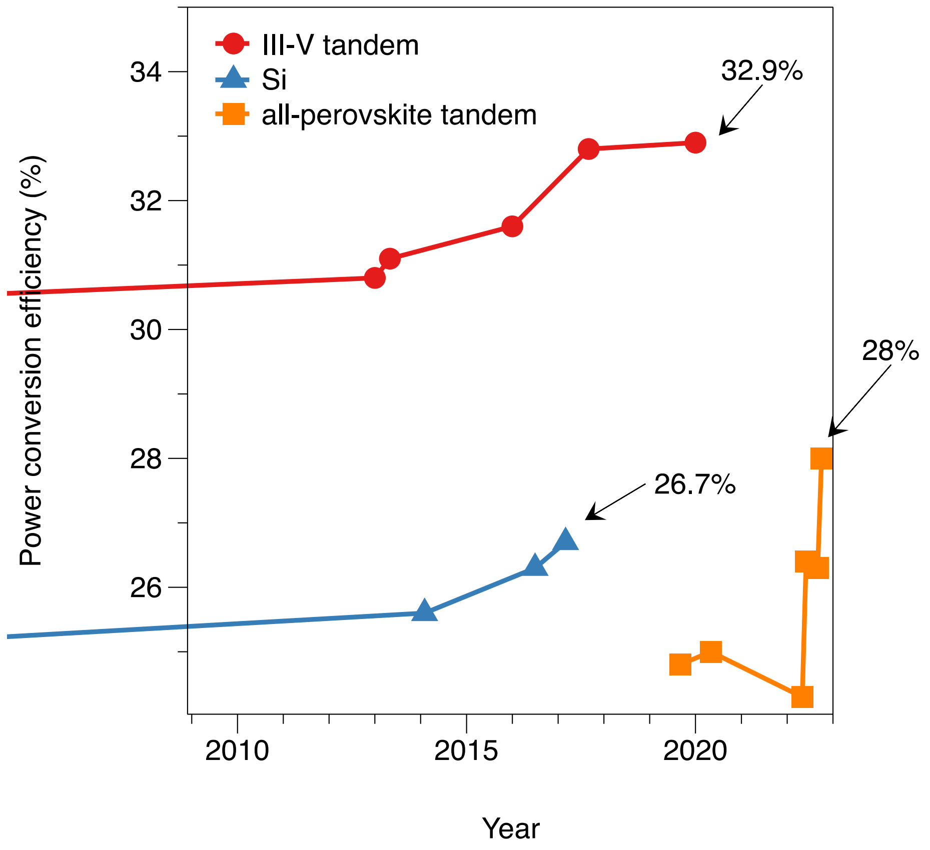
Perovskites: Flexible Bandgaps (cont.)

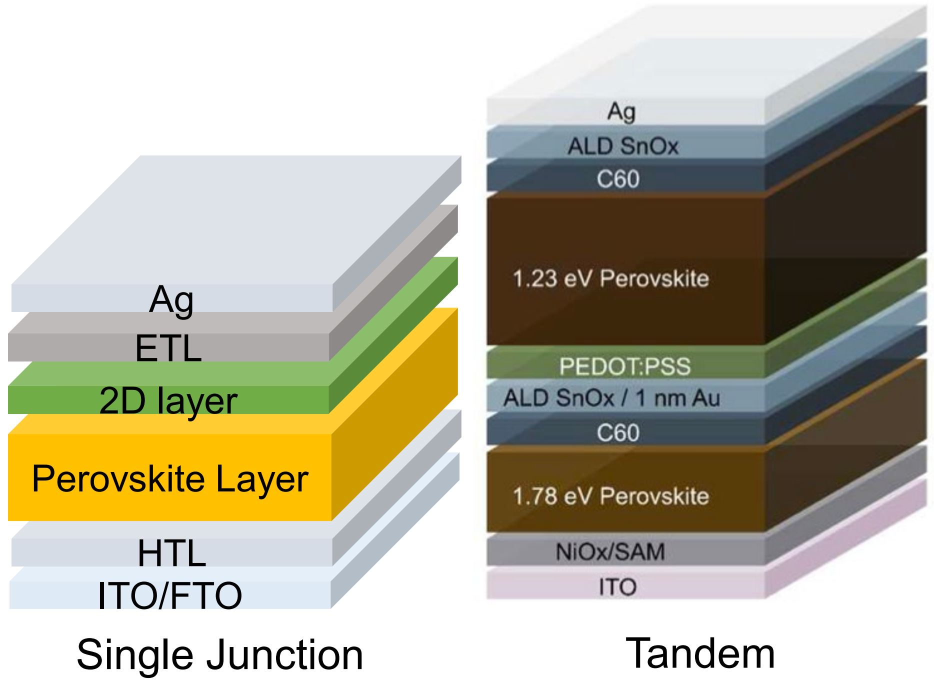




Sutherland, B., and E. Sargent. "Perovskite Photonic Sources." *Nature Photonics*, vol. 10, pp. 295–302, 2016.

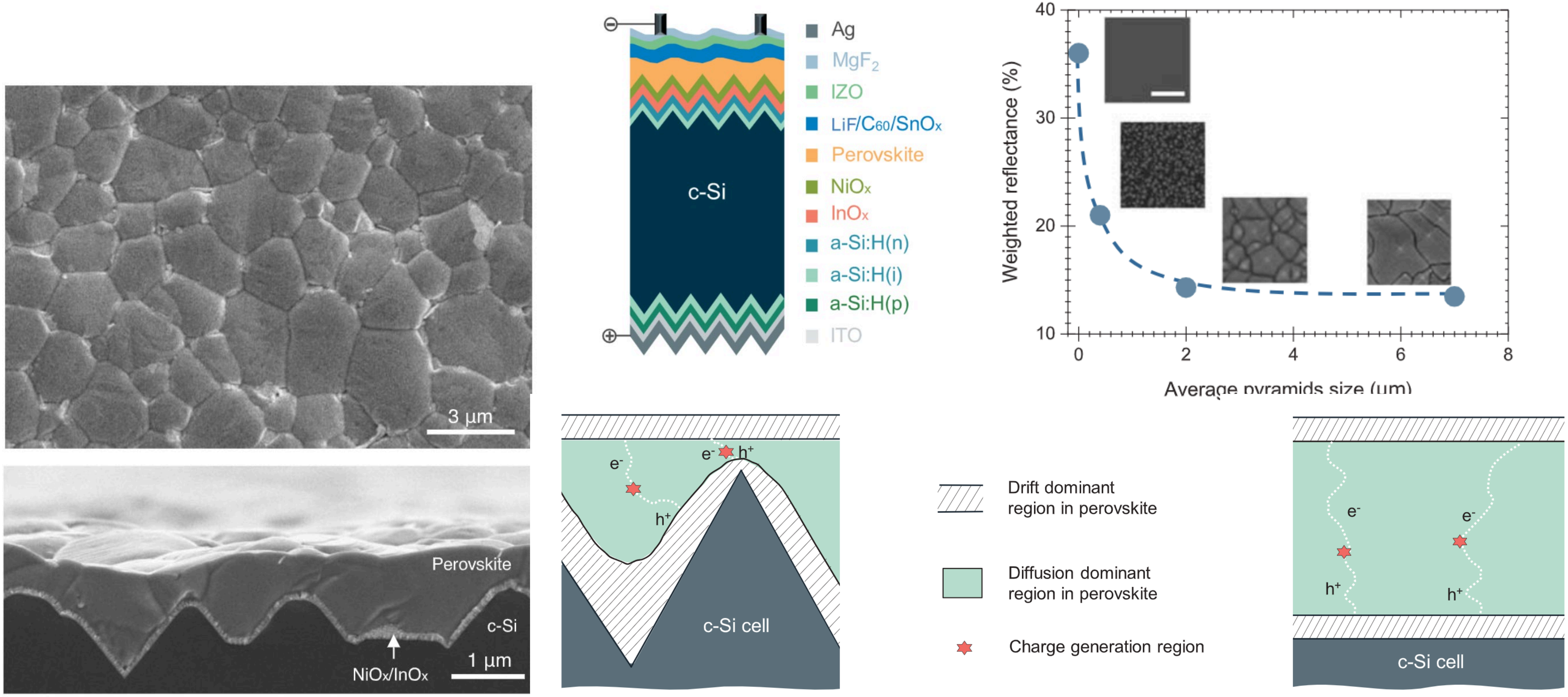
Perovskite Tandem Cells





This plot is courtesy of NREL, Golden, CO.

Perovskite Tandem Cells With Si



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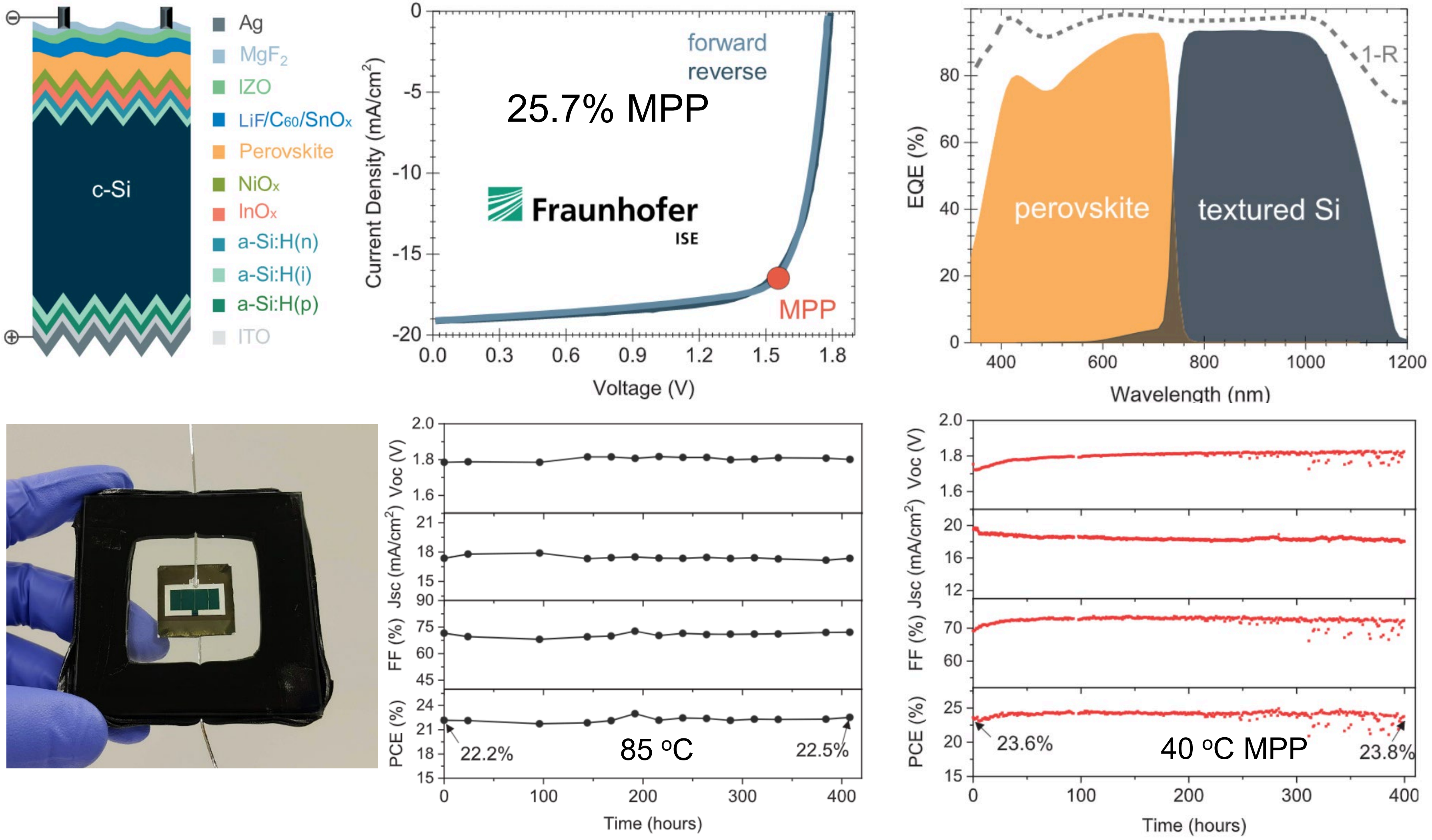
Perovskite Tandem Cells With Si (cont.)



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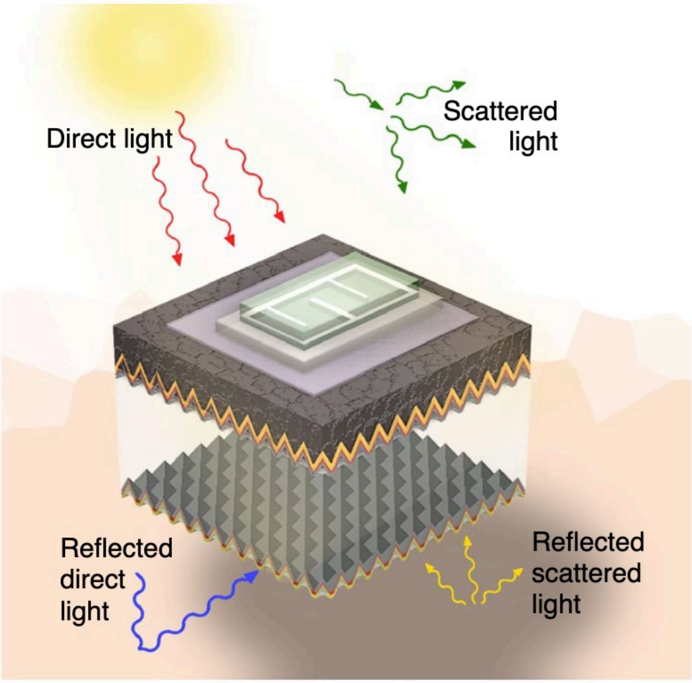
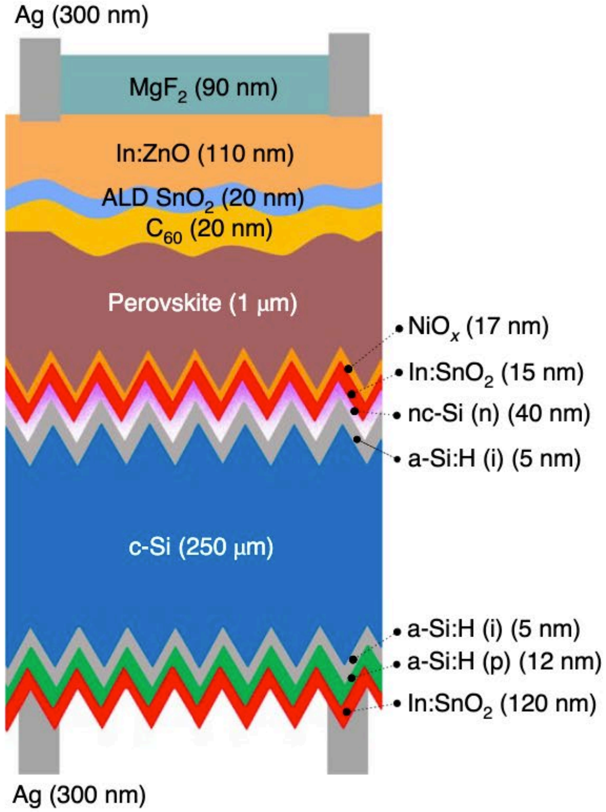
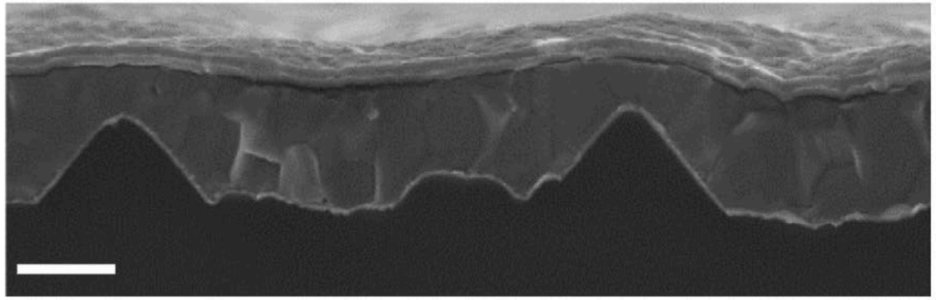
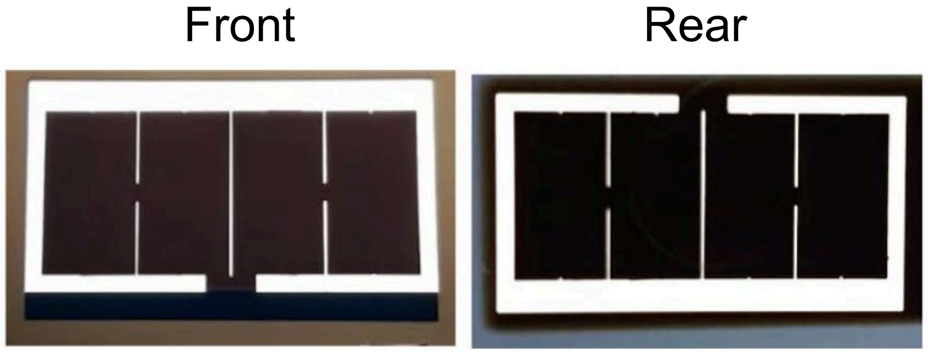


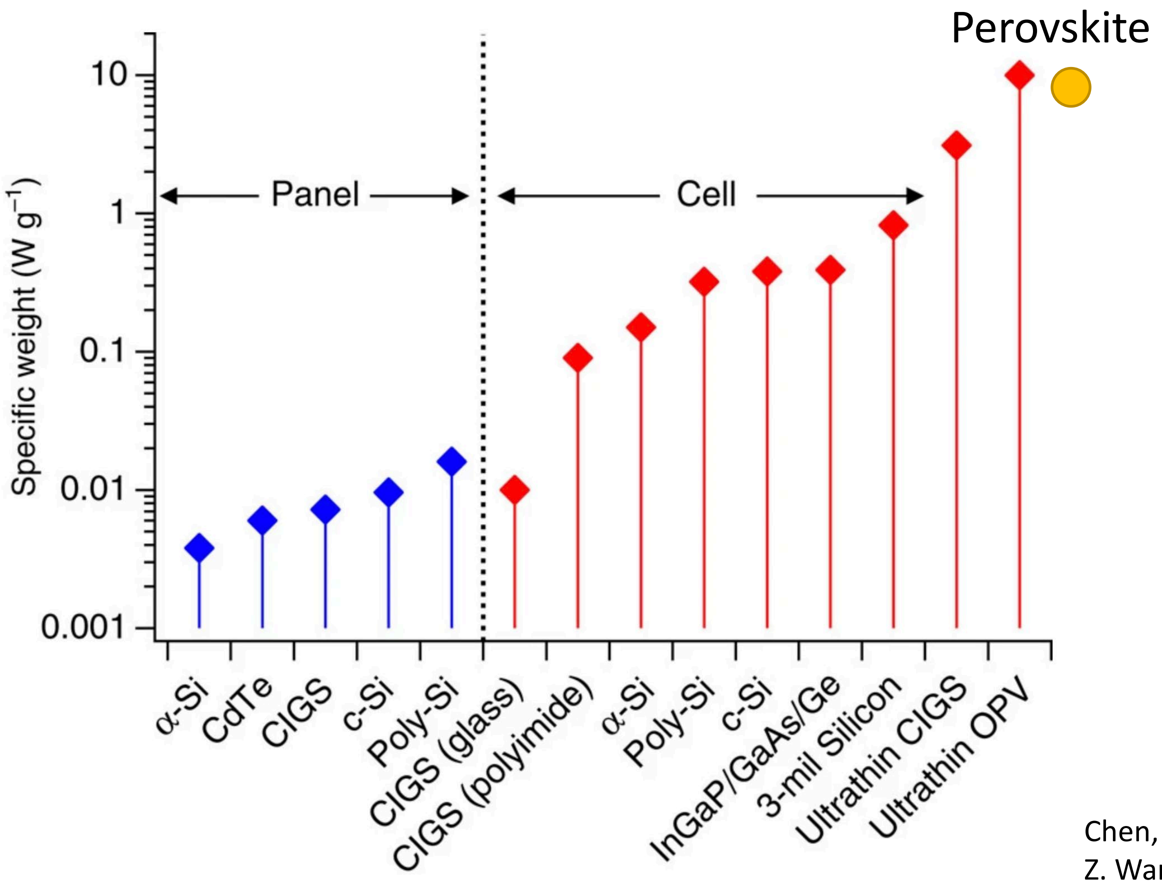






De Bastiani, M., A. J. Mirabelli, Y. Hou, G. Gota, E. Aydin, T. G. Allen, J. Troughton, A. S. Subbiah, F. H. Isikgor, J. Liu, L. Xu, B. Chen, E. Van Kerschaver, D. Baran, B. Fraboni, M. F. Salvador, U. W. Paetzold, E. H. Sargent, and S. De Wolf. "Efficient Bifacial Monolithic Perovskite/Silicon Tandem Solar Cells via Bandgap Engineering." *Nature Energy,* vol. 6, pp. 167–175, 11 January 2021.

Flexibility and Lightweightness Need All-Perovskite Tandems



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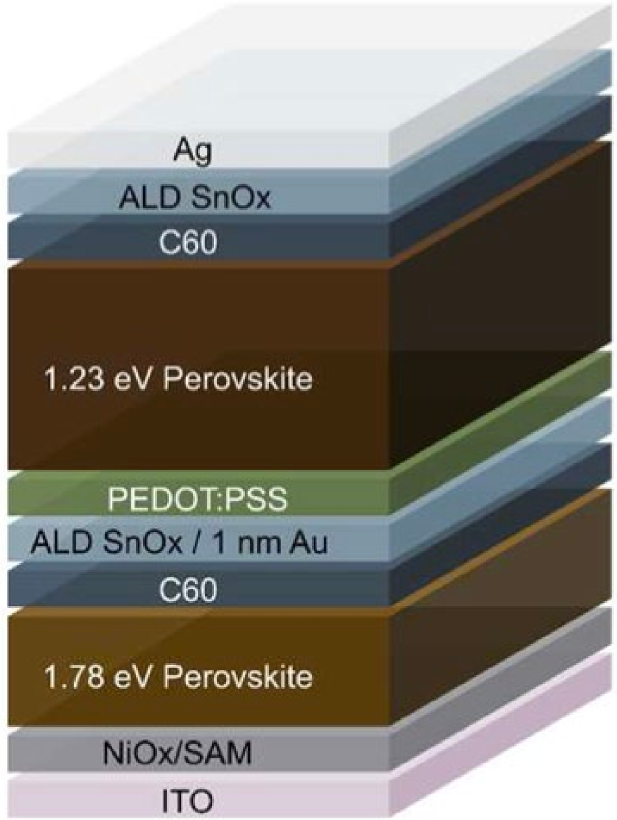

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All-Perovskite Tandem

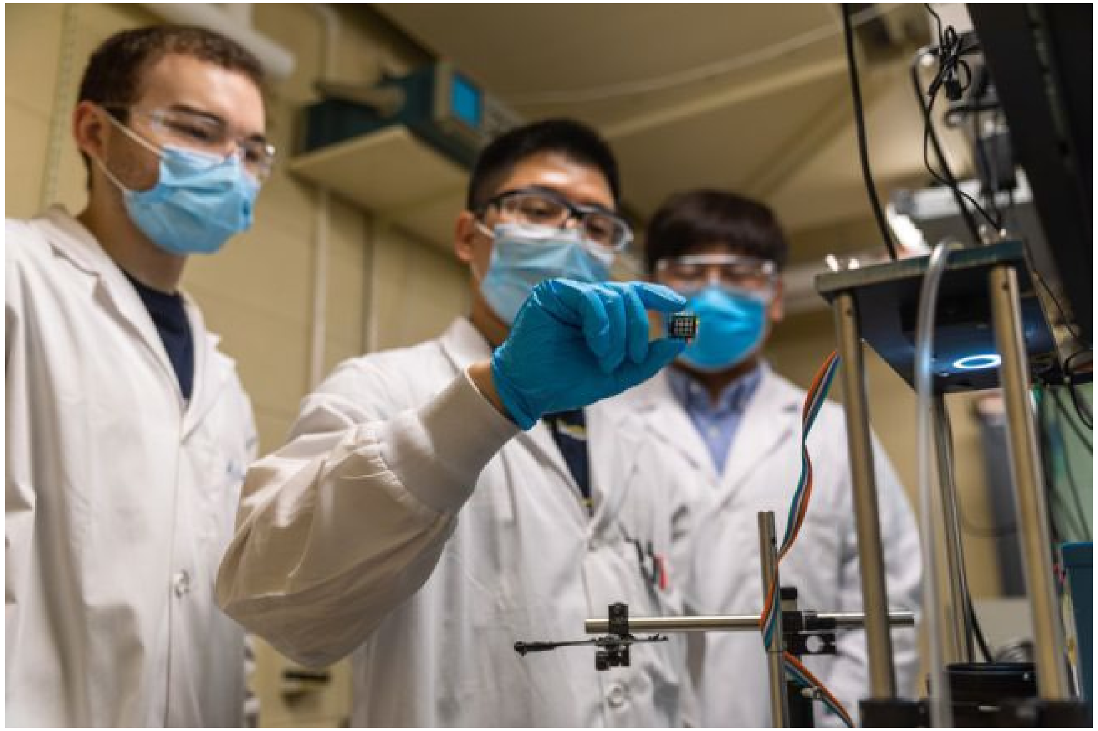
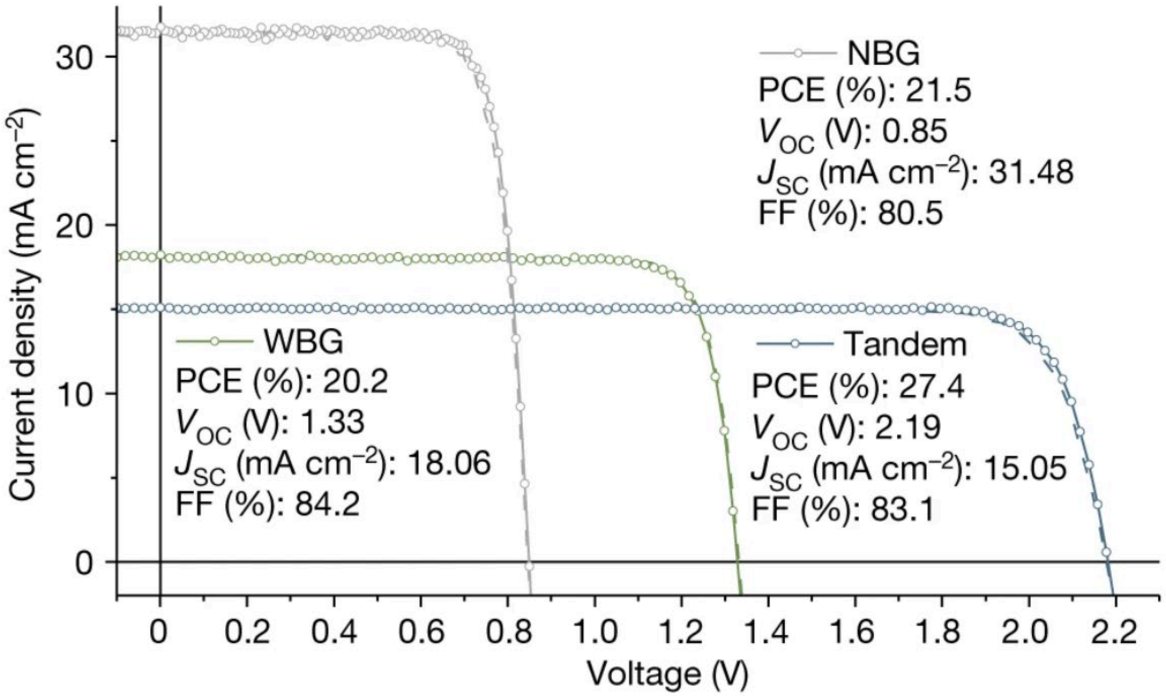


Photo: Aaron Demeter, used with permission.

Champion Device 27.4%
NREL Certified 26.3%



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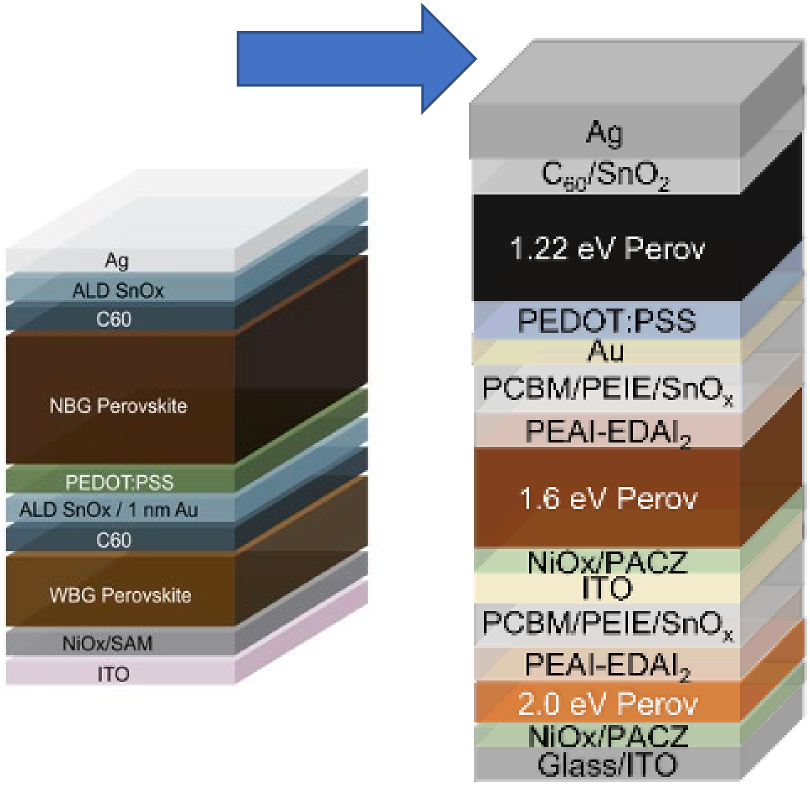
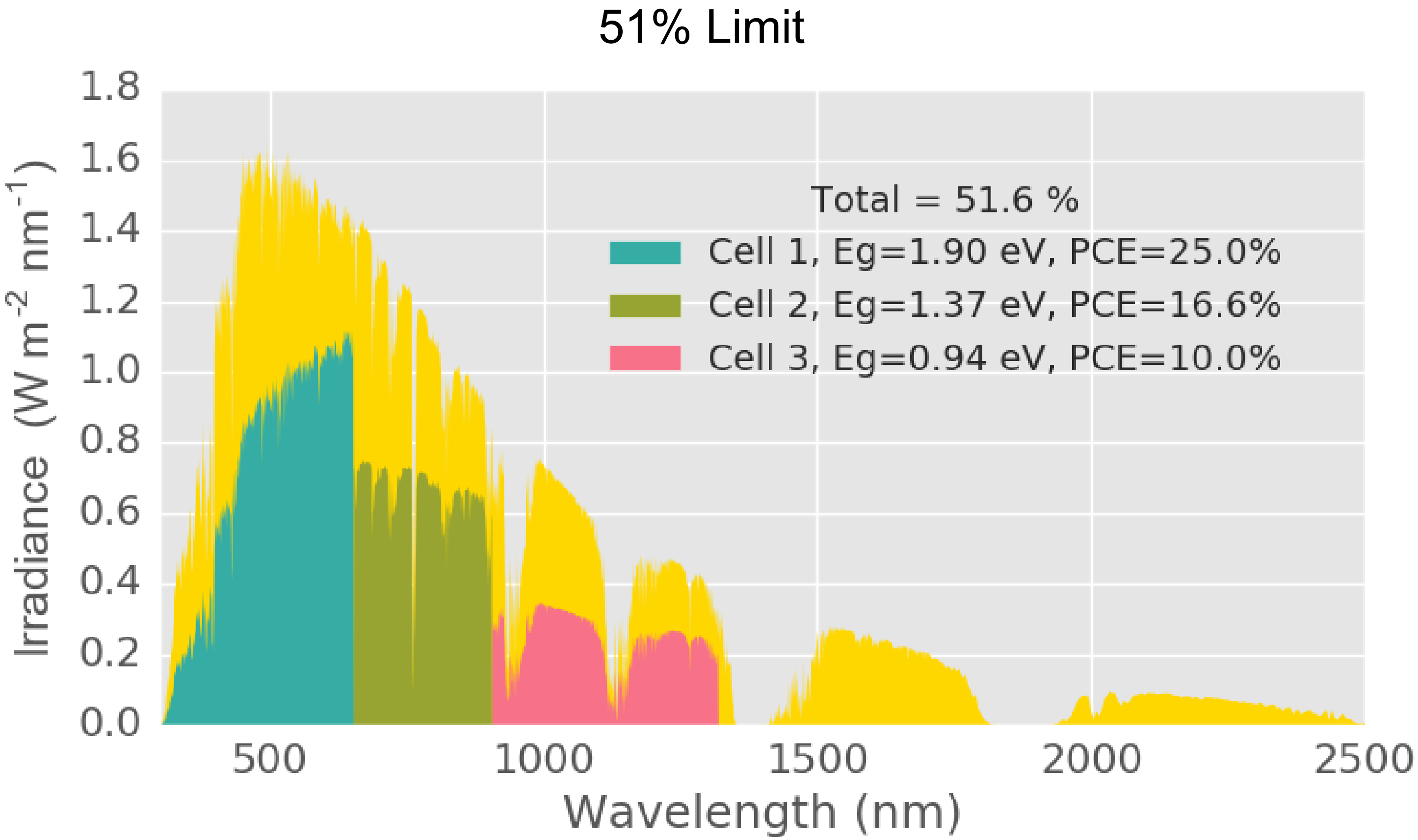
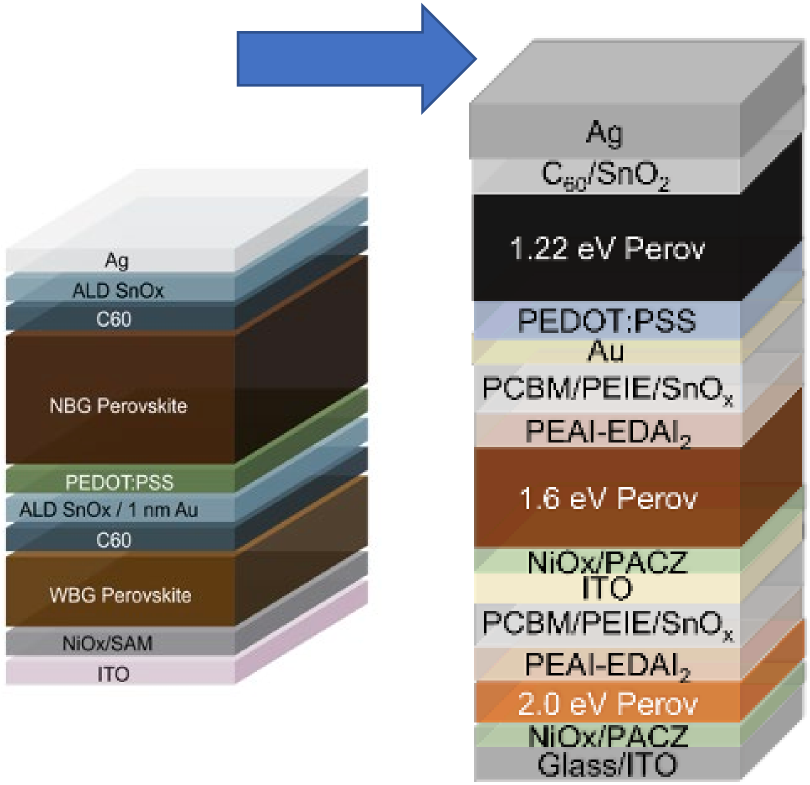
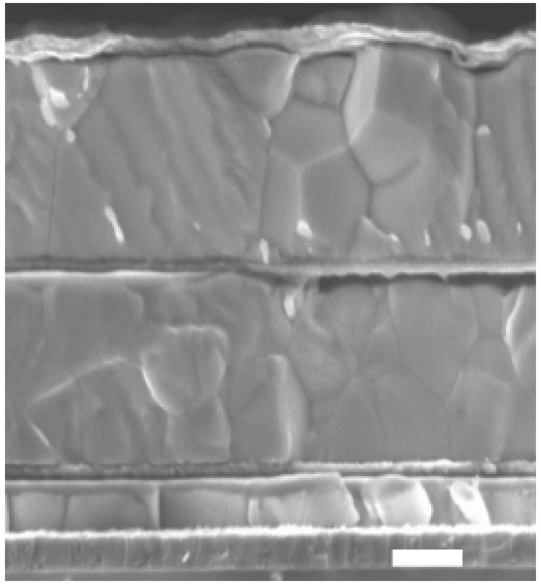
Pushing the Limit: Triple-Junction Cells

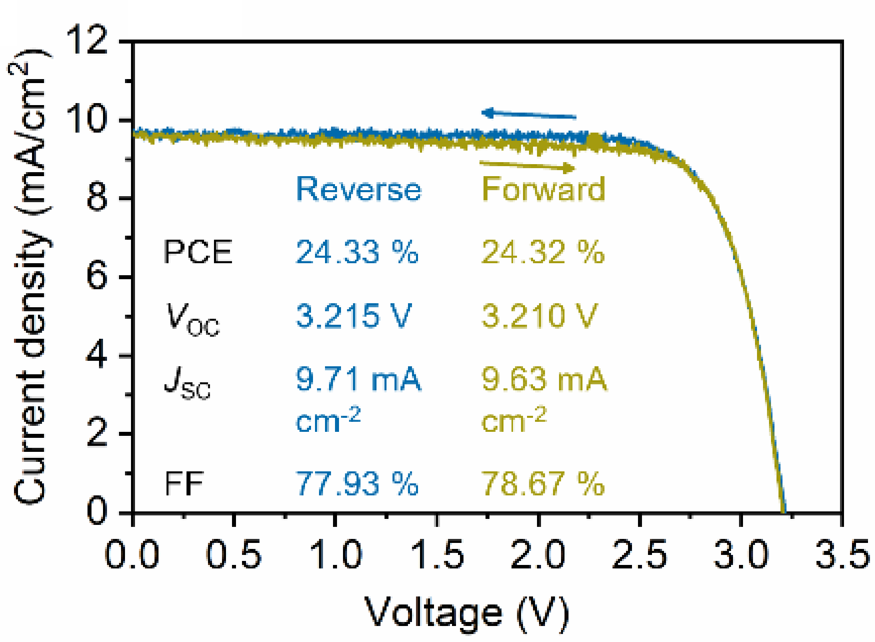




Pushing the Limit: Triple-Junction Cells (cont.)

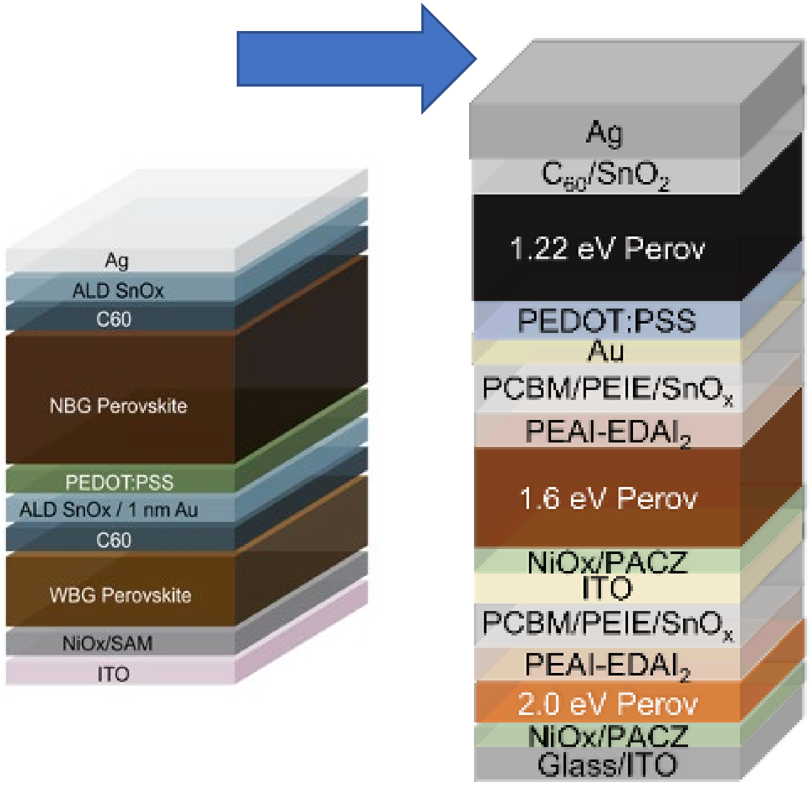


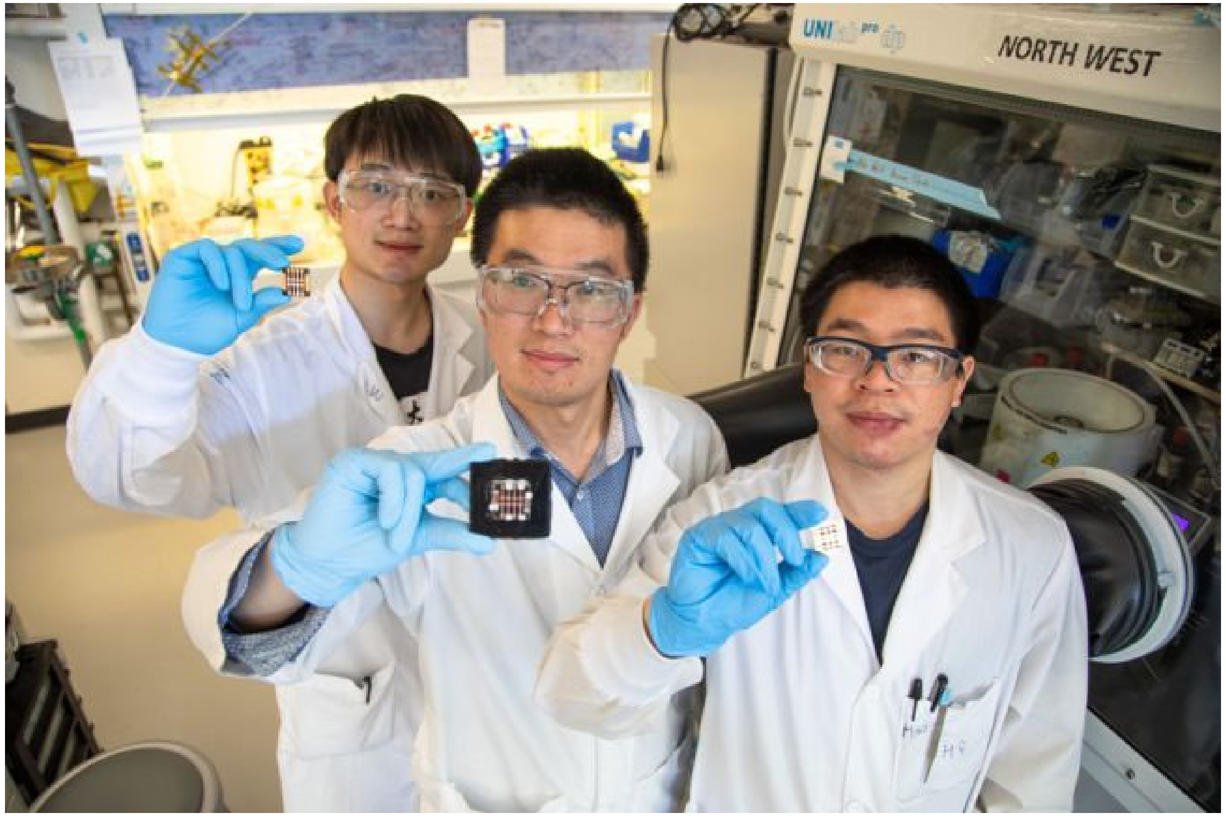




Wang, Z.,…E. H. Sargent. *Nature,* 2023. (In Press)

Pushing the Limit: Triple-Junction Cells (cont.)





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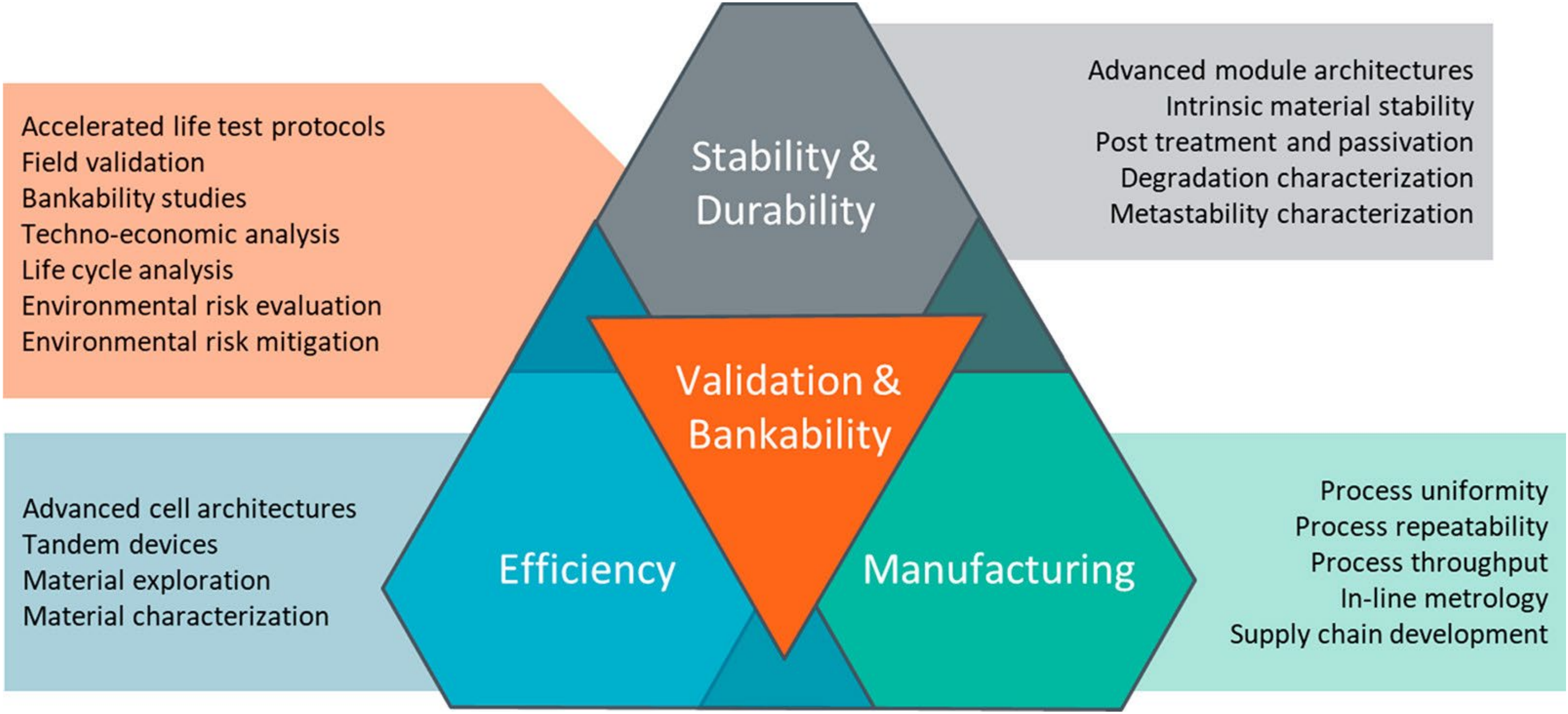
Wang, Z.,...E. H. Sargent. *Nature,* 2023. (In Press)

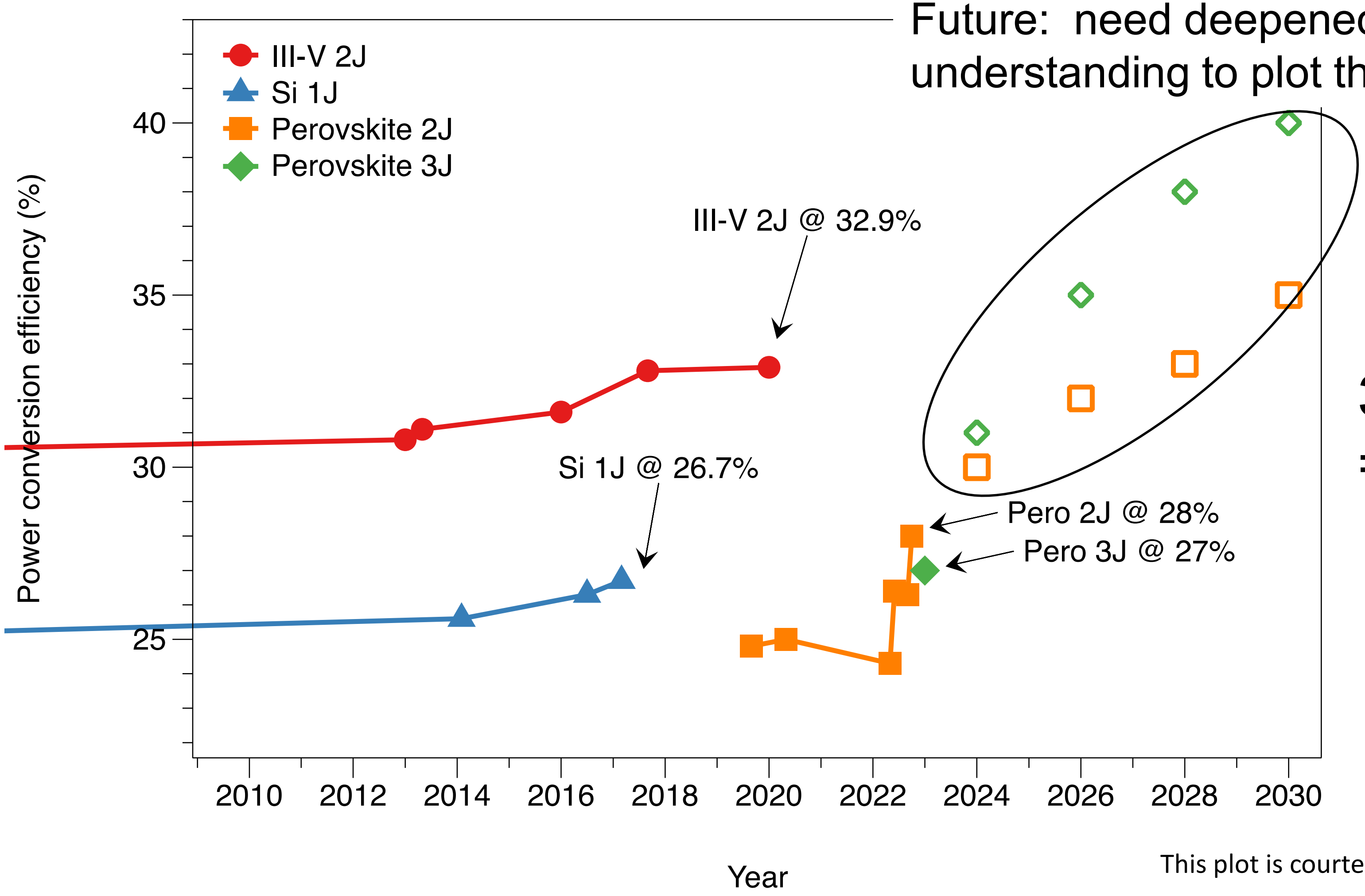
Roadmap for Perovskite PV Deployment



ACS Energy Lett. Vol. 7, pp. 1728–1734, 2022. (Licensed) (Copyright 2022 American Chemical Society)

Efficiency: Not-Yet-Realized Potential of Perovskite Multijunctions

Future: need deepened mechanistic understanding to plot the path forward to >30%



35% tandem at 6 g/m2 = **58** w/g

This plot is courtesy of NREL, Golden, CO.

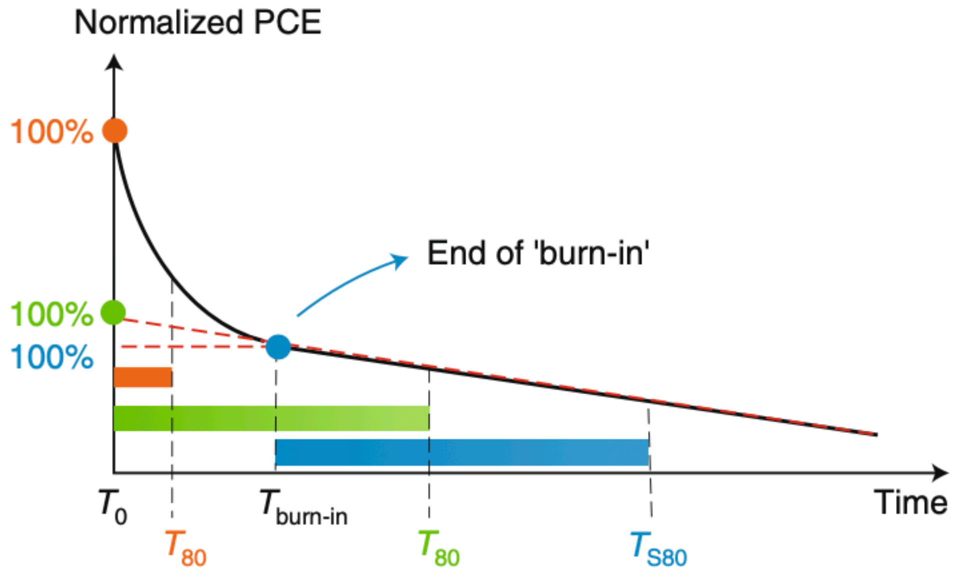
Stability: Accelerated Testing

ISOS: International Summit on Organic PV Stability

Light-soaking (ISOS-L)						
ISOS-L-1	Solar simulator	Ambient (23 ± 4 °C)	Ambient	Light only	Solar simulator	MPP or OC
ISOS-L-2	Solar simulator	65, 85 °C	Ambient	Light & temperature	Solar simulator	MPP or OC
ISOS-L-3	Solar simulator	65, 85 °C	~50%	Light, temperature & RH	Solar simulator	MPP

Increasing T

Increasing RH



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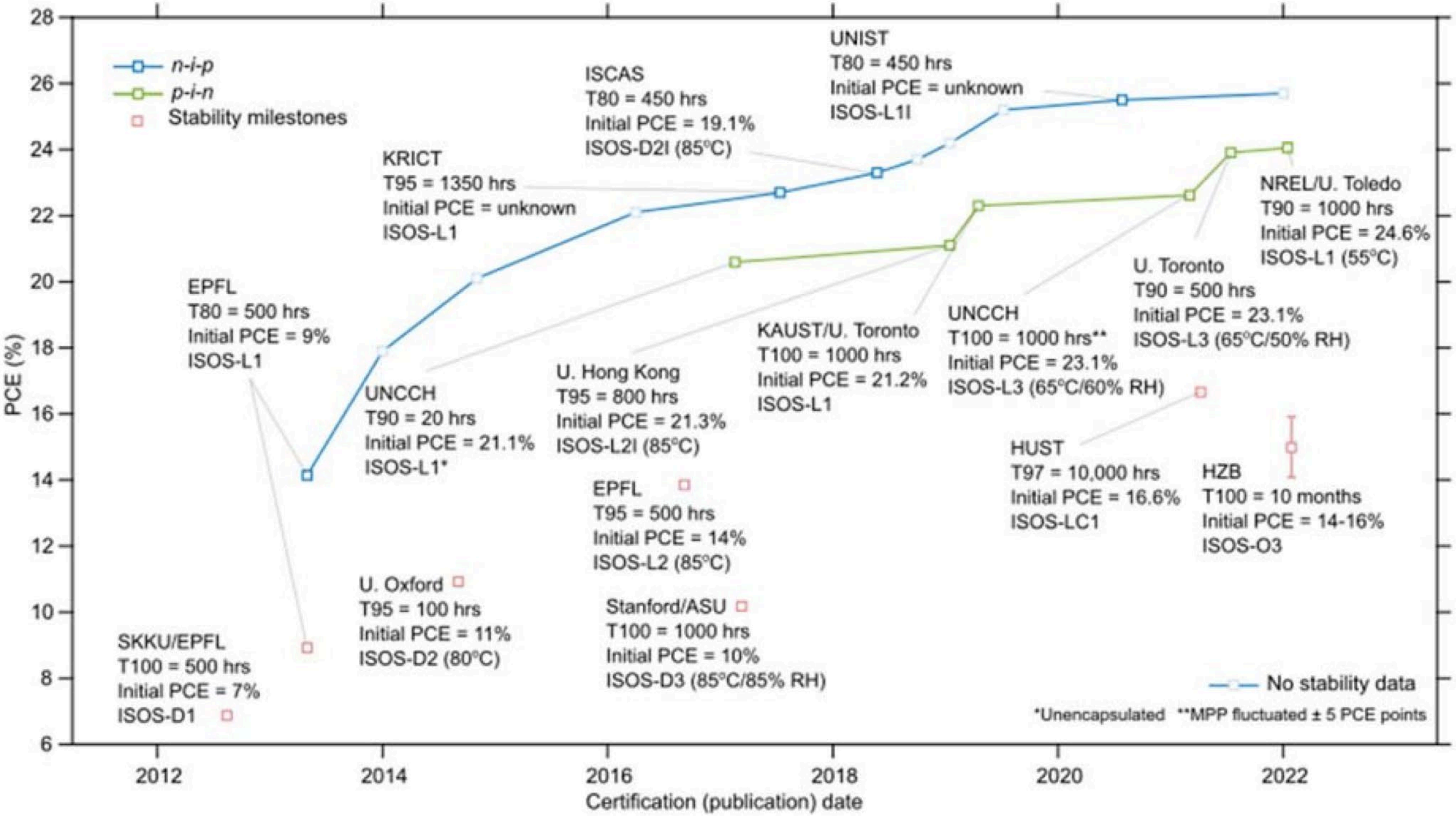
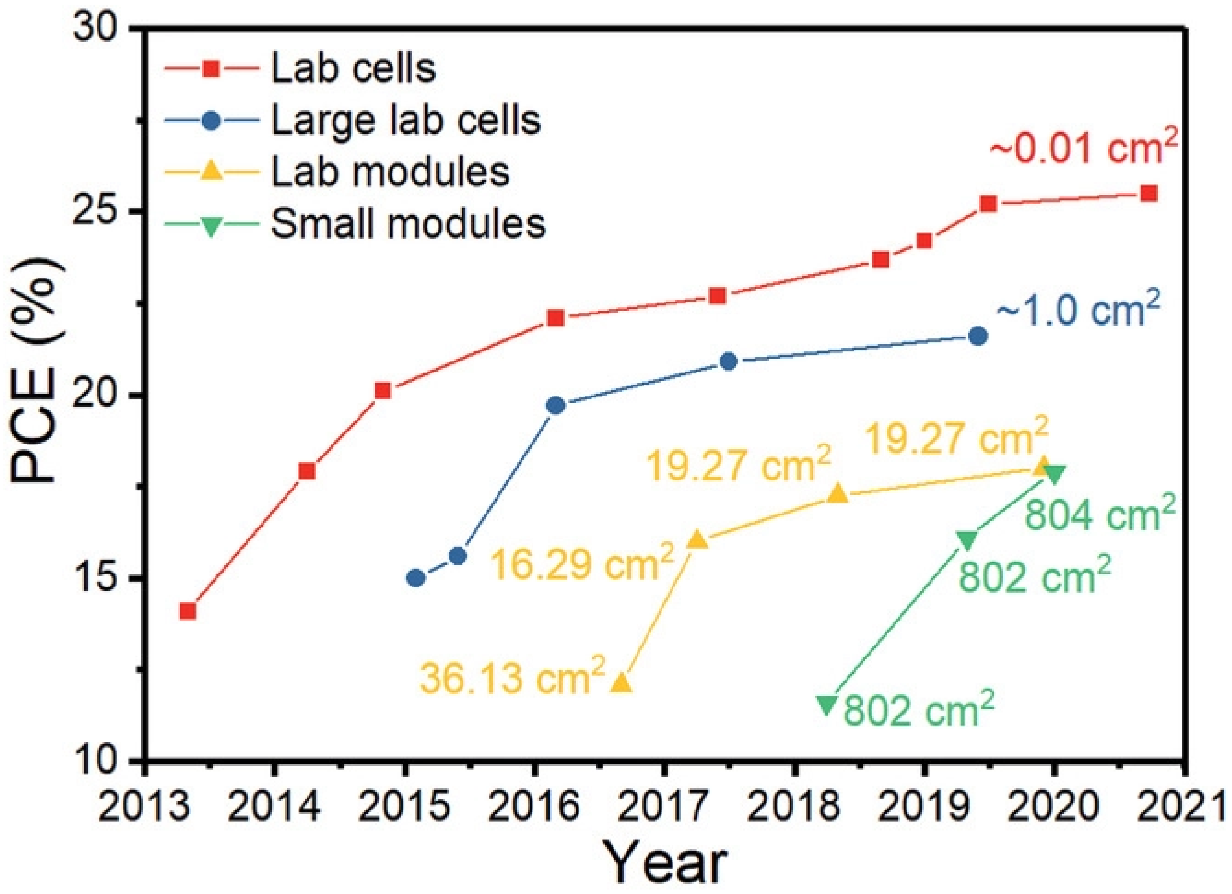
Stability: Accelerated Testing (cont.)



Sargent et al.

Manufacturing: Scale-Up



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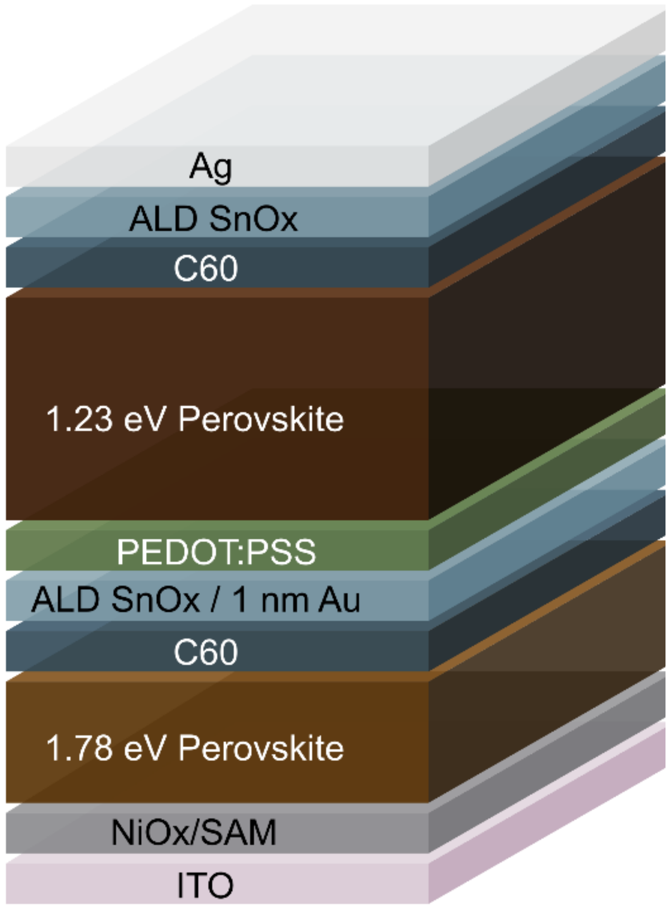
Core Topics for Multijunction Development

- Efficient and Stable Materials Development
- Accelerated Lifetime Testing
- Encapsulation Technology
- Large-Scale Fabrication



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