MULTI-JUNCTION THIN FILM PV FOR SPACE POWER GENERATION

Space Power Workshop, April 25-29, 2022

THE UNIVERSITY OF TOLEDO

WRIGHT CENTER for PHOTOVOLTAICS INNOVATION AND COMMERCIALIZATION

Robert Collins, Michael Heben, Yanfa Yan, Randy Ellingson, Nikolas Podraza, Adam Phillips, Zhaoning Song, Jacques Amar, and Sanjay Khare

The University of Toledo
Toledo, Ohio

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OUTLINE

- Introduction to UToledo's Wright Center for PV Innovation and Commercialization (PVIC)
- Thin Film Space PV R&D at PVIC
- Next Steps for TF Space PV
- Conclusion

PVIC – HIGH IMPACT PHOTOVOLTAICS R&D

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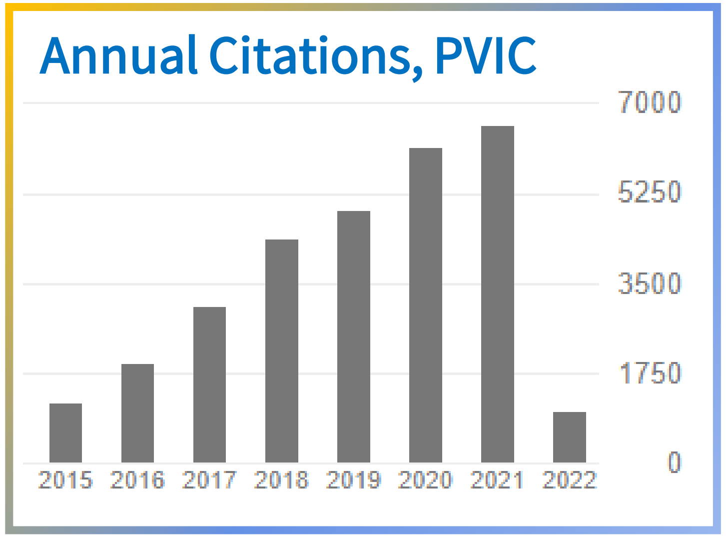
- 20,000 sq. ft. laboratory R&D facility, addressing basic science through commercial deployment
- > 50 people: faculty, research professors, staff, and students
- Key Technologies (UToledo)
  - CdTe (20%, back-illuminated at 8 %)
  - Perovskite (23.2%, tandem cell 23.4%)
- Numerous industry and national lab partners
- Leadership in Two Major Technology Consortia



US-MAC Manufacturing of Advanced Cadmium Telluride

www.usa-cdte.org

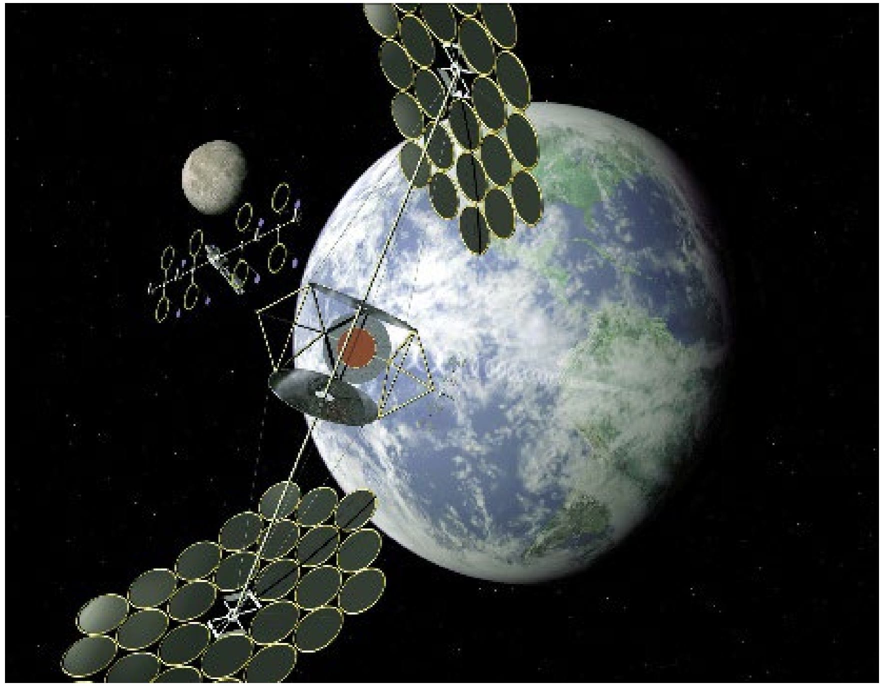
U.S. MAP Manufacturing of Advanced Perovskites

www.usa-perovskites.org

Selected Recent Funding Awards

Year	Sponsor	Partners	Subject
2021	AFRL/USSF (Space Vehicles)	UT (NASA, AFRL)	PV Sheets -- Space-Based Solar Energy Harvesting
2019	AFRL (Space Vehicles)	UT (NASA, AFRL)	Low Cost Flexible Tandem Space Solar Cells
2019	DOE (Solar Energy Technology)	NREL, First Solar	Perovskite PV Stability
2019	DOE (Solar Energy Technology)	CSU, NREL, First Solar, UIC	CdTe PV Technology

THIN FILM PV'S ROLE IN SPACE



- Thin film PV technology has reached efficiencies in the range of 20% - 25%, and have been demonstrated at the 100 cm^2 size range.
- Applications such as SBSP call for larger arrays
- TF PV offers the possibility of stowability, lower costs, and high specific power (both W/kg and W/m^2)
- Such space arrays are a natural place for TF PV

Materials innovation and the level of understanding make TF tandem cells a real possibility, with the potential for efficiencies of 30% and cell/module specific powers of 10 kW/kg.

HIGH SPECIFIC POWER CdTe PV DEVICES ON FLEXIBLE SUBSTRATES

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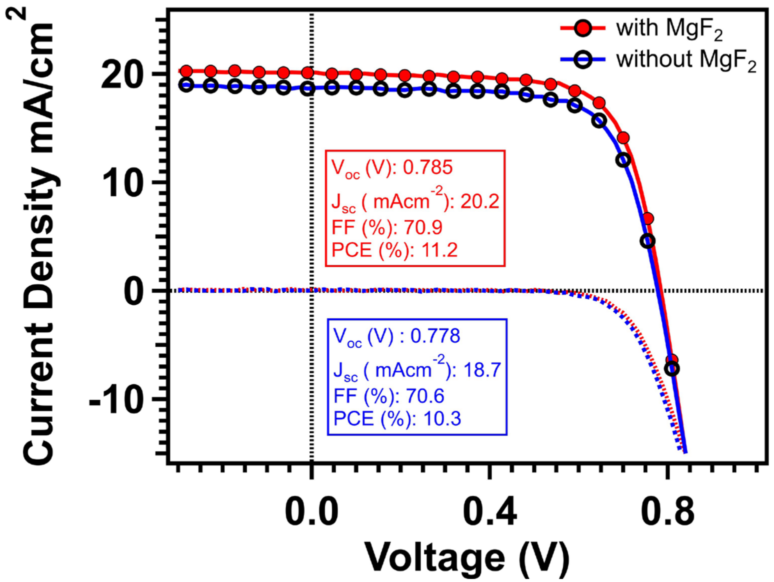
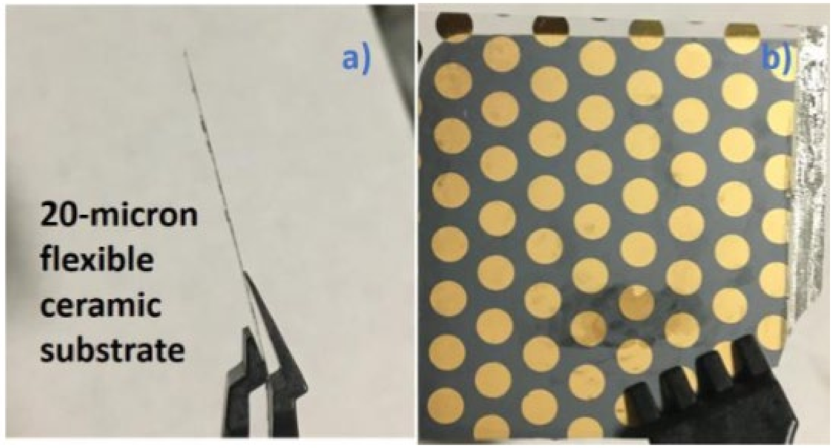
Typical CdTe devices grown on 3.2 mm glass can achieve efficiency of 20% (AM1.5)
→ Glass makes devices too heavy for space applications
Move to thinner, lighter substrates
→ Y-stabilized ZrO (YSZ), highly flexible ceramic substrate with high temperature stability

Example: CSS CdS/CdTe on 20 µm thick 3 mol % Y (3YSZ)





Substrate	20 µm 3YSZ	3.2 mm Tec™ 15M
Efficiency	11.2 %	20.0%
Specific Power W/kg	6,300	325

Higher specific powers by:

High temp deposition
Replace CdS with $(In_xGa_{1-x})_2O_3$

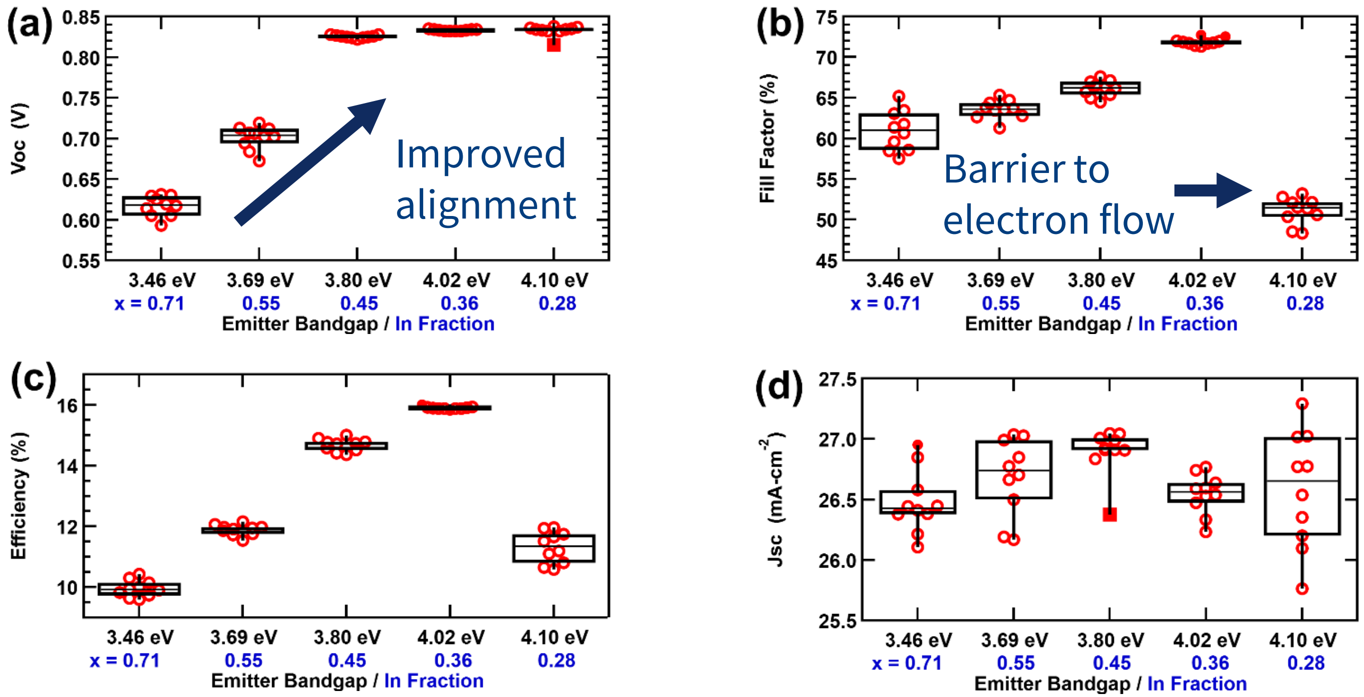
After preliminary demonstration, there are several routes to increase efficiency to 20%.

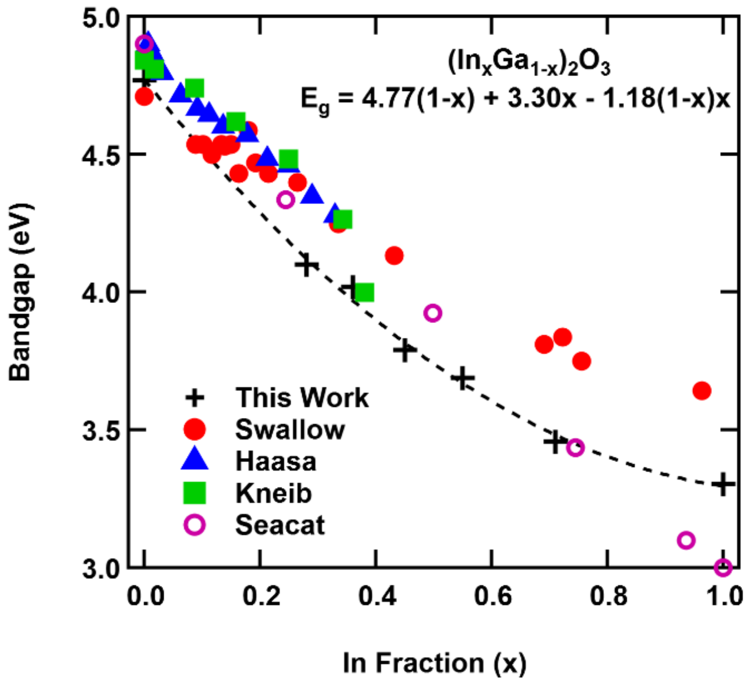
NEW CLASS OF TUNABLE EMITTERS

- Full range of compositions from In_2O_3 to Ga_2O_3 -- e.g. $(In_xGa_{1-x})_2O_3$ ("IGO")
- Relevance to tandem device development
- Straightforward and robust fabrication

Proper band alignment at front contact for reduced recombination → Higher V_{OC}

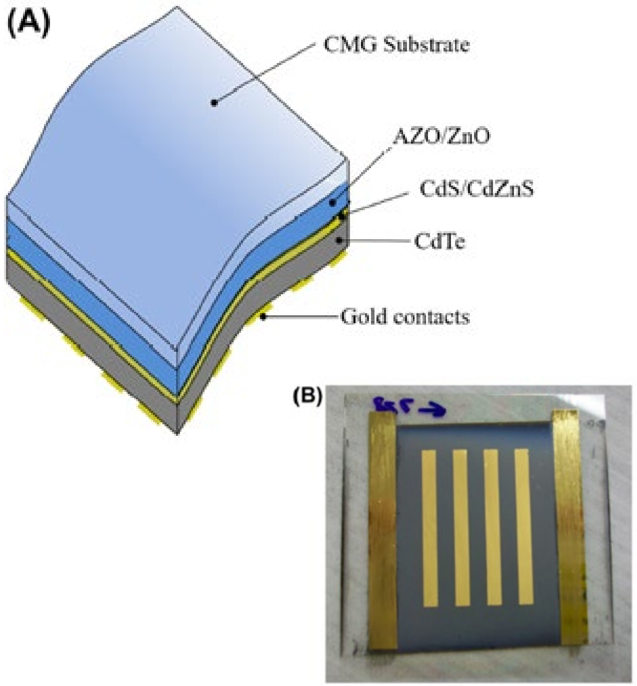
For $CdSe_xTe_{1-x}$:





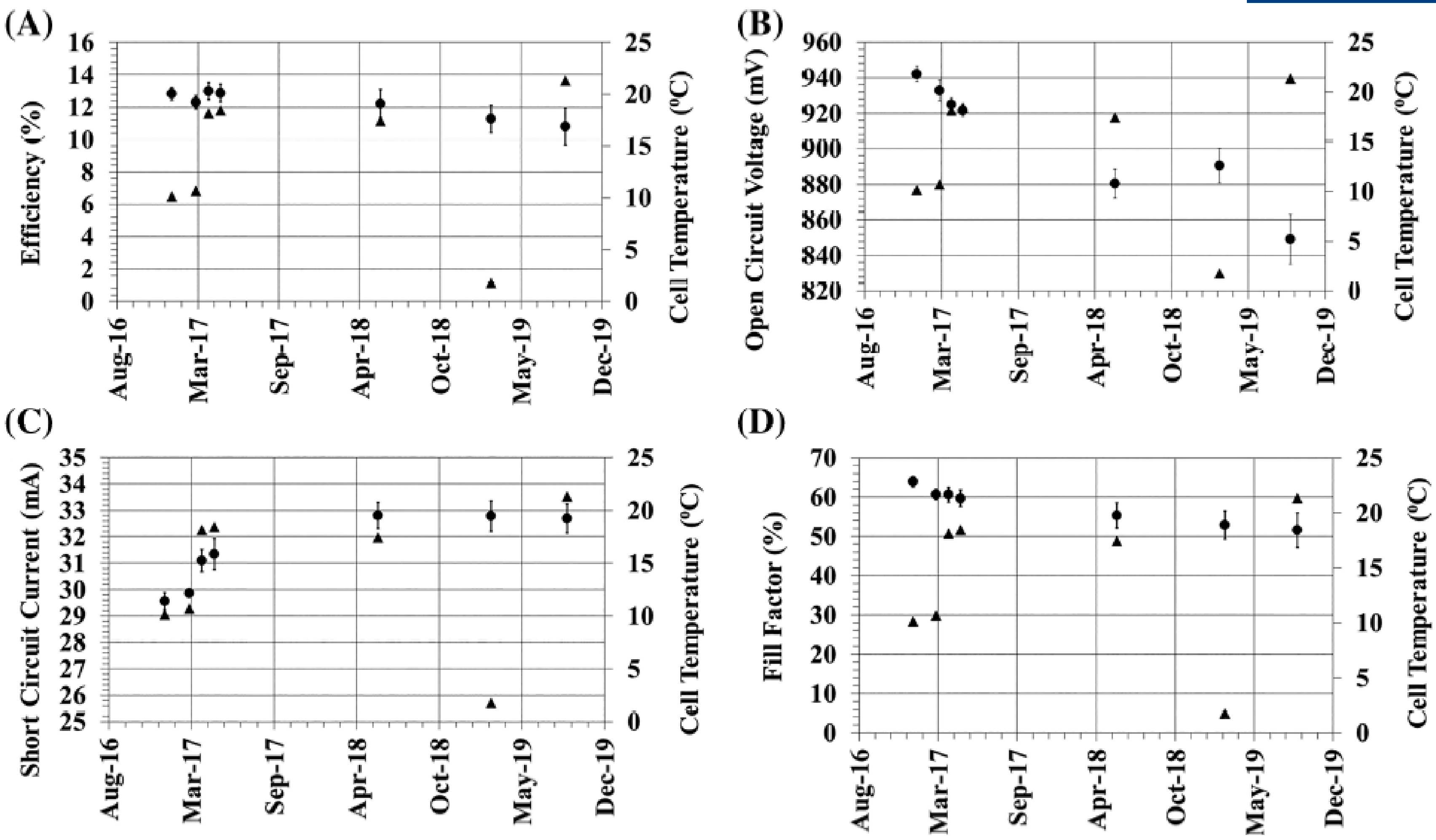
Bandgap from 3.30 - 4.77 eV
Can dope with SnO_2/ITO target

CdTe CELLS ARE RADIATION HARD



- CdTe device design
- 60 x 60-mm w/ 100 µm cover glass

LEO 3 YR Test (2021 UK colleagues' results)

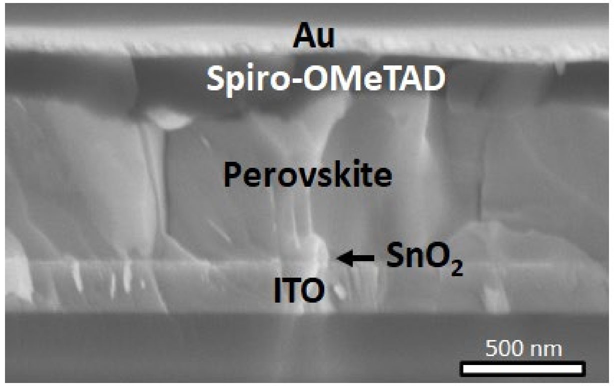


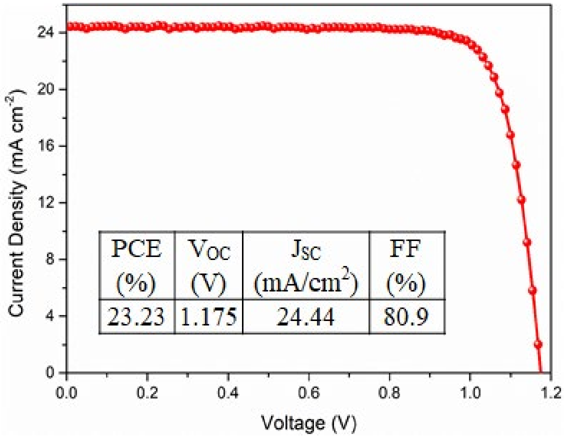
D. A. Lamb et al., **Thin film cadmium telluride solar cells on ultra-thin glass in low earth orbit -- 3 years of performance data on the AlSat-1N CubeSat mission**, *Progress in Photovoltaics* (2021), DOI: 10.1002/pip.3423

FLEXIBLE PEROVSKITES FOR SPACE

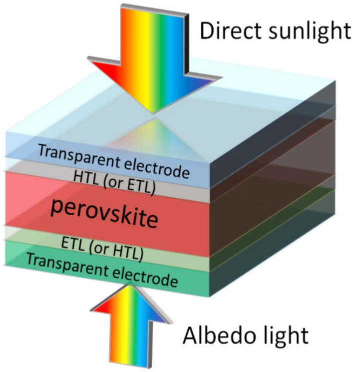
- Demonstrated >23% efficient perovskite solar cells on rigid glass substrates.
- Demonstrated ~18% efficient perovskite solar cells on flexible lightweight plastic (PET) substrates.
- Demonstrated >18% efficient bifacial perovskite solar cells with a bifaciality factor of 96%.

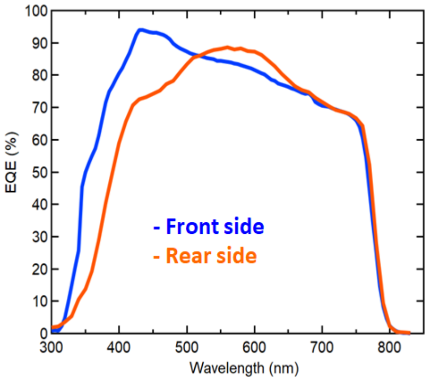
Perovskite solar cell on a rigid glass substrate

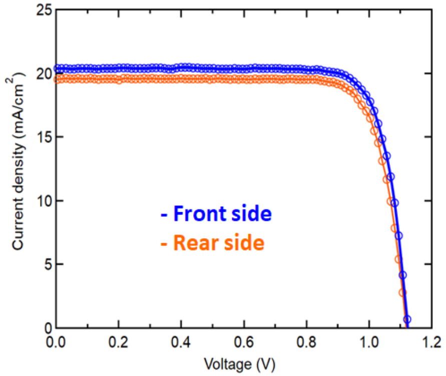




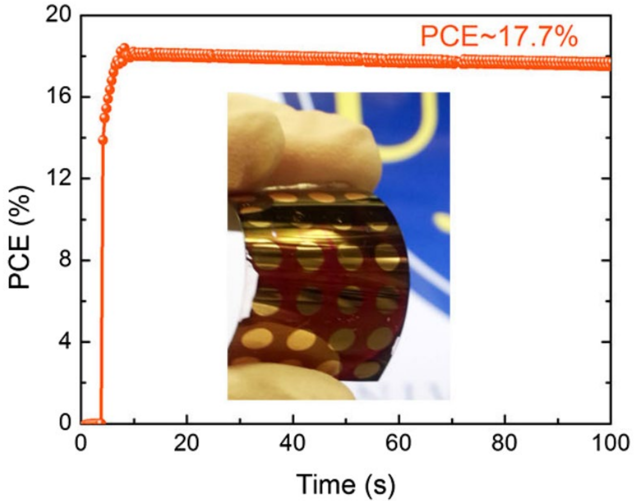
Bifacial perovskite solar cells







Sustainable Energy Fuels 5, 2865 (2021). *Adv. Mater. 34,* 2196805 (2022).

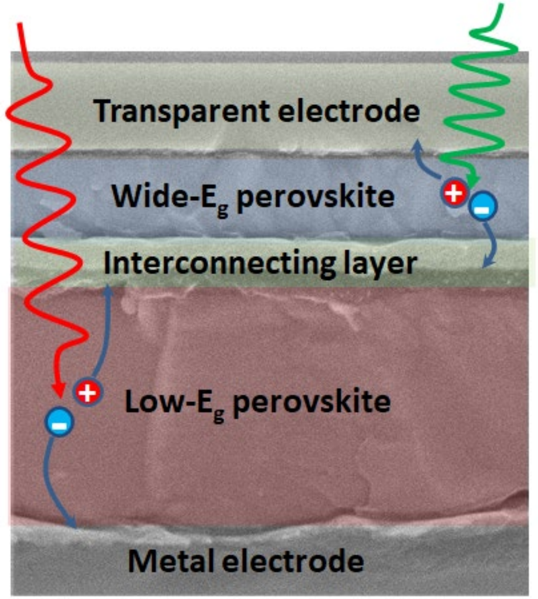


Perovskite solar cells on a flexible plastic substrate

ACS Energy Lett. 2, 2118 (2017).
Solar RRL 3, 1900078 (2019).

HIGH EFFICIENCY PEROVSKITE TANDEMS

- Perovskite/perovskite thin-film tandem solar cells
  - 1.75-eV wide-bandgap Pb perovskite
  - 1.25-eV low-bandgap Sn-Pb perovskite
- Demonstrated >23.3% efficient perovskite/perovskite tandem solar cells on rigid glass substrates.
  - Once the best in the world (2019)
- Demonstrated >21% efficient perovskite/perovskite tandem solar cells on flexible lightweight plastic substrates.
  - A high specific power of > 850 W/kg

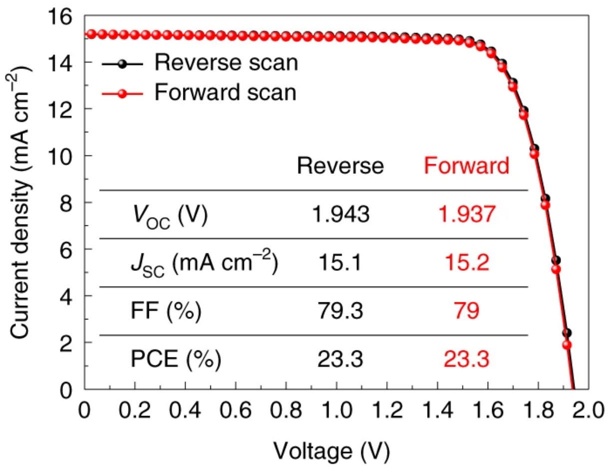


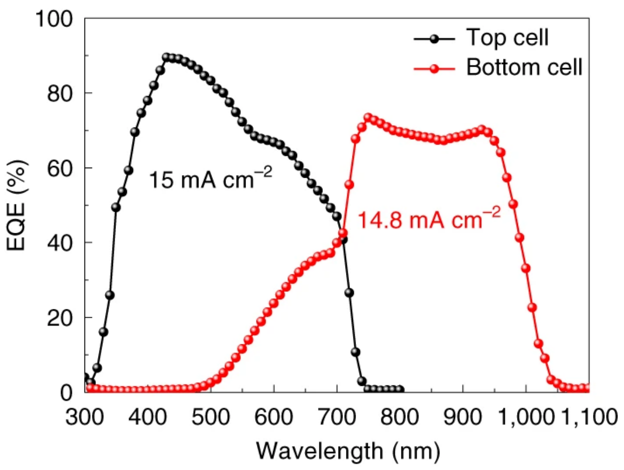
High efficiency perovskite/perovskite tandem solar cells

Nat. Energy 3, 1093 (2018).
Science 364, 475-479 (2019).
Nat. Energy 5, 768–776 (2020).

Flexible perovskite/perovskite tandems on lightweight PET substrates

J-V and EQE of the best-performing cell

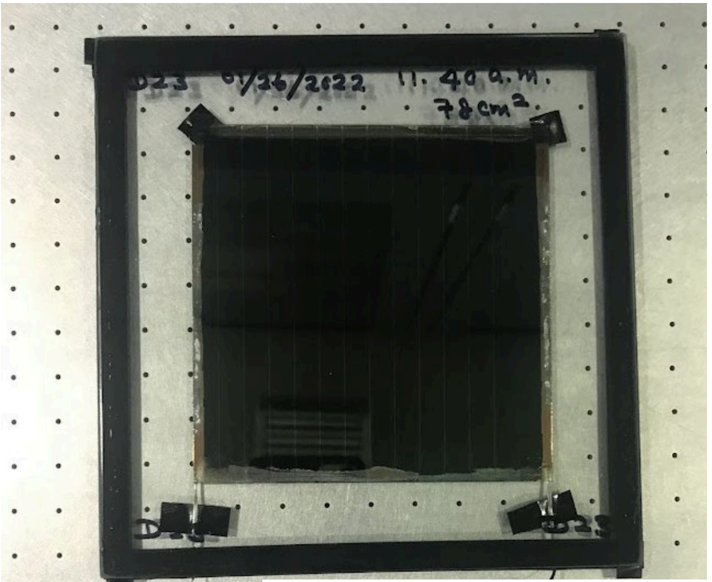


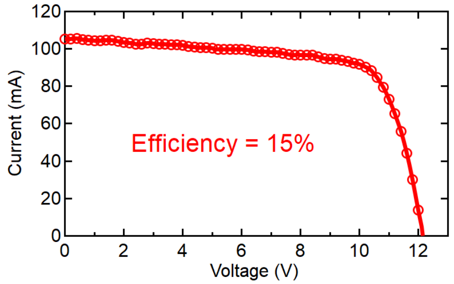


SCALING TOWARDS PV SHEETS

- Demonstrated >15% efficient perovskite mini-modules, ~100 cm^2 area using scalable deposition methods.
  - Slot-die coating, blade coating, evaporation.
  - Perovskite films are processed in ambient.
  - Glass-glass encapsulation with edge sealing.

Perovskite solar modules encapsulated in a 6” by 6” package





UT module outdoor test @ NREL

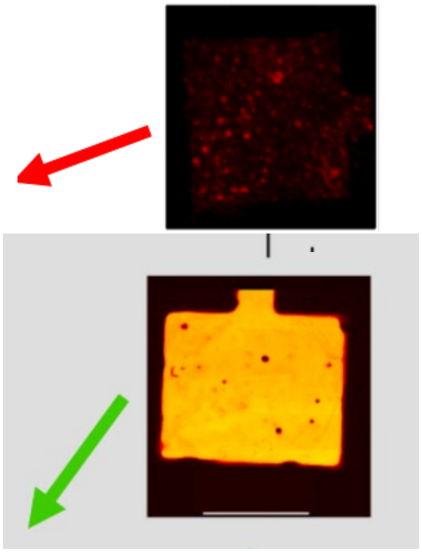
Climate control room

PEROVSKITE CELL RADIATION RESILIENCE

In collaboration with NASA Glenn Research Center and Naval Research Laboratory

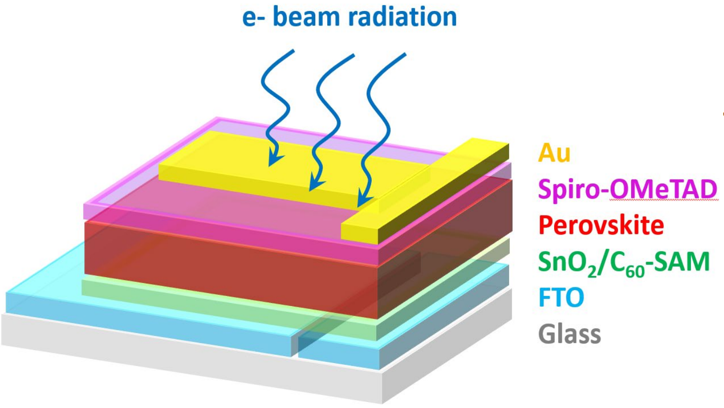
- Irradiated cells retained high V_{OC} and FF after high-fluence electron radiation.
- The pronounced loss in J_{SC} is mainly due to the glass discoloration.
- Potential for perovskite space PV -- if stable perovskite compositions and space-suitable substrates are employed.

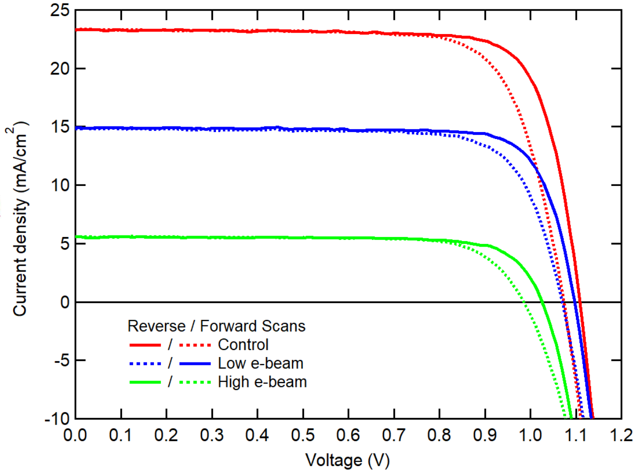
No barrier

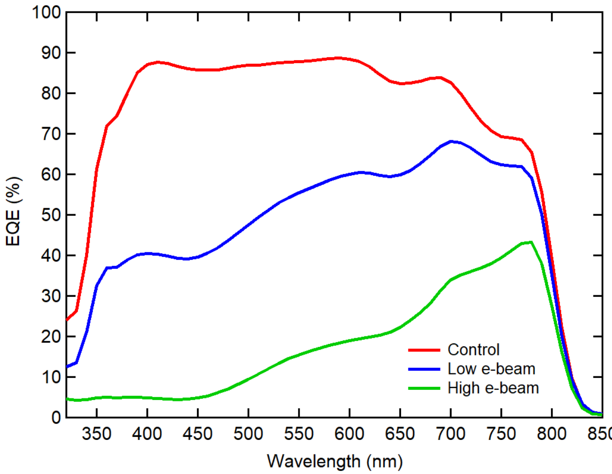


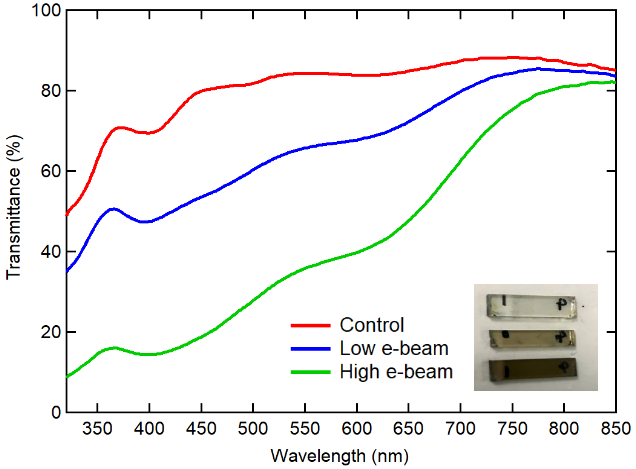
Control: ambient
Low e-beam: 10^{13} e/cm^2
High e-beam: 10^{15} e/cm^2

Perovskite solar cells after electron beam radiation





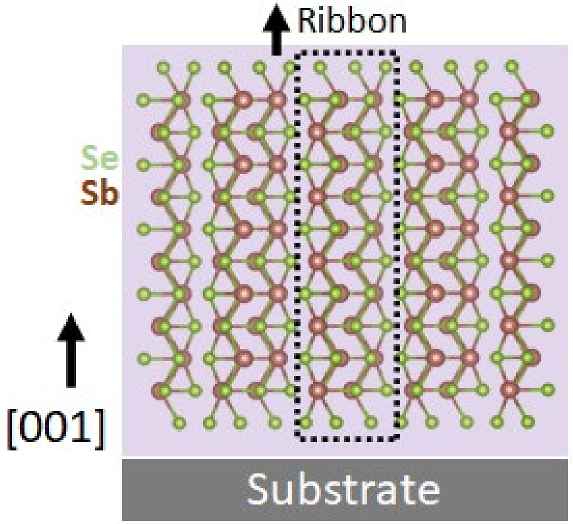




J. Phys. Chem. C 124, 1330–1336 (2020).

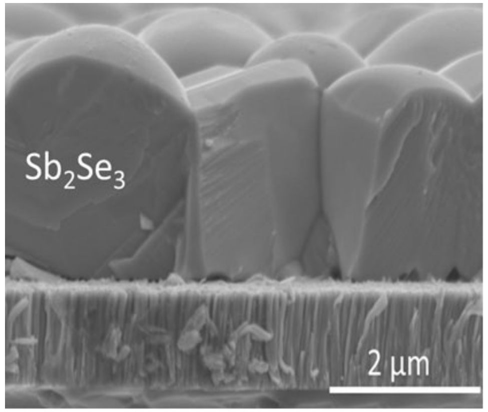
NOVEL ABSORBERS

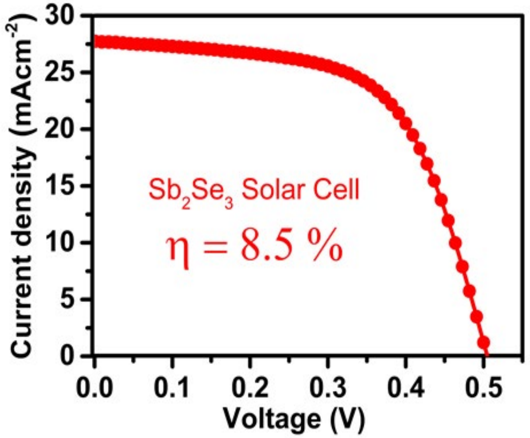
- Antimony chalcogenide
  - Earth-abundant, low toxicity, low-cost
- Demonstrated >8.5% efficient low-cost antimony selenide (Sb_2Se_3) solar cells.
  - Prepared by scalable close space sublimation
  - One of the best efficiencies for this technology
- Developed a hydrothermal methods to prepare 6% Sb_2S_3 and >8.4% efficient $Sb_2Se_{3\text{-}x}S_x$ solar cells.
  - Low-cost solution materials and processing



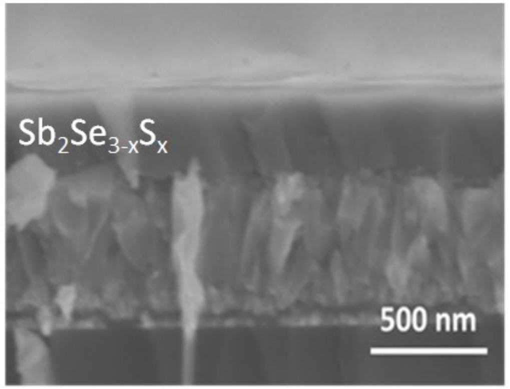
Crystal structure of 1D Sb_2Se_3

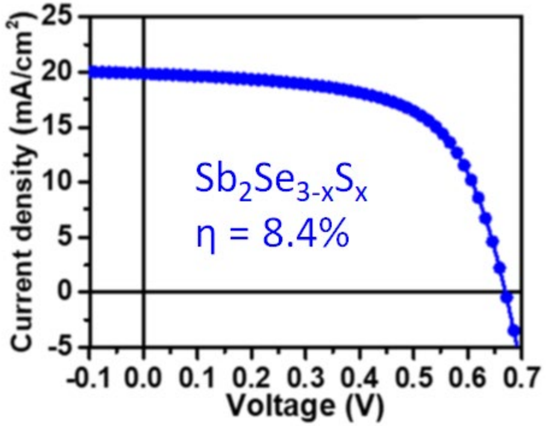
Sb_2Se_3 prepared by close-space sublimation





Adv. Funct. Mater., DOI:10.1002/adfm.202110032 (2021).
ACS Appl. Energy Mater. 4, 4313–4318 (2021).



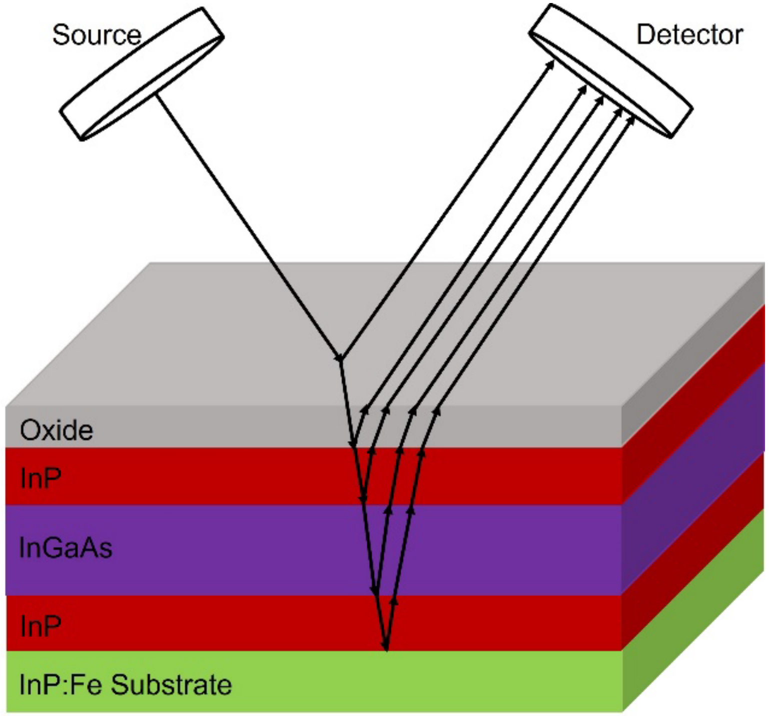


$Sb_2Se_{3\text{-}x}S_x$ prepared by hydrothermal growth

THZ RANGE ELLIPSOMETRY AND OPTICAL HALL EFFECT MEASUREMENTS

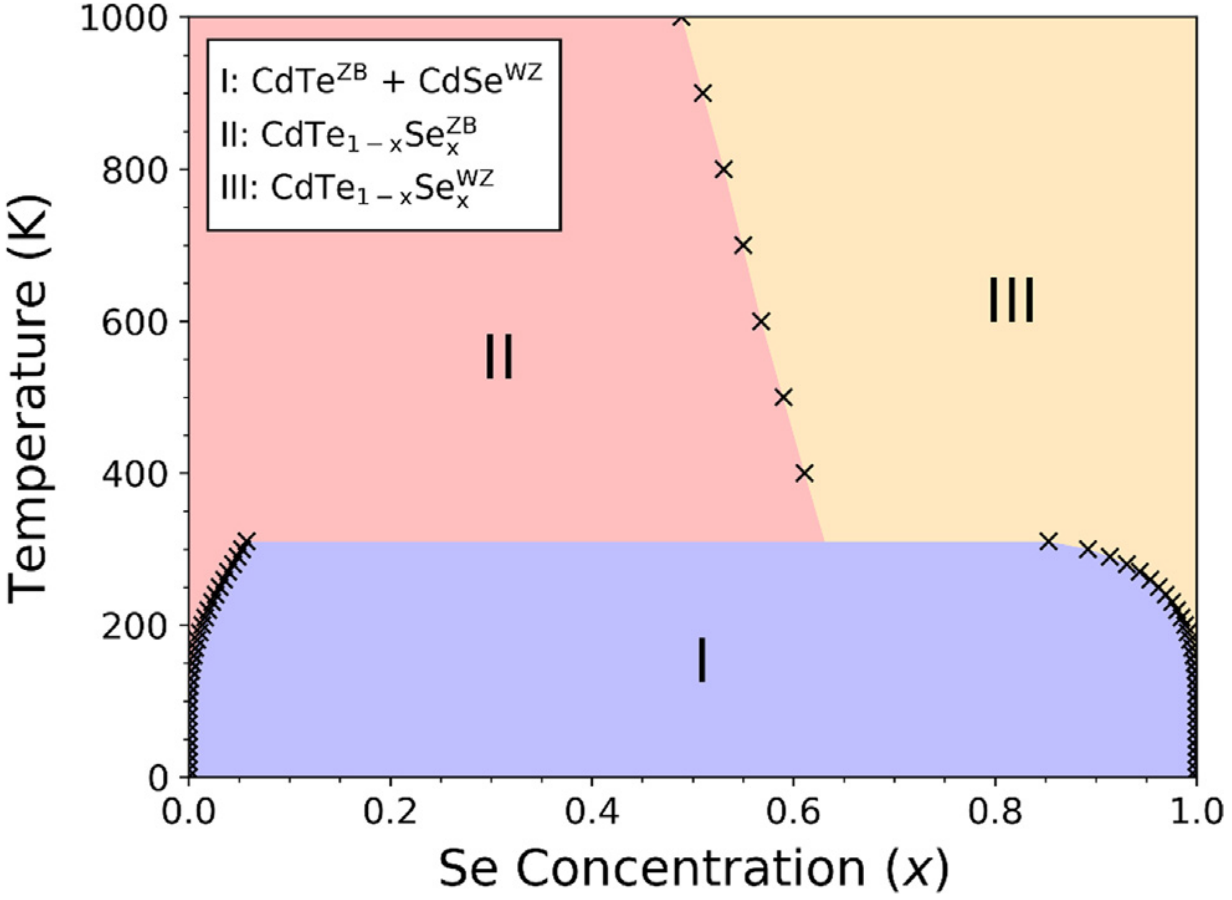
Determine charge carrier transport properties of epitaxial III-V compounds in multilayer stacks and component layers in perovskite PV

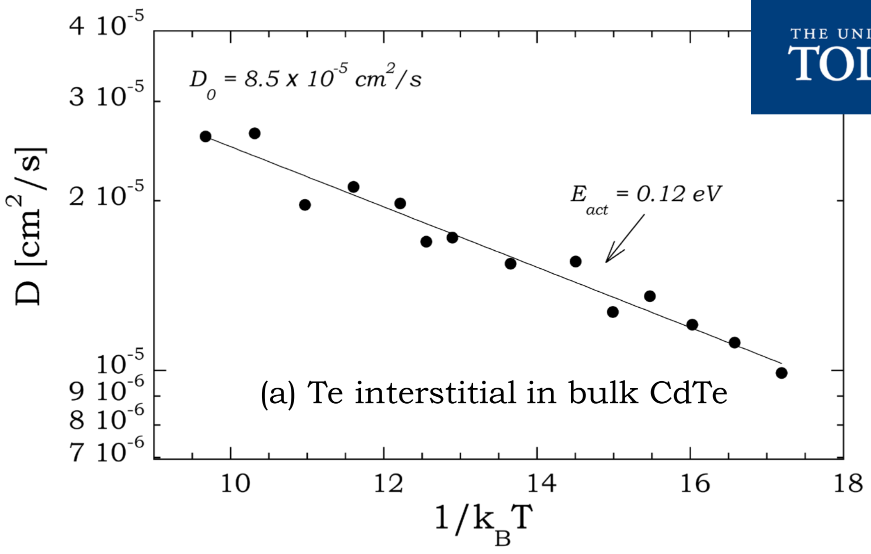
Demonstrated sensitivity to a wide range of transport properties for wafer (Si), epitaxial (InGaAs, InAlAs), polycrystalline (hybrid organic-inorganic perovskites, CdTe, CIGS) semiconductors, transparent conducting oxides (ITO, AZO, ZnO), and electron/hole transport layers (PEDOT:PSS)

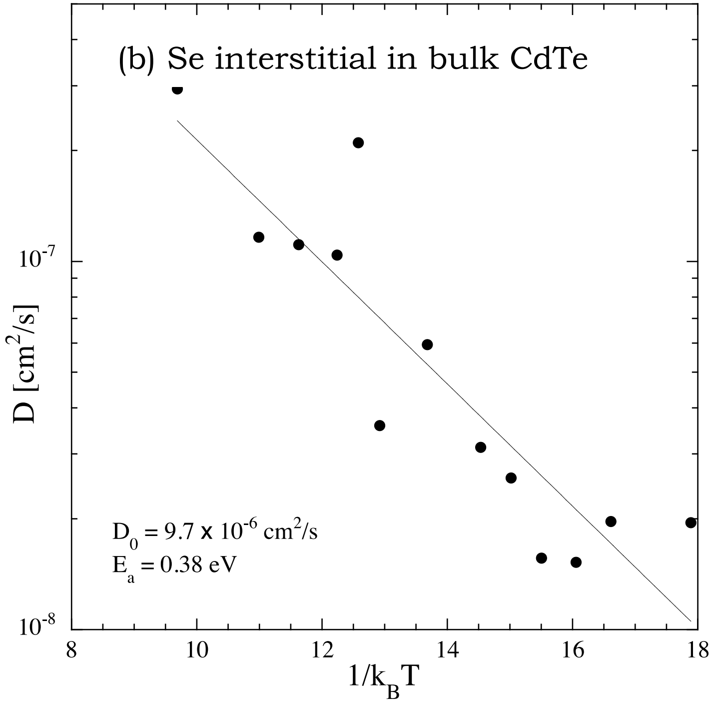


Device	Layers	Mobility μ (cm^2/Vs)	Carrier concentration N (cm^{-3})
III-V	InGaAs	9978 ± 130	(1.52 ±0.01) × 10^{17}
	InAlAs	4435 ± 312	(5.3 ± 0.3)× 10^{16}
Perovskite	ITO	32.7	(2.8 ± 0.6) × 10^{20}
	PEDOT:PSS	0.7	(2.6 ± 0.4) × 10^{22}
	Perovskite	2.5	(1..5 ± 0.1) × 10^{18}

COMPUTATIONAL STUDIES ($CdSe_xTe_{1-x}$)



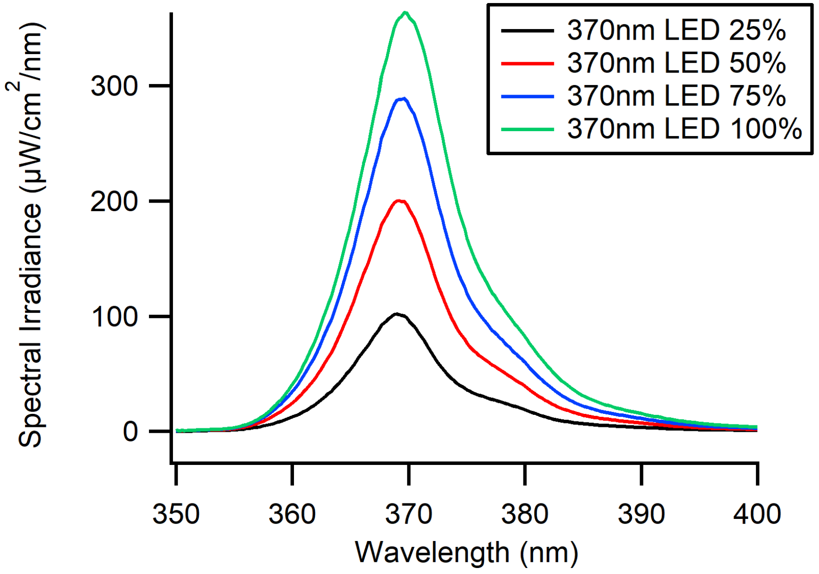




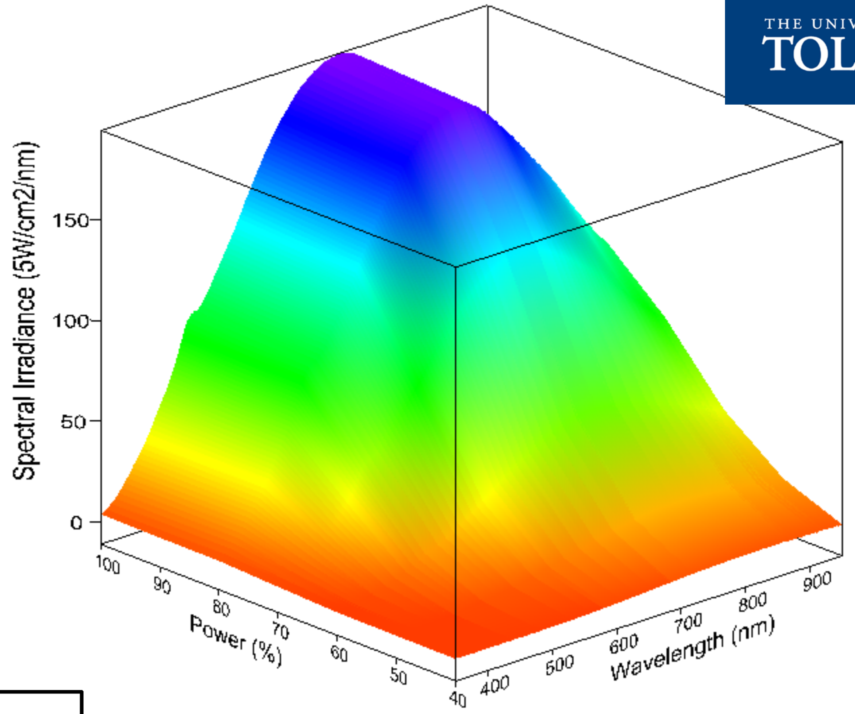
ZB = Zincblende
WZ = Wurtzite

From B. B. Dumre et al., Solar Energy 192, 742 (2019).

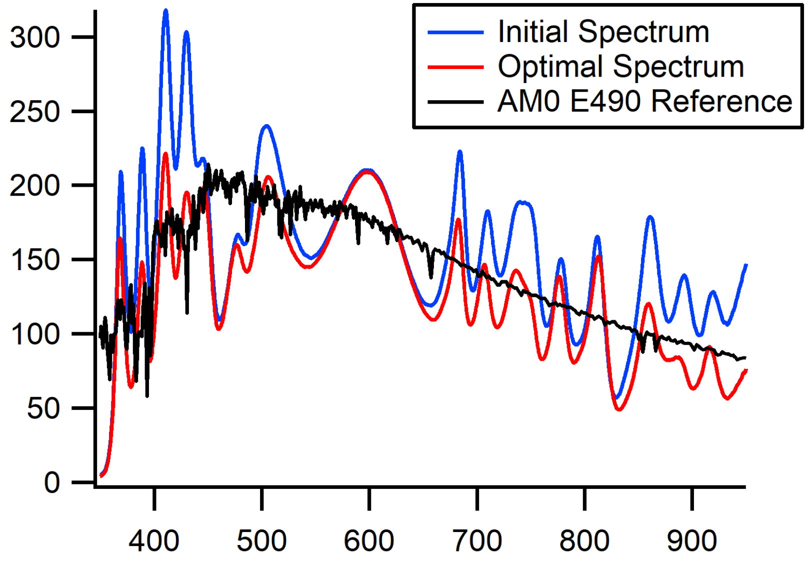
LED SOLAR SIMULATORS -- AM0 CALIBRATION



Measure each LED source at several intensities



Use bilinear interpolation to construct spectrum based on each source's intensity



Minimize the sum of squared differences, estimated vs. reference spectra, by multi-start global minimization algorithm

S-111A QUALIFICATION

	S-111A Qualification	In-house Testing Capability
1	Solar cell Weld/Solder	N/A (for CdTe & perovskites)
2	Solar cell integration	N/A
3	Cell-level humidity *	Possible
4	Electron radiation	Partnerships
5	Proton radiation	Partnerships
6	Bend test	Can be added in next 6-12 months

	S-111A Qualification tests (AM0)	In-house Testing Capability
7	Mechanical strength	N/A
8	Light J-V at different T	Available
9	Dark J-V	Available
10	QE	Available
11	Capacitance effects	Available
12	Electrostatic Discharge (ESDS)	-
13	Accelerated Life Test*	Possible

Notes: 3. **Cell Level Humidity Test:** 60 days at 95 ± 5% RH at 45°C

8. **Light JV at different T**: Part 1: Measure Isc, Voc, Vmp, Imp, Pmp and the entire I-V curve between -150°C and 150°C in 20°C increments on cells with no fluence; Part 2: I-V after 1 MeV electron fluences of 1×10^{14}, 1×10^{15}, and 1×10^{16}

11. **Capacitance effects:** Characterize solar cell capacitance at room temperature from 10 Hz to 1.5 MHz under simulated AM0 irradiance and spectrum at Vmp and Voc

13. **Accelerated life test:** develop reliability estimates by characterizing the Mean Time to First Failure (MTTFF), and the Failure in time (FIT) rates of solar cells at 50°C, 80°C and 110°C (not much mentioned after this test)

PVIC Partners, Clients

(incomplete list)

PVIC – KEY FACULTY

WRIGHT CENTER for PHOTOVOLTAICS INNOVATION AND COMMERCIALIZATION

Robert Collins
Scientific Director, NEG Endowed Chair in Photovoltaics, Distinguished University Professor

Michael Heben
Managing Director, McMaster Chair in Photovoltaics

Yanfa Yan
ORSP Chair in Photovoltaics, Distinguished University Professor

Randy Ellingson
PVIC Chair in Photovoltaics

Nikolas Podraza
Advanced optical characterization of solar cells

Research Faculty -- essential:
Adam Phillips
Zhaoning Song
Shan Ambalanth
Ebin Bastola