High-Efficiency Cd(Se,Te) Solar Cells on Space-Qualified Cover Glass

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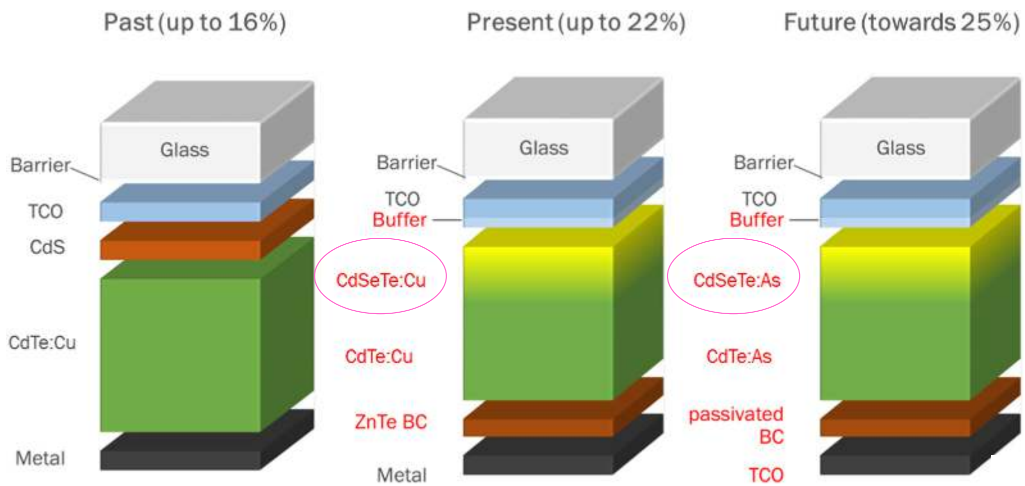
Space Power Workshop-2026, April 22, 2026   Torrance, CA

This material is based on research sponsored by Air Force Research Laboratory under agreements FA9453-19-C-1002 and FA9453-21-C-0056. The work was authored in part by the National Laboratory of the Rockies for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Solar Energy Technologies Office and Critical Minerals and Energy Innovation Solar Energy Technologies Office under programs 37989, 38257, 52778, and DE-EE0008974. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon. The views expressed are those of the author(s) and do not necessarily reflect the official policy or position of the Department of the Air Force, the Department of Defense, or the U.S. government. Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2026-1759.

Industry-Grade CdSeTe/CdTe PV Device Architecture



Above: from Scarpulla, McCandless et al. 2023

"Thin films are the next technological battleground for the solar industry because they are key to commercializing tandem devices, which are anticipated to be the next disruption in photovoltaics."

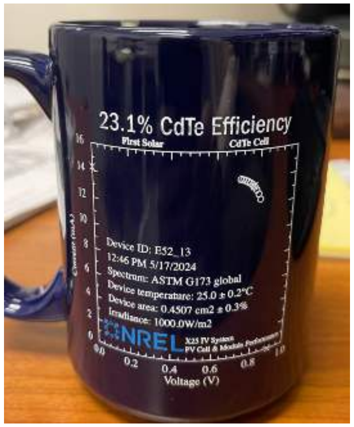
Mark Widmar, First Solar CEO, July 2024

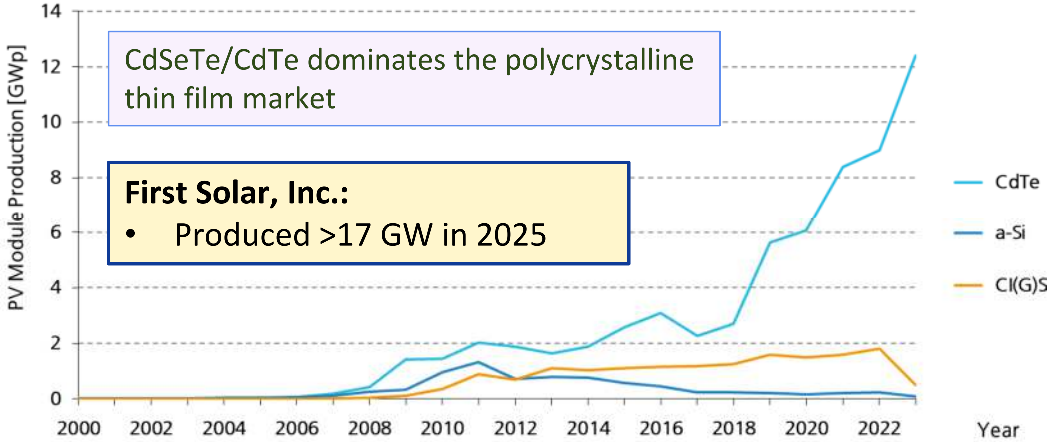
https://www.pv-magazine.com/2024/07/19/first-solar-opens-us-research-facility/

Record AM1.5 efficiency @ 23.1%

- CdSeTe lab-scale cell efficiency → AM0/AM1.5G ≈ 0.88 for current devices
- 23.1% AM1.5G PCE → <u>20.3% AM0 PCE for record CdSeTe device</u>

https://www.linkedin.com/posts/xionggang_231-cdte-activity-7220443357020401664-KS0V/





CdSeTe/CdTe dominates the polycrystalline thin film market

First Solar, Inc.:

- Produced >17 GW in 2025

https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/Photovoltaics-Report.pdf

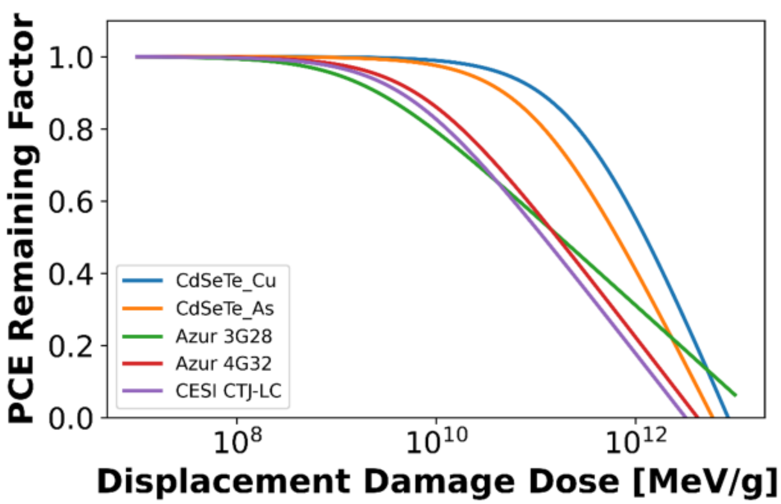
CdTe-based PV for Space

Motivation

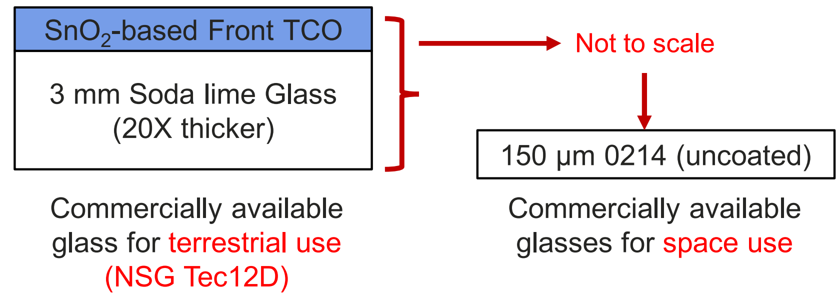
Expanding space PV needs:

- Power needs increasing 1 kW, 10 kW, 100 kW, 1 MW (LEO smallsats to GEO platforms)
- --> scale up cell size
- Increase production capacity by orders of magnitude

Zawisza, Lambright *et al. APL Energy* (2025)



Gap Addressed by this work



High efficiency CdTe-based devices (used on earth) are:

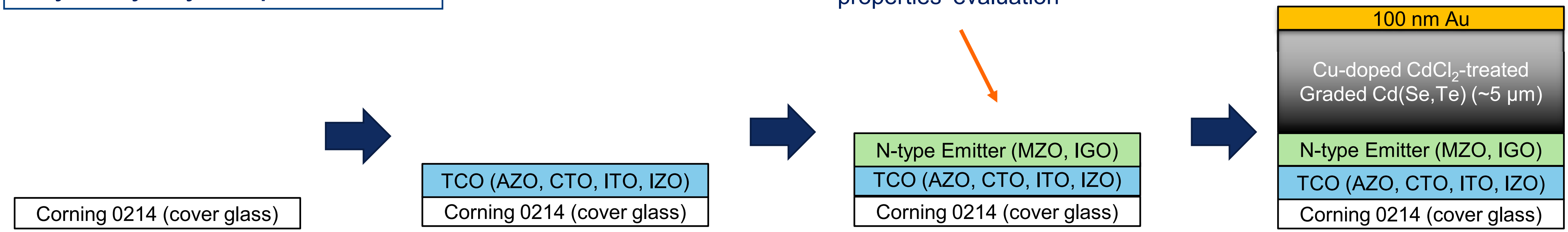
- Not tested on space-qualified substrates
- Limited by lack of compatible front contacts (TCO/emitter) on ultra-thin cover glass (150 µm)

Fabrication on Space-Qualified Cover Glass

Superstrate configuration:
Layer-by-layer optimization

For optoelectronic properties' evaluation

For device studies



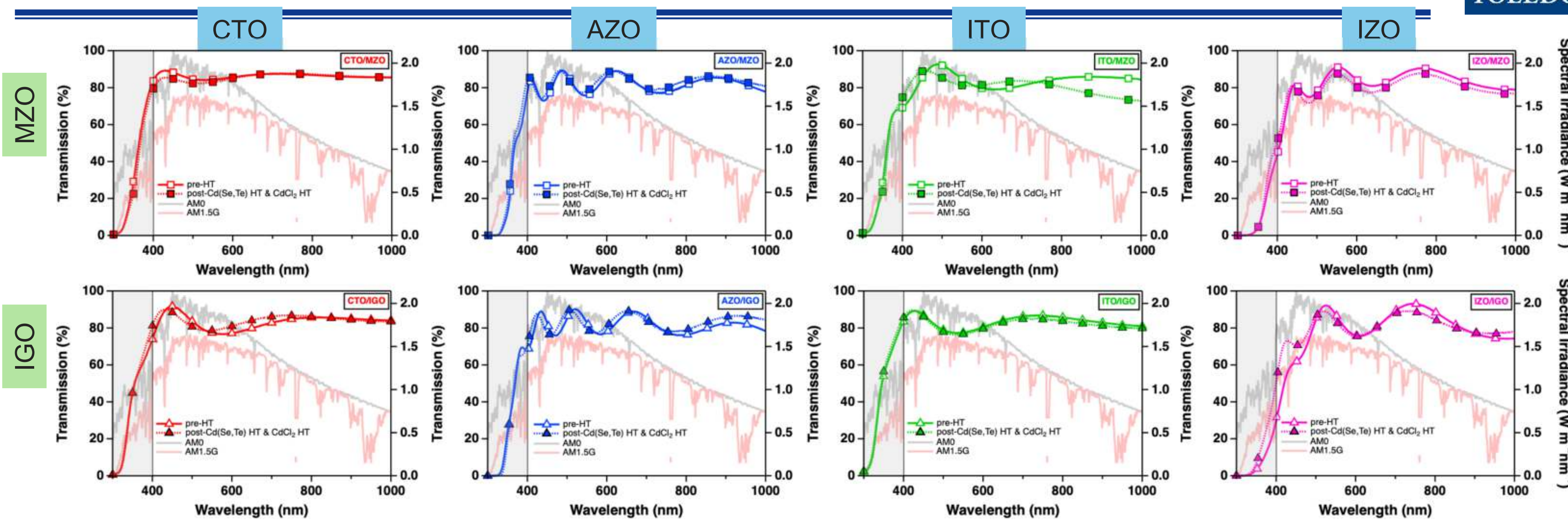
- **Front contacts' studies:** Corning 0214 (space-qualified cover glass, 150 µm thick, 0.75% Ce-doped)
- **For baseline comparison:** Tec12D (Soda lime/FTO)

- **4 different TCOs** (thickness optimized):
  - AZO
  - CTO (Cd_2SnO_4)
  - ITO
  - IZO

- **2 different Emitters** (thickness & bandgap optimized):
  - MZO
  - IGO (co-sputtered from In_2O_3 and Ga_2O_3 targets)

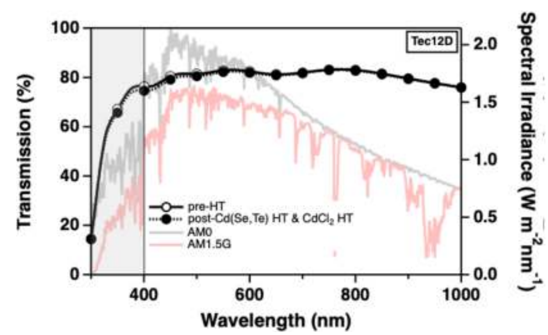
- **Absorber** ($T_{substrate}$ varied):
  - Multisource evaporated $CdSe_{0.3}Te_{0.7}$/CdTe
  - Followed by CSS $CdCl_2$ treatment, Cu-doping and Au evaporation

Front Contacts: Optoelectronic Properties (T%)



- Determined chemical and thermal stability under high temperature CdTe processing

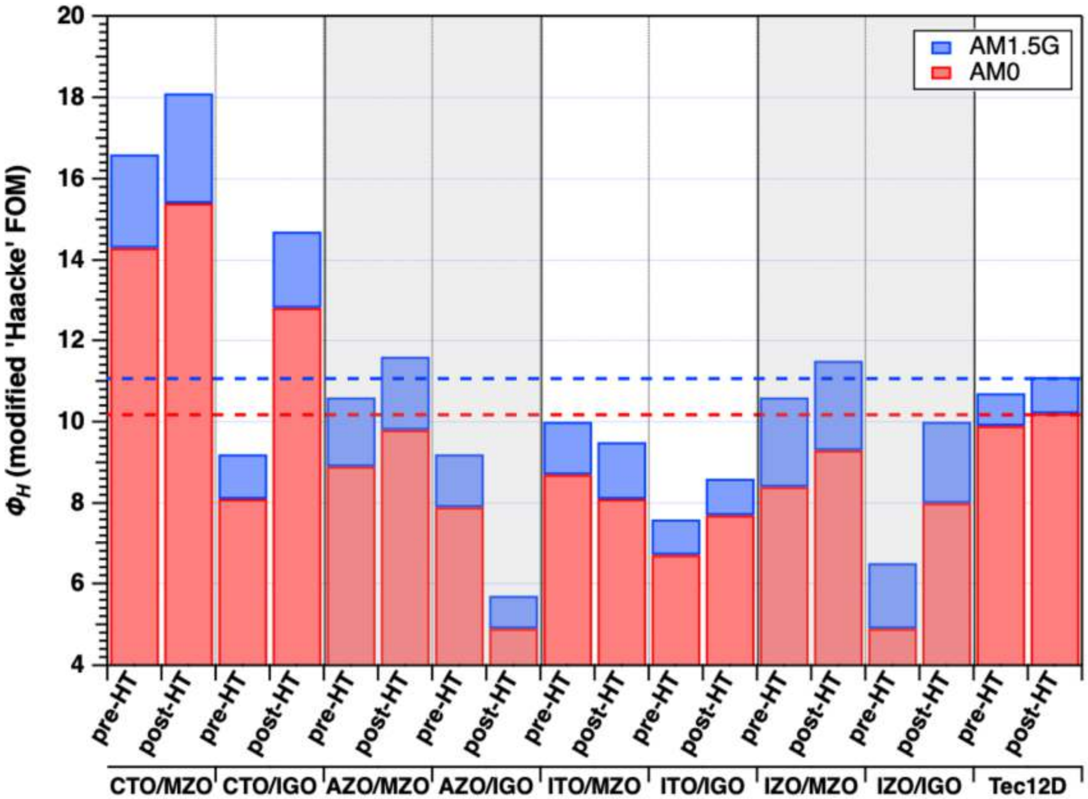
- Except for the interference fringes, a major difference is seen in the TCOs' UV-cut off wavelengths (300-400 nm) compared to baseline Tec12D



Baseline

Front Contacts: Optoelectronic Properties

Figure-of-Merit (FOM)



Equations:

$$WT(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} G(\lambda)T(\lambda)\,\delta\lambda}{\int_{\lambda_1}^{\lambda_2} G(\lambda)\delta\lambda}$$

$$\phi_H = \frac{WT(\lambda)^{10}}{R_s} \times 1000$$

where, WT(λ): solar-weighted transmission (300-1000 nm)
G(λ): wavelength-dependent solar flux (AM1.5G and AM0)
R_s: sheet resistance (Ω sq^{-1})
Φ_H: modified 'Haacke' figure of merit (FOM)

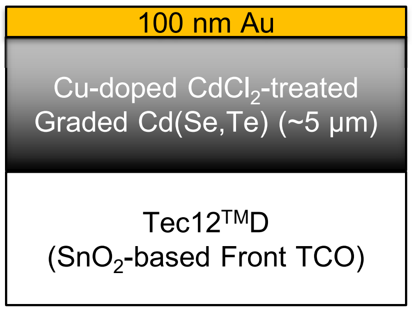
Barnes *et al.* (2012)

Device Performance: AM1.5G and AM0 (Uncertified)

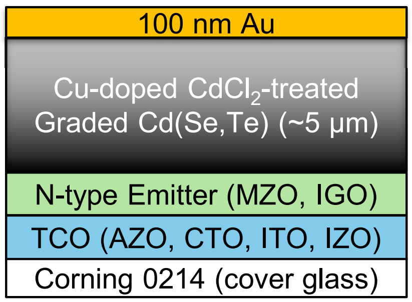
Device Schematics

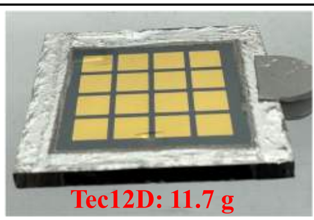
(Not to scale)

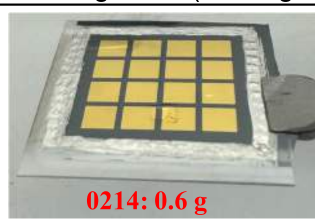
Baseline



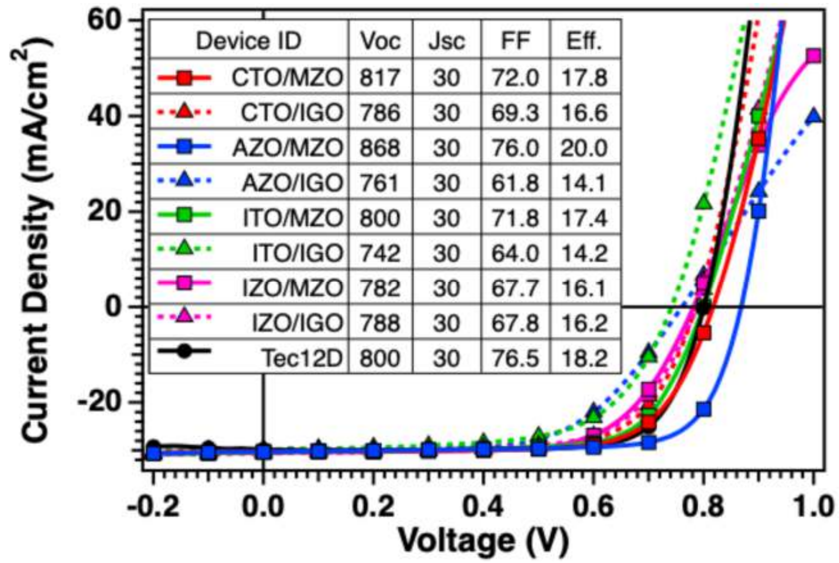
TCO/Emitter varied







AM1.5G

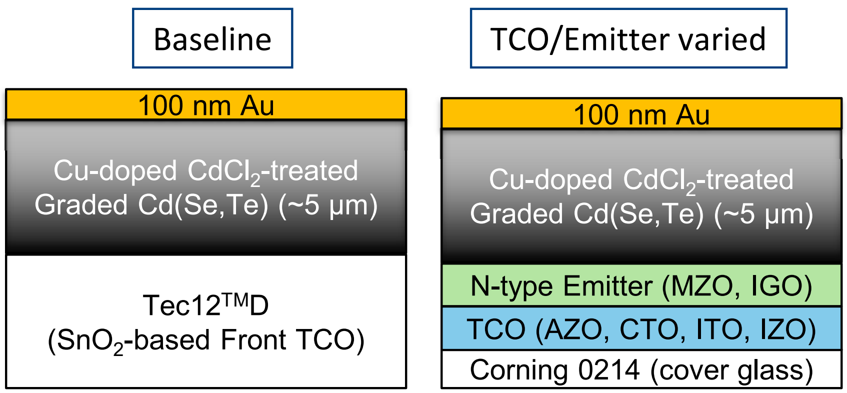


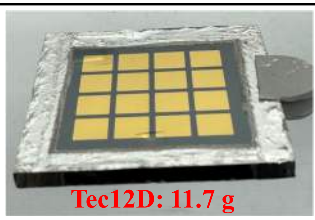
AM0

Device ID	Voc (mV)	Jsc (mA/cm²)	FF (%)	AM0 Eff. (%)
CTO/MZO	796	32.0	64.7	12.1
CTO/IGO	811	32.7	68.7	13.4
AZO/MZO	849	31.1	71.4	13.8
AZO/IGO	776	31.1	59.6	10.6
ITO/MZO	818	31.4	69.2	13.1
ITO/IGO	763	33.2	65.2	12.1
IZO/MZO	784	29.2	66.1	11.1
IZO/IGO	806	29.4	65.3	11.4
Tec12D	795	31.7	67.3	12.5

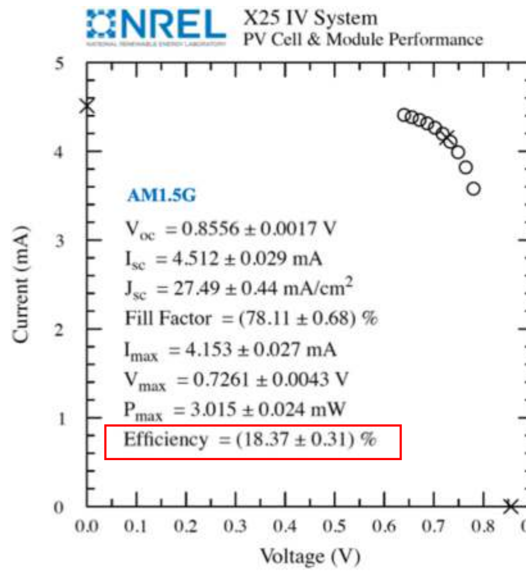
Certified Device Performance: AM1.5G and AM0

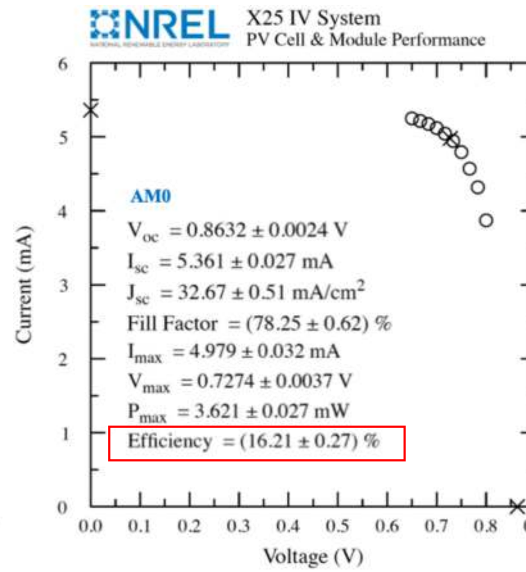
Device Structure (not to scale)





NREL (now NLR)-certified Device Performance (under AM1.5G and AM0)





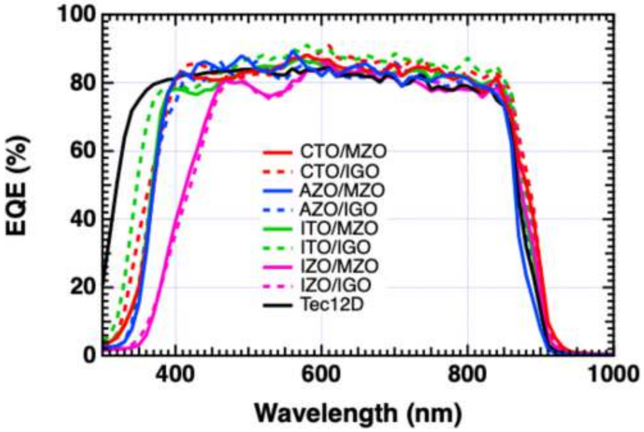
- **First CdTe-based PV device certified for AM0 conditions**
- **New NREL (now NLR)--certified AM1.5G (18.4%) and AM0 (16.2%) records for CdSeTe/CdTe on ultra-thin glass**

(Publication Under Review)

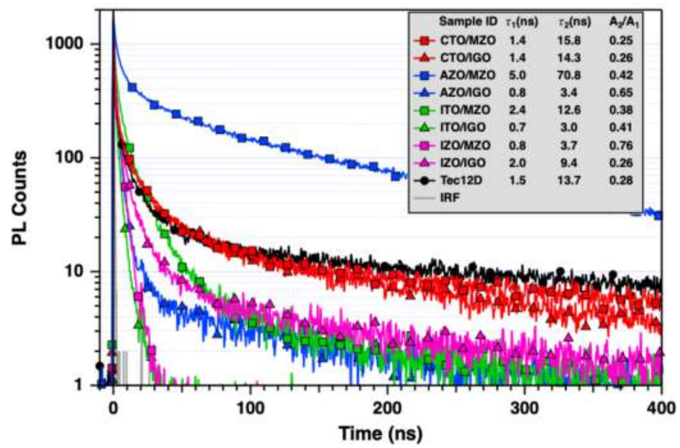
NREL Transforming ENERGY

Device Performance: Junction Quality & Loss Mechanisms

EQE

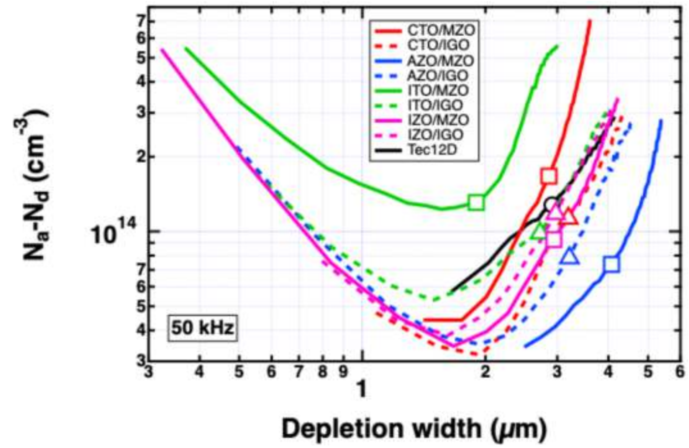


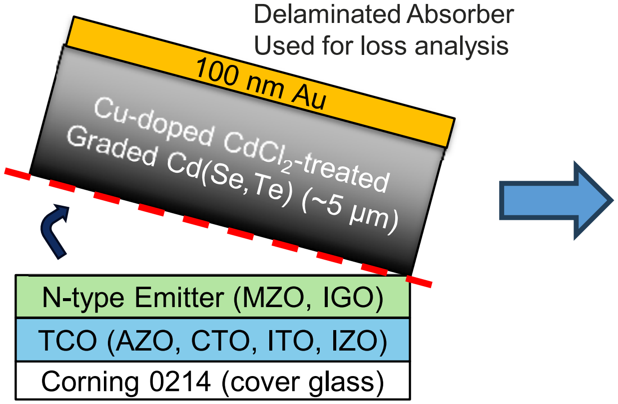
TRPL



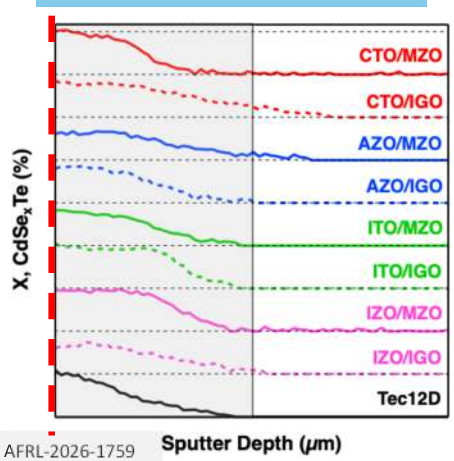
Sample ID	τ_1(ns)	τ_2(ns)	A_2/A_1
CTO/MZO	1.4	15.8	0.25
CTO/IGO	1.4	14.3	0.26
AZO/MZO	5.0	70.8	0.42
AZO/IGO	0.8	3.4	0.65
ITO/MZO	2.4	12.6	0.38
ITO/IGO	0.7	3.0	0.41
IZO/MZO	0.8	3.7	0.76
IZO/IGO	2.0	9.4	0.26
Tec12D	1.5	13.7	0.28
IRF			

C-V

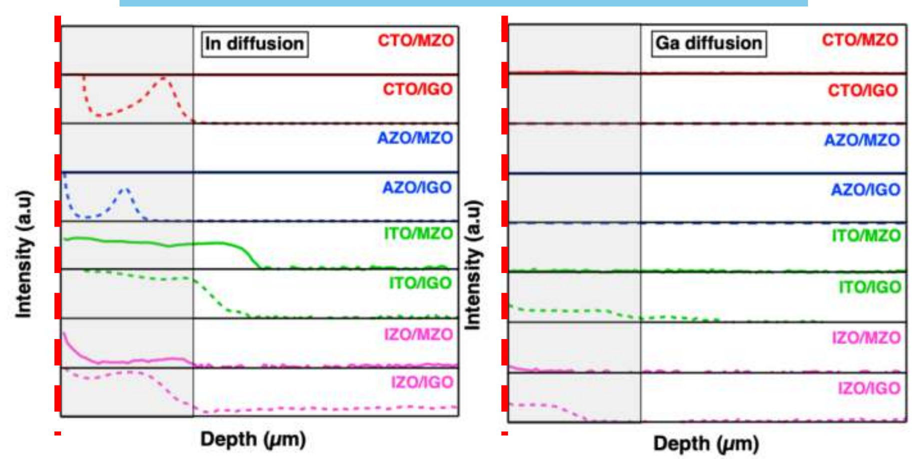




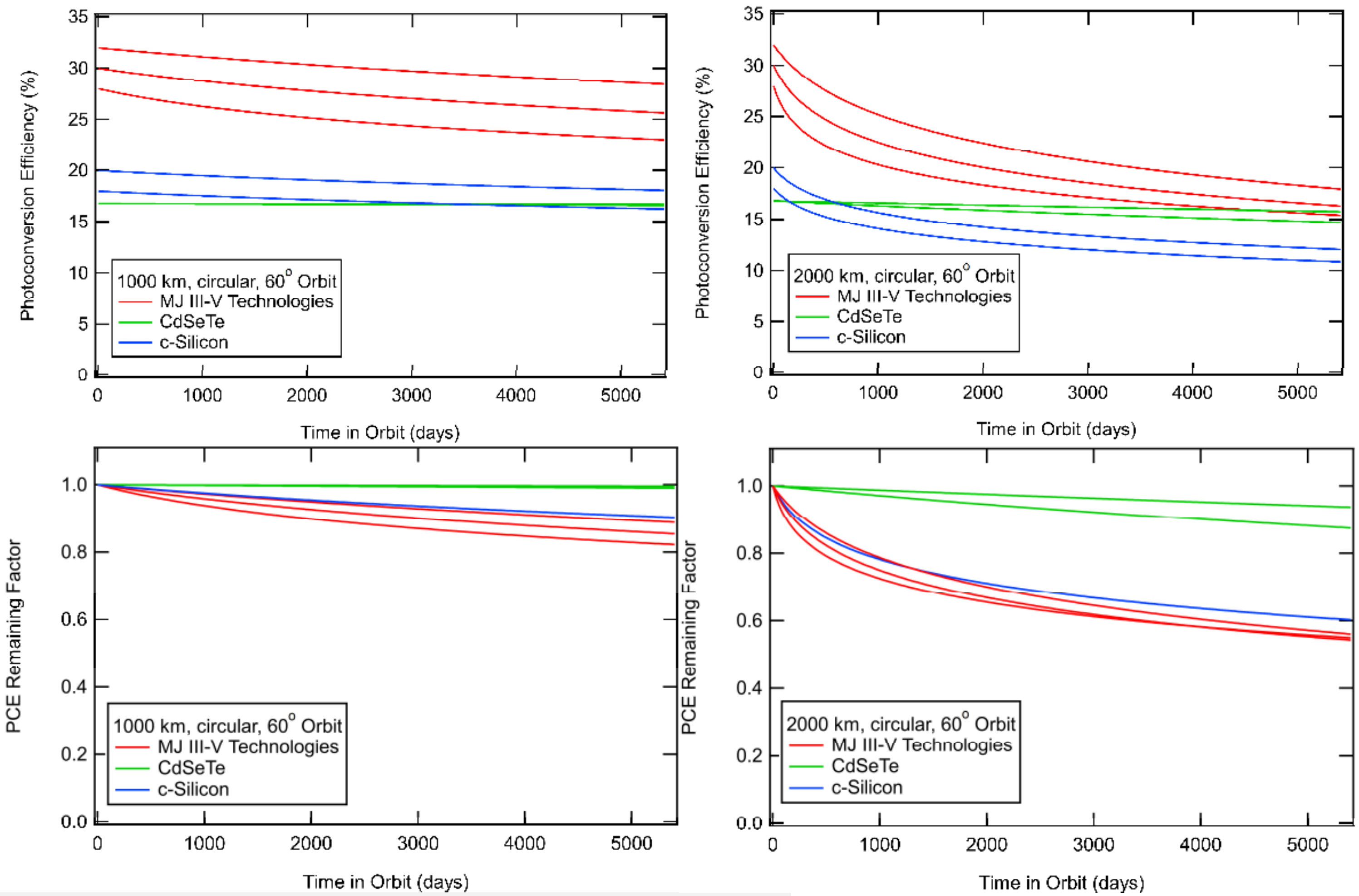
Se Profiles



In/Ga Diffusion from Front Contacts



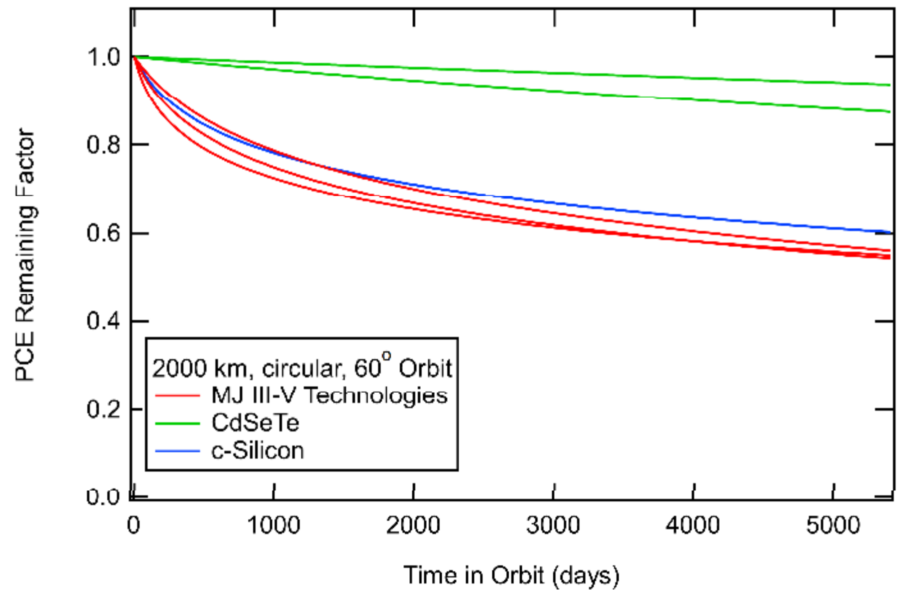
EOL Performance Predictions – SPENVIS Simulations



- DDD modeling used to simulate remaining PCE for CdSeTe devices in particular orbit as function of days in orbit and compared to commercially available multijunction (MJ) III-V device data (Lambright *et al.*)
- CdSeTe PV devices demonstrate clear advantage when compared with MJ III-V modules of the same beginning-of-life (nameplate) performance.

Mass Production Thin Film PV for Space – Status/Outlook?

Criteria	III-V MJ	c-Si	Perovskite	CIGS	CdTe
Efficiency	✅	⚠️	✅	⚠️	⚠️
Space Resilience	⚠️	⚠️	⚠️	⚠️	⚠️
Specific Power	✅	✅	✅	✅	✅
Cost/Scale /Stability	⚠️	⚠️	⚠️	✅	✅



Stability under thermal cycling under e.g. -100 C to + 100 C

- Perovskite PV cells face challenges w/ CTE, interface stability, volatility of organics (e.g., Song et al., *Energy Mater.* 2026)
- CdSeTe PV research cells tested: 5600 cycles, -/+ 100 C (simulated 1 year LEO) → preliminary results → single digit % PCE decrease.

Next steps:

- Proton & electron irradiation testing on 0214 devices
- Thermal cycling on full stack architecture

Acknowledgments

University of Toledo (PVIC)

Prof. Randy J. Ellingson
Prof. Adam B. Phillips
Prof. Zhaoning Song
Prof. Nikolas J. Podraza
Prof. Michael Heben
Suresh Chaulagain
Prabodika N. Kaluarachchi
Scott Lambright
Dr. Samuel Erickson

NLR (formerly NREL)

Dr. Matthew O. Reese
Dr. Ryan Muzzio
Robert Morrissey
Matthew R. Young
Christian Velez
Joshua A. Brown
Dr. Joel N. Duenow
Dr. B. Edward Sartor
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Swansea University

Prof. Stuart Irvine (Emeritus)

Thank You

Questions?

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