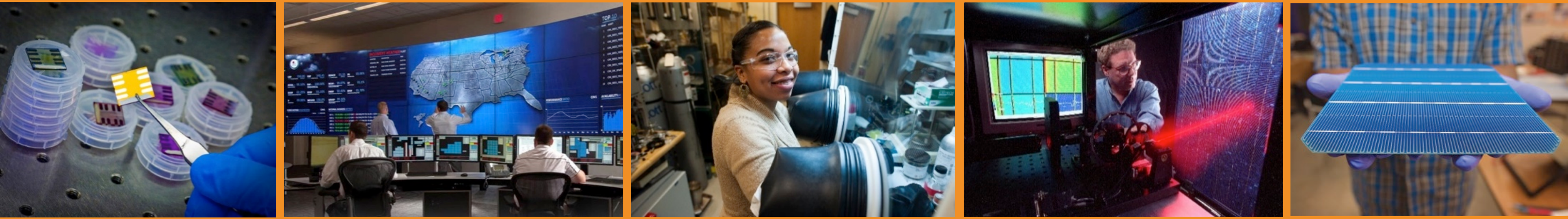
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

SOLAR ENERGY TECHNOLOGIES OFFICE



Commercial Thin Film Research Overview

Photovoltaics Track

Brion Bob, Technology Manager

Solar Energy Technologies Office

energy.gov/solar-office

Overview

- **Introduction to Commercial Thin Films**
- Current Research Topics in Cadmium Telluride
- Current Focus Areas in Copper Indium Gallium Selenide
- Summary of High Level Goals for Commercial Thin Films

Commercial Thin Film Technologies

Image Credit: First Solar

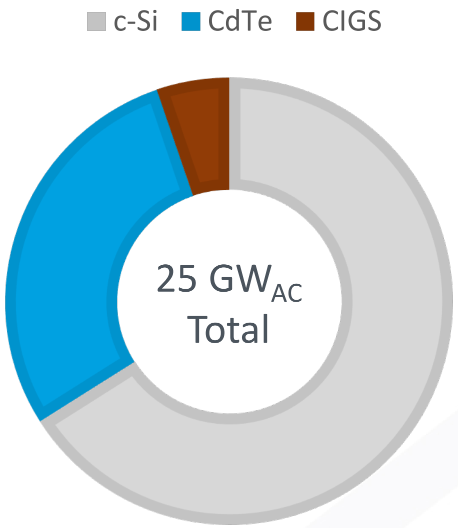
Cadmium Telluride (CdTe)

Image Credit: Solar Frontier

Copper Indium Gallium Selenide (CIGS)

Commercial Thin Film Technologies

A Few Thin Film Highlights



US Utility Scale Fleet as of 2019, Including ~30% Thin Film Capacity

(Data from the 2019 Utility Scale Solar Report from Lawrence Berkeley National Lab)

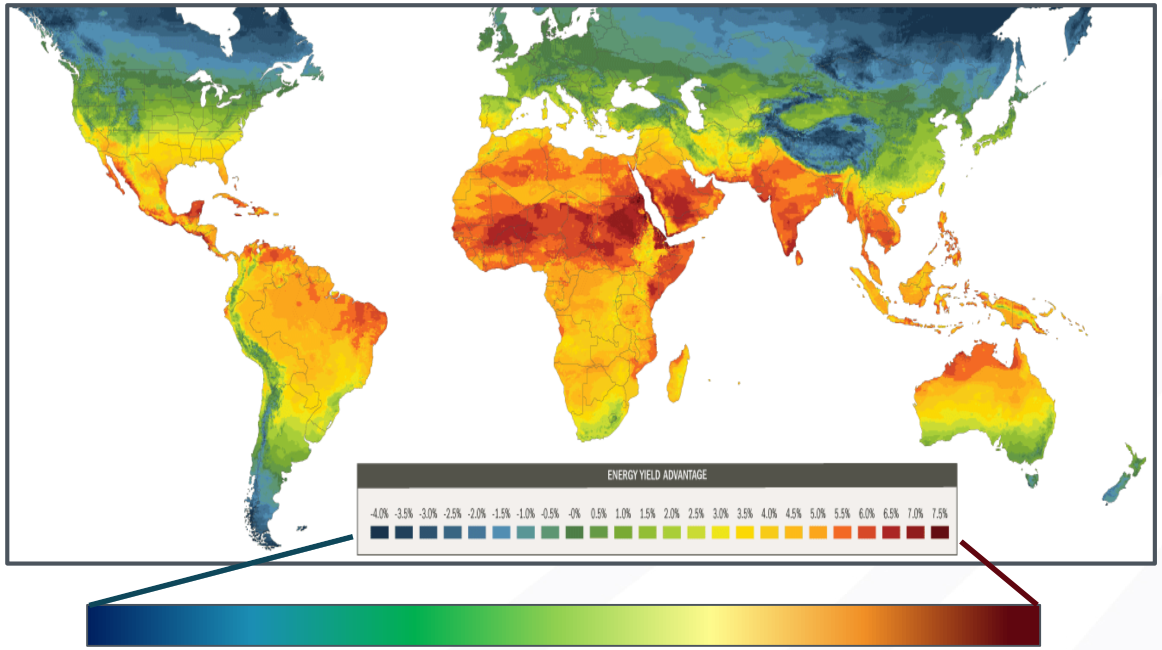
Image Credit: Solar Power World

- CdTe (First Solar) Currently Represents the Majority of Domestic Cell Manufacturing Capacity.
- Raw Materials can be Converted into Completed Thin Film PV Modules in just a Few Hours.
- First Solar's Estimated Cell and Module Manufacturing Labor Intensity was Roughly 50% Lower than Canadian Solar's in 2018/19 (0.9 FTE/MW vs. 1.8 FTE/MW)

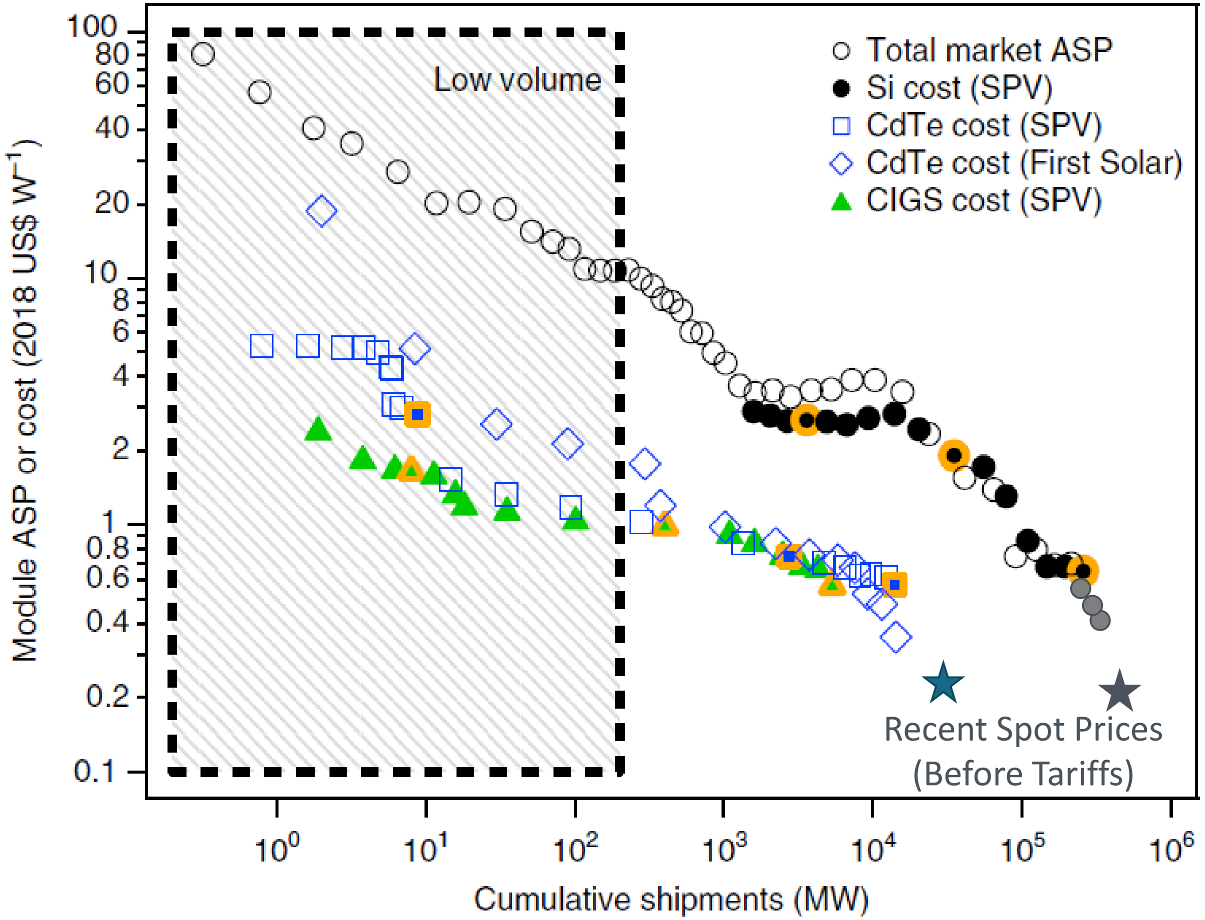
The Potential for Cost Advantages

Figure Credit: Reese and Haegel et al. 2018, *Nature Energy, 3, 1002–1012*

Image Credit: First Solar

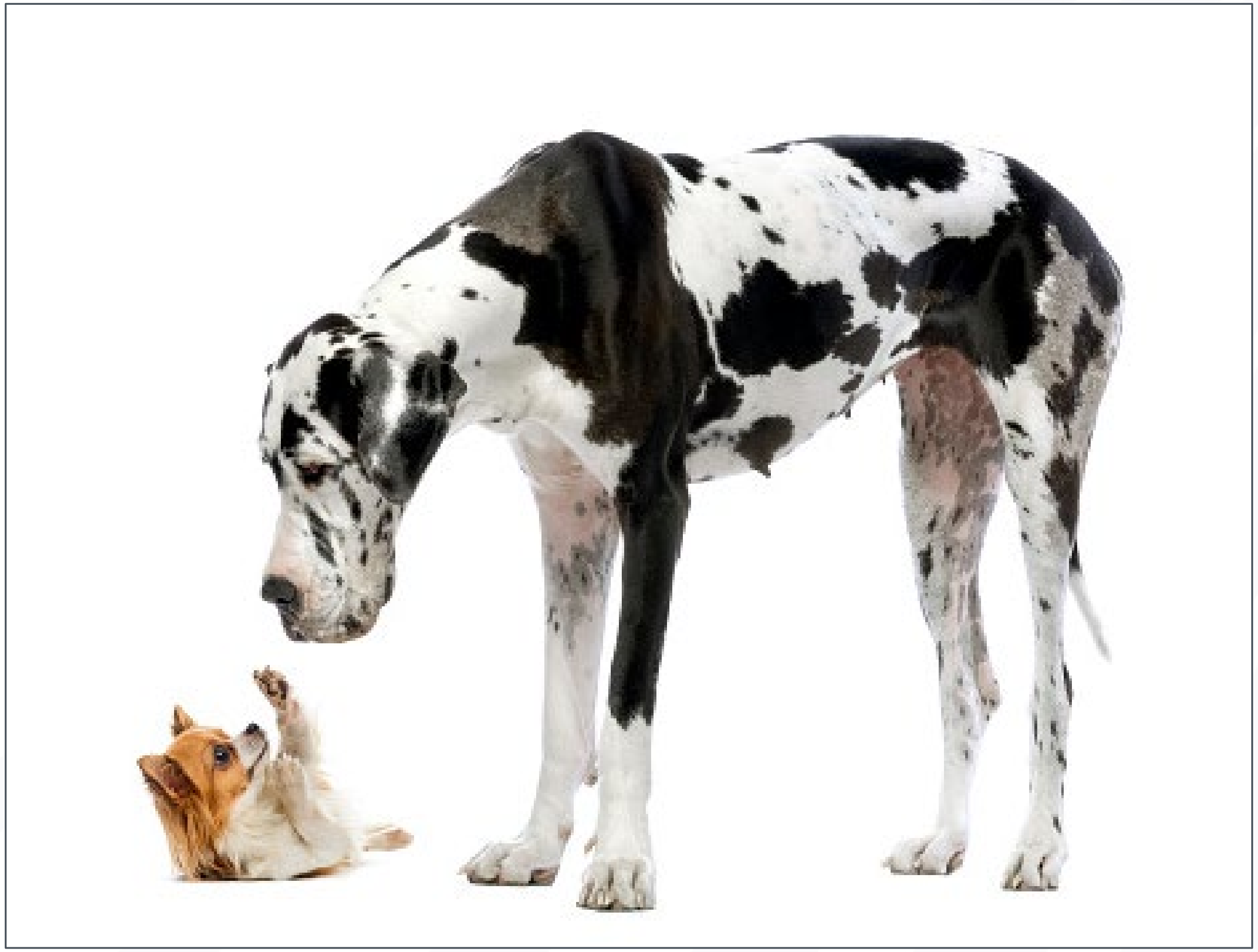


CdTe Fielded Energy Yield Compared to Silicon

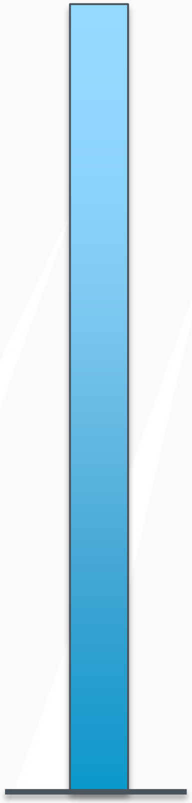


Global Thin Film Market Update

≈ 10 GW/yr
Supply Chain



≈ 150 GW/yr Supply Chain



Continuous Technology Advances are Needed in Order for Thin Films to Maintain Competitiveness

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CdTe Performance Targets

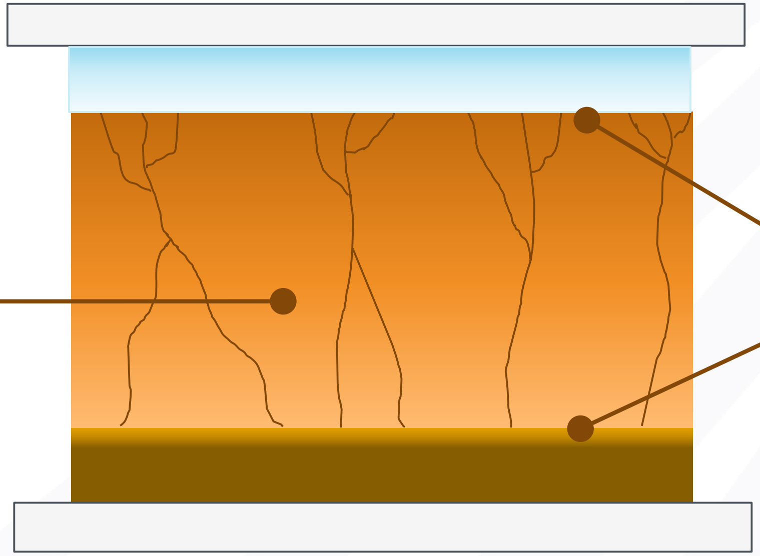
Absorber

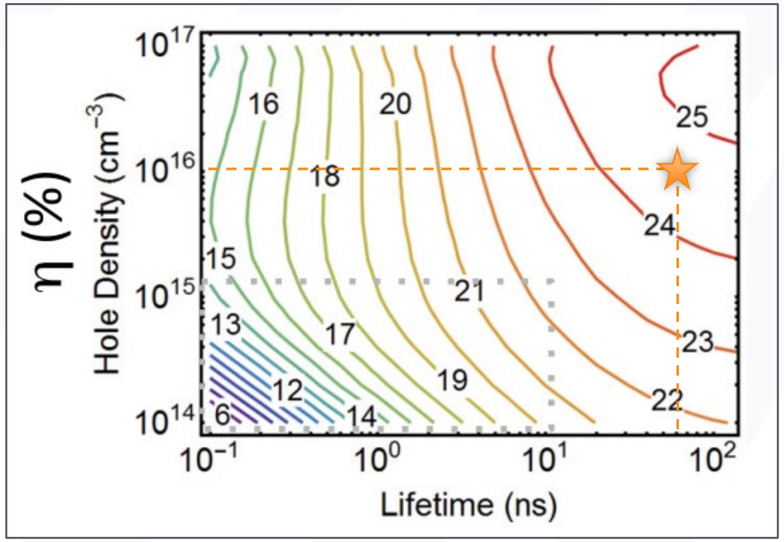
Current Status

Cu Doping	GrV Doping
10^{14} cm^{-3}	10^{16} cm^{-3}
1 μs	10 ns

24% Efficiency Goals

Low Doping	High Doping
10^{15} cm^{-3}	10^{16} cm^{-3}
3 μs	50 ns





Contacts

Current Status

Front SRV	Rear SRV
10^{2} cm/s	10^{5} cm/s

24% Efficiency Goals

Front SRV	Rear SRV
10^{2} cm/s	10^{2} cm/s

Figure Credit: Kanevce et al. 2017, *J Appl Phys*, ***121***, *214506*

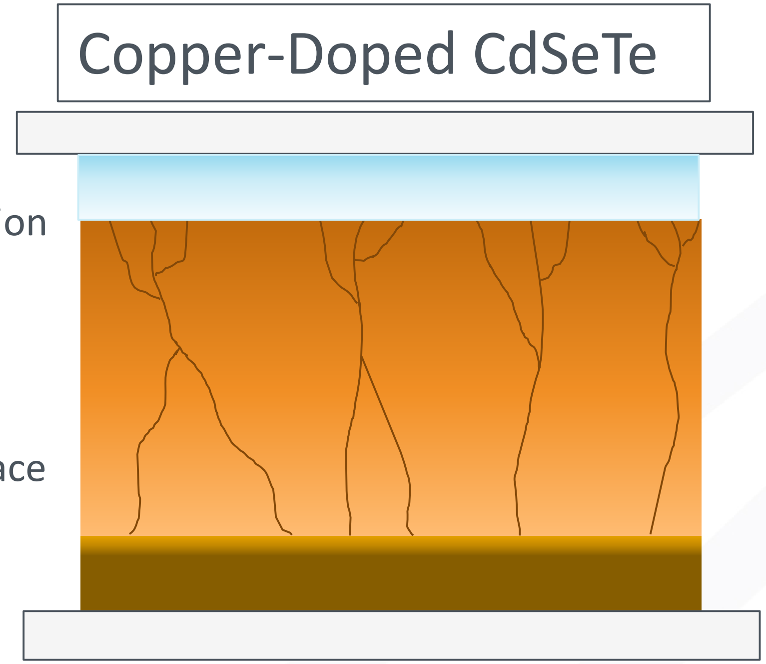
CdTe Research Areas

Front Barrier and TCO

Front Interface and Junction

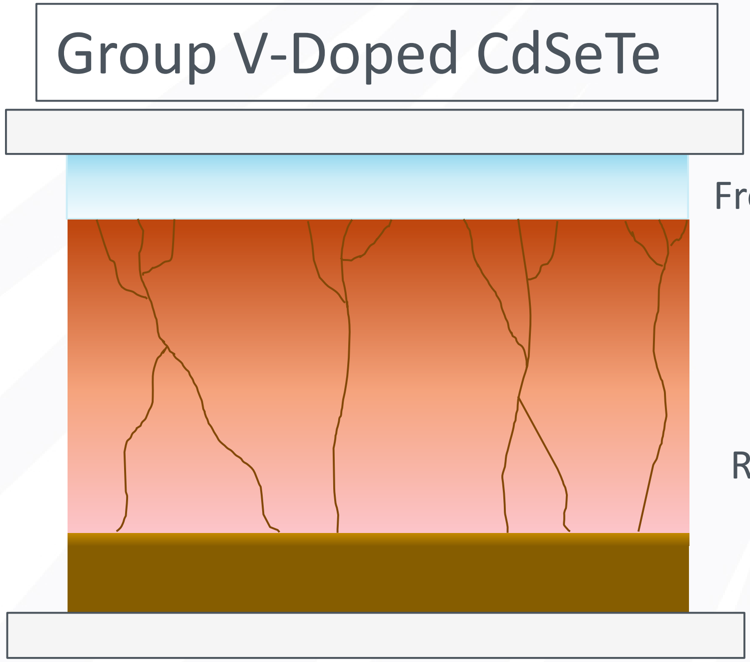
Rear Contact and Interface

Rear Metallization and Barrier



CdTe Layer Formation and Post-Treatments

Bulk Loss Mechanisms



Front Barrier and TCO

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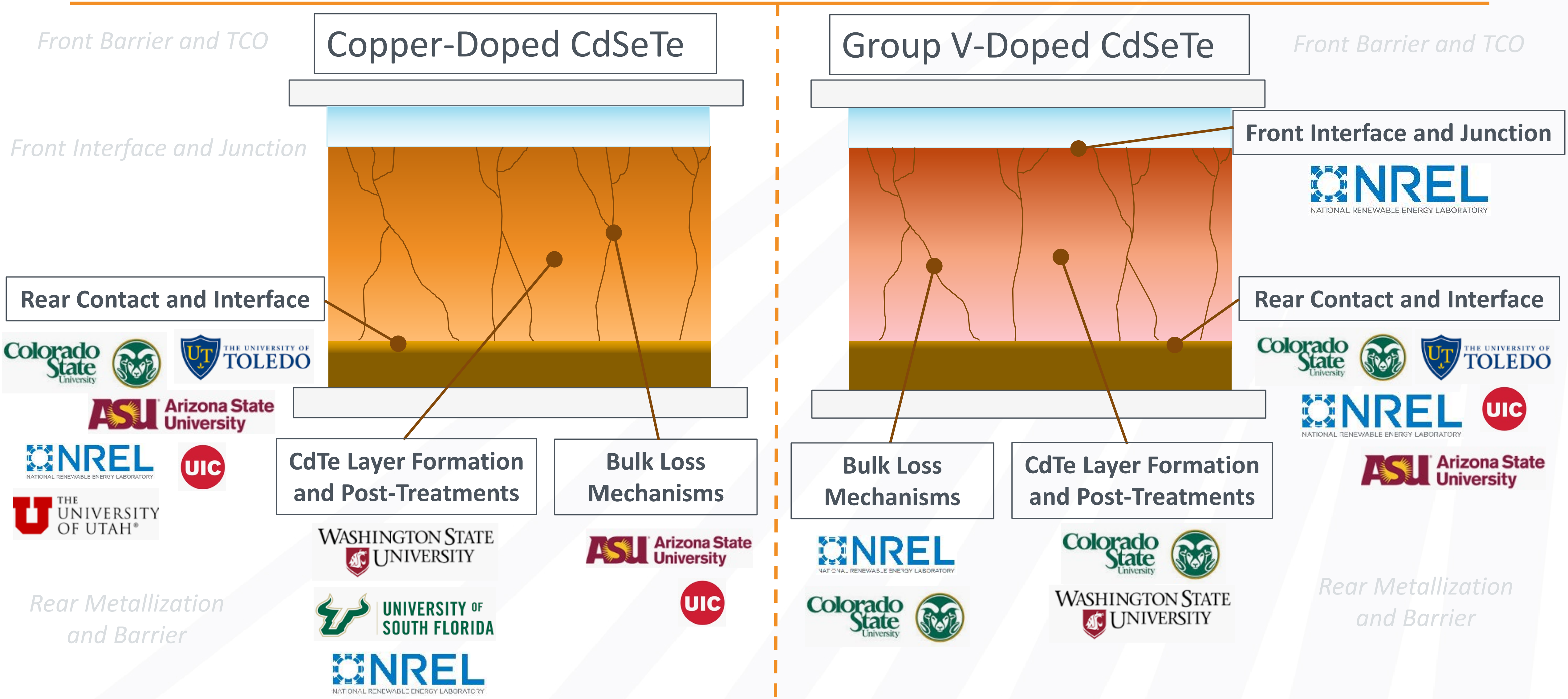
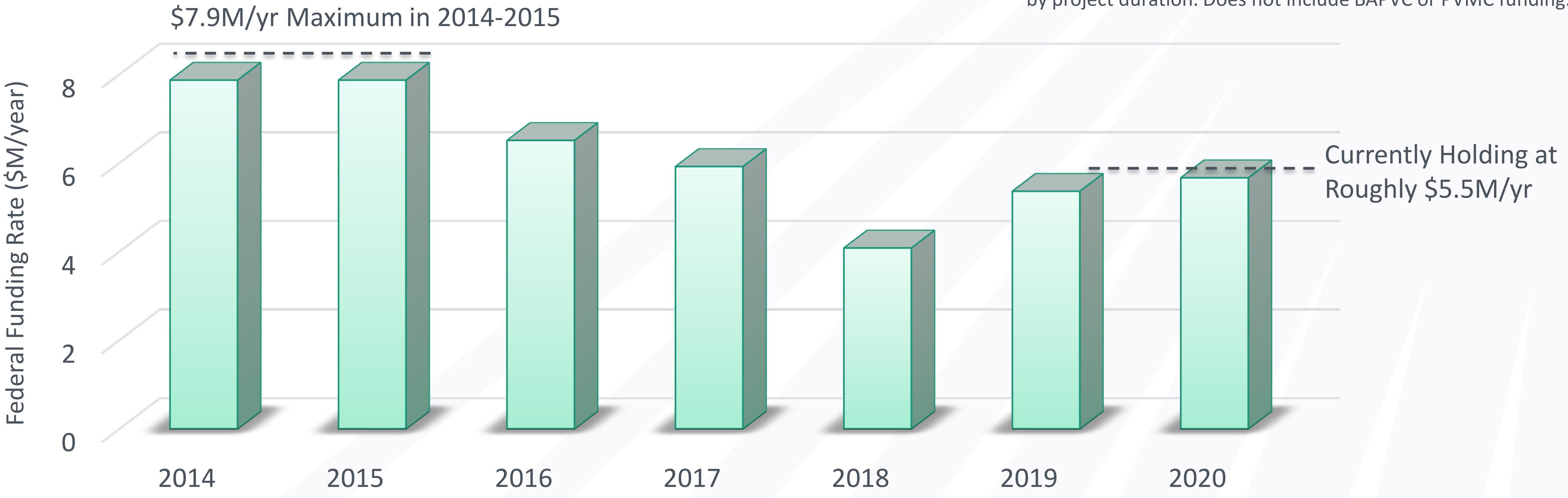
CdTe Research Areas



Approximate CdTe Historic Federal Funding Levels

Funding rates were annualized by dividing overall federal funding by project duration. Does not include BAPVC or PVMC funding.



- ➢ Annual Funding Estimates are Approximate, and can vary Significantly based on how Projects are Sorted.

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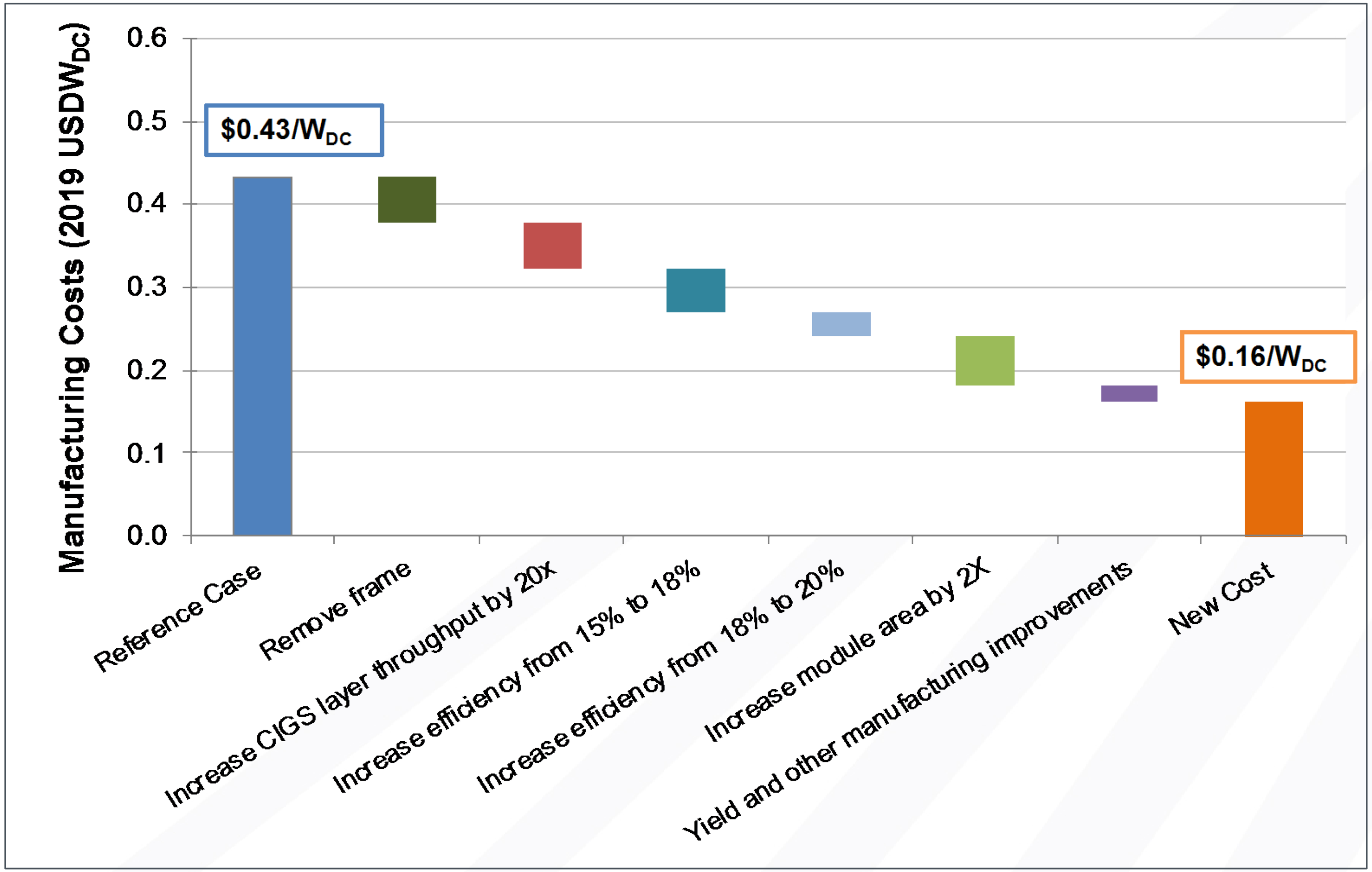
CIGS Research Overview

Figure Credit: NREL Strategic Energy Analysis Center, *Draft Analysis*



Front Barrier and TCO

Front Interface and Junction

CIGS Layer Deposition and Post-Treatments

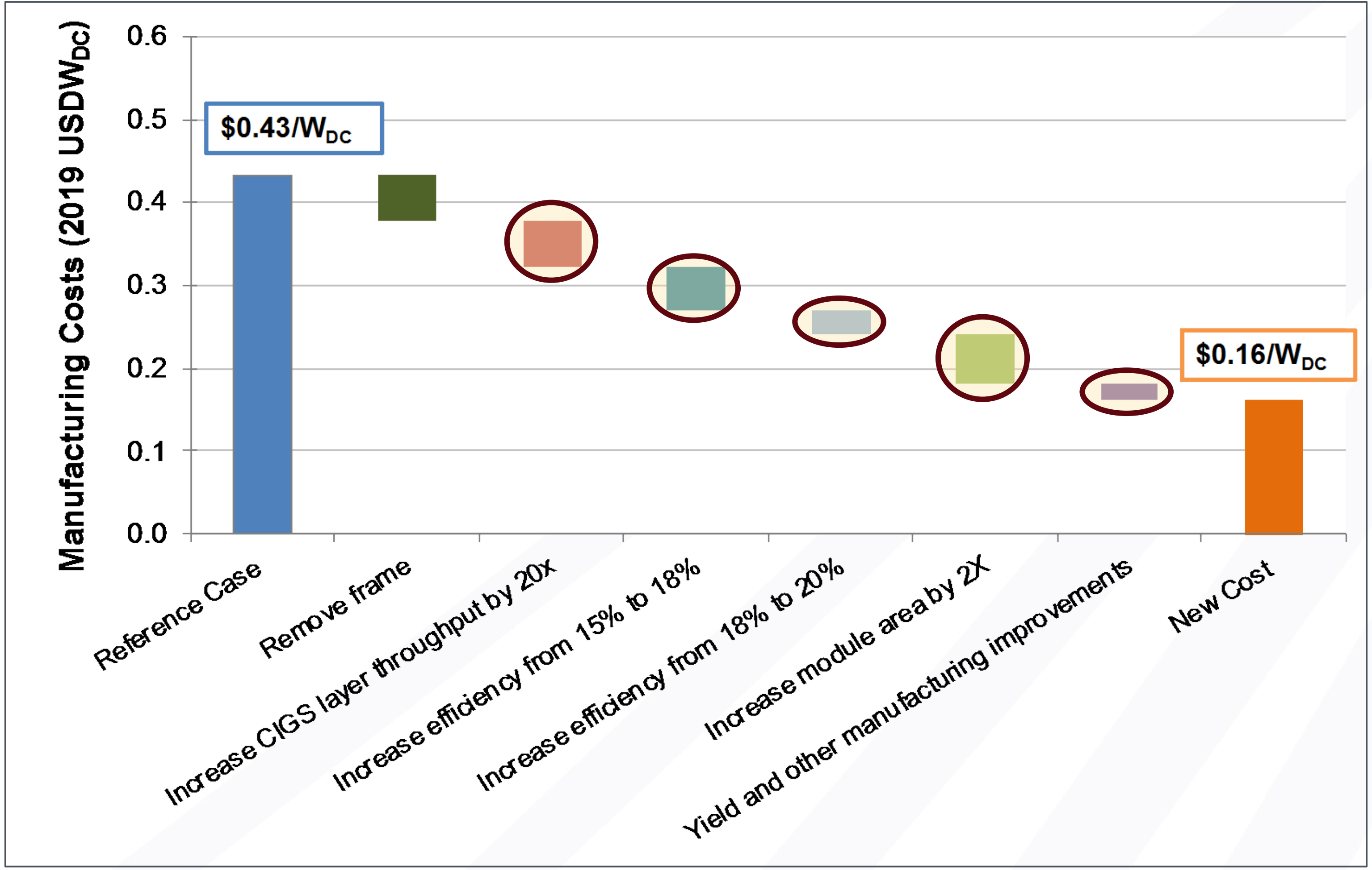
Rear Contact and Interface

Bulk Loss Mechanisms

Rear Metallization and Barrier

CIGS Research Overview

Figure Credit: NREL Strategic Energy Analysis Center, *Draft Analysis (Preliminary)*



Cu(In,Ga)Se_2 module technologies face significant challenges in high quality, large area absorber fabrication.

CIGS Layer Deposition and Post-Treatments

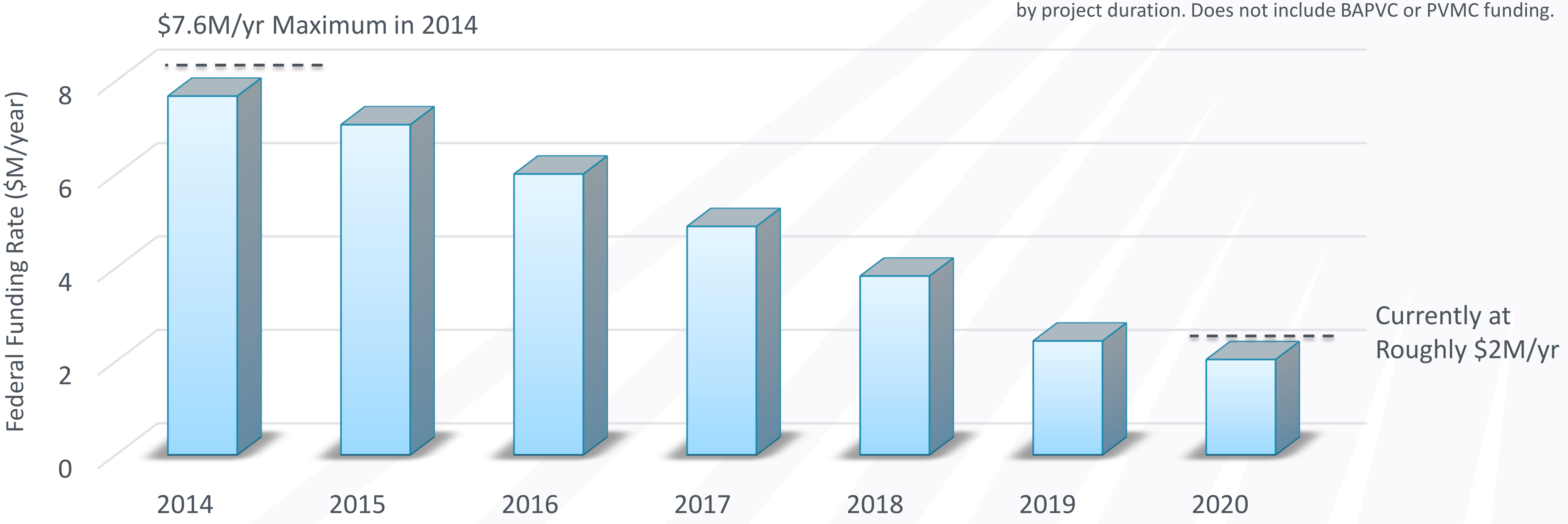
NREL National Renewable Energy Laboratory; University of Washington; Colorado School of Mines; Old Dominion University

Bulk Loss Mechanisms

Ohio State; Colorado School of Mines; NREL National Renewable Energy Laboratory

Approximate CIGS Historic Federal Funding Levels

Funding rates were annualized by dividing overall federal funding by project duration. Does not include BAPVC or PVMC funding.



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Summary of High Level Goals

Cadmium Telluride (CdTe)

- **Increase cell efficiency** without increasing manufacturing cost or reducing service lifetime.
- **Identify new materials and architectures** that will continue to expand the roadmap for future technology improvements.

Image Credit: First Solar

Copper Indium Gallium Selenide (CIGS)

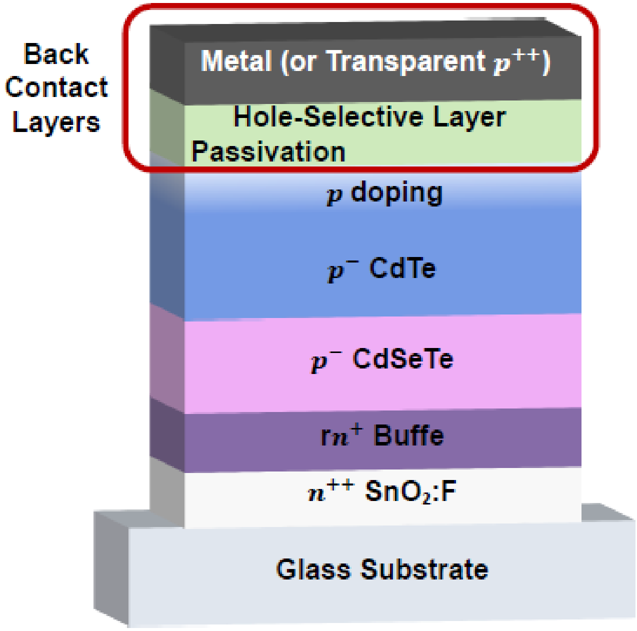
- **Develop and improve manufacturing methods** that undercut the $/$W_{DC}$ costs of industry-leading cell and module technologies.
- **Identify use cases** that value flexibility, light weight, or substrate fabrication architectures.

Image Credit: Solar Frontier

THANK YOU!

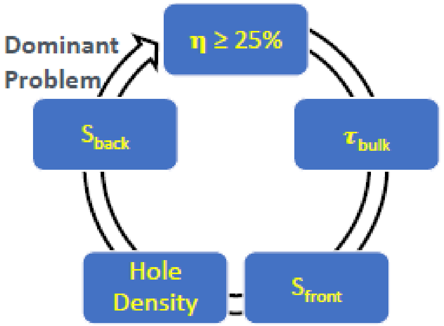
…QUESTIONS?

Highlights for SETO2 8974 (CSU, Sites)

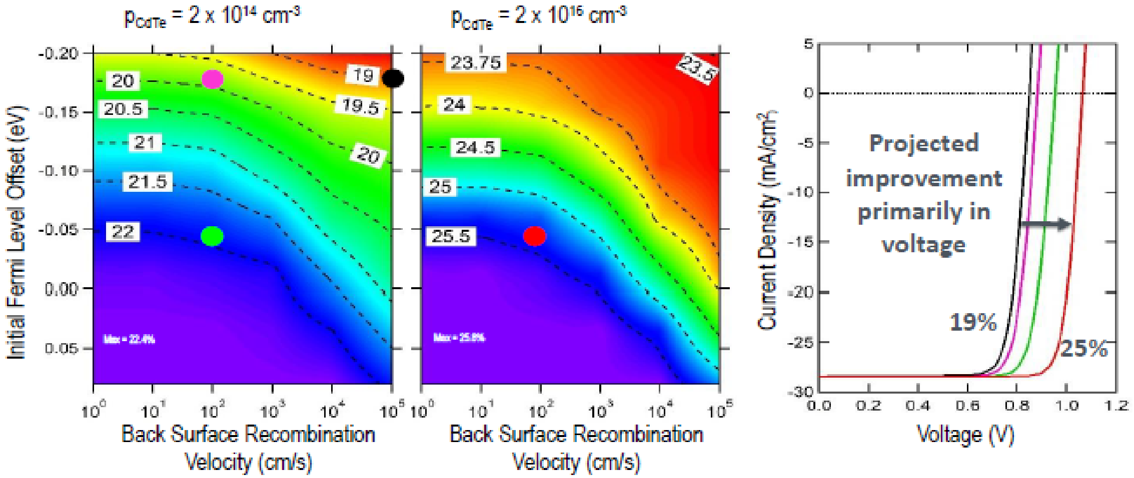


Thin-film CdTe cell structure highlighting the back contact.

Strategy is to start from current baseline (black dot), reduce back-surface recombination (pink dot), reduce the initial Fermi-level offset (green dot), and increase the absorber carrier concentration (red).

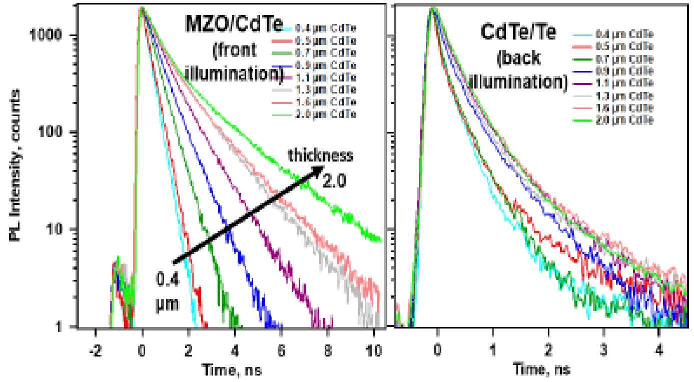


CdTe efficiency path.



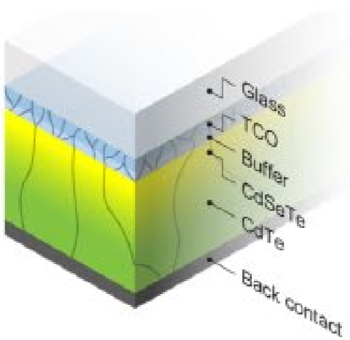
CdTe efficiency issues are being systematically addressed. Back contact remains the dominant problem.

Evidence: back-illumination TRPL recombination is low; front-illuminated increases dramatically with thickness.

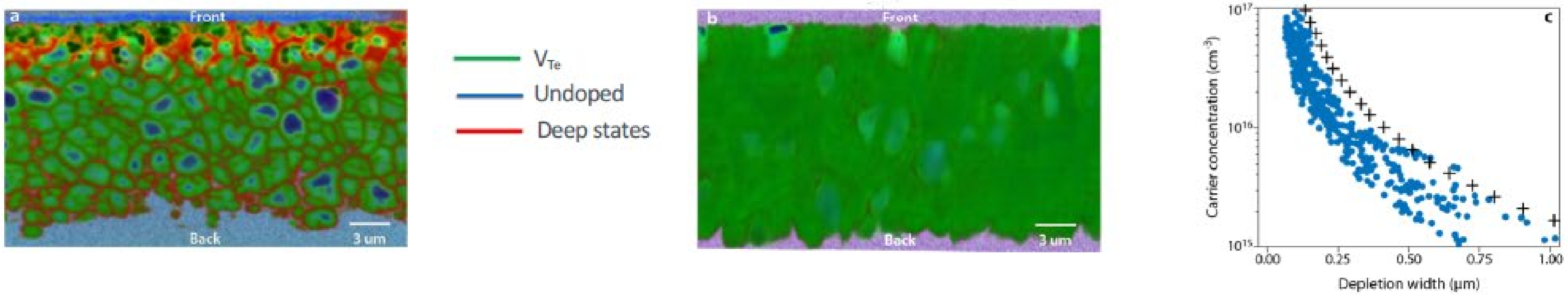


Additional project contributors: University of Toledo; First Solar, Inc.; National Renewable Energy Laboratory; University of Illinois at Chicago

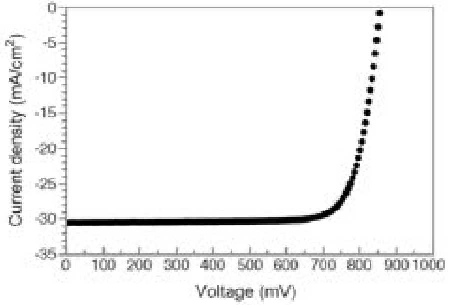
Highlights for Lab Call19-21 34353 (NREL, Metzger)

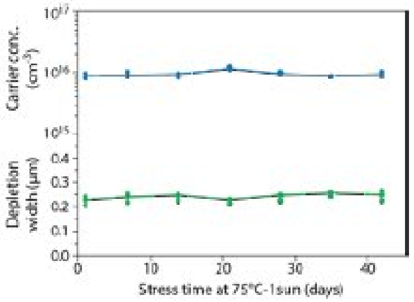


Schematic of a typical CdTe solar cell. The thin (3 μm) absorber is deposited in seconds on a glass/TCO substrate.

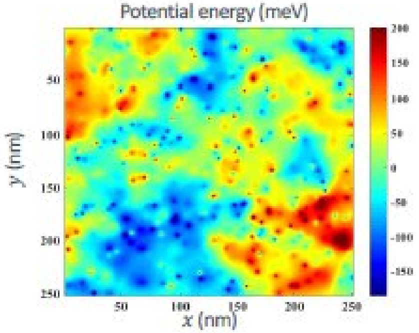


Thin film solar cells usually have poor carrier concentration control. CdTe was no different and limited to ca. 10^{14} cm^{-3}, well below the 10^{16} – 10^{17} cm^{-3} ideal. The state-of-the-art dopant, Cu moves and creates stability issues. We shifted to placing group V elements (P, As, Sb) on the Te lattice site. Cathodoluminescence shows (a) ex-situ processes are non-uniform, (b) in-situ group V doping is uniform, (c) and hole density can now reach 10^{16} – 10^{17} cm^{-3}.

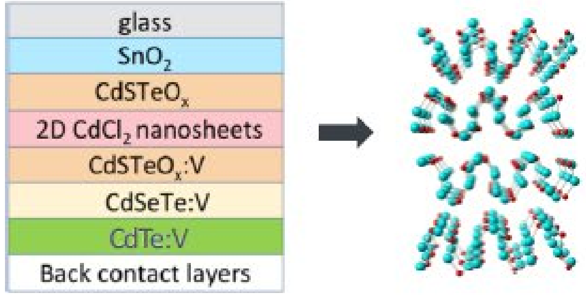




For the first time cells can be made by manufacturing methods without Cu. The efficiency has reached 21%, and the energy yield is greater than state-of-the art cells. The approach also removes CdTe's largest stability issue, Cu doping.



The 10^{18} cm^{-3} GrV incorporation needed today creates potential fluctuations, decreasing V_{OC}. We are researching dopants, defects, and new methods.



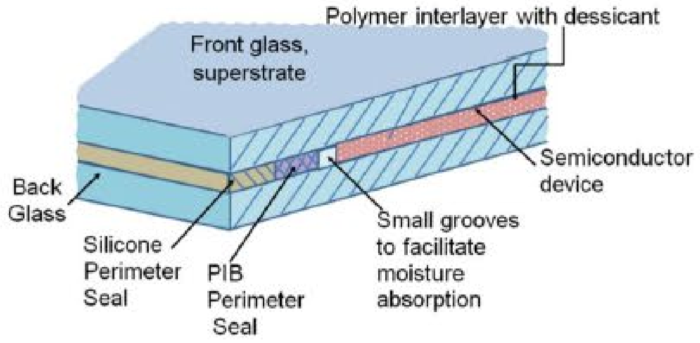
Planar, atomically smooth cleaves have provided seminal interface discoveries. We are reengineering the buried p-n interface to enhance performance.

Additional project contributors: University of Illinois at Chicago, First Solar

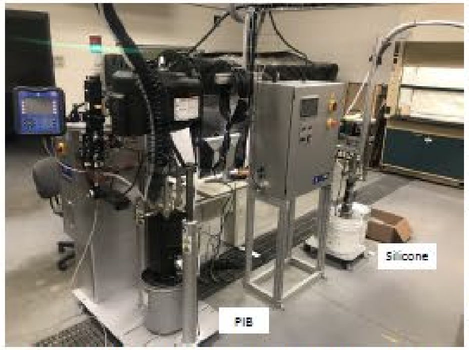
Nature Energy, **4**, 837

Highlights for PVRD2 8161 (CSU, Barth)

New Module Architecture



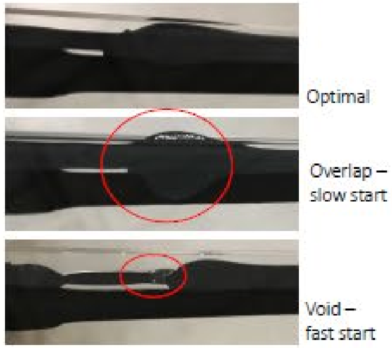
Encapsulation Prototype Tool



High viscosity pumping systems: PIB is a heated line, while silicone is not

Dispensing systems: 4 axis motion control, 2 dispense heads, vacuum table

Dispense Optimization

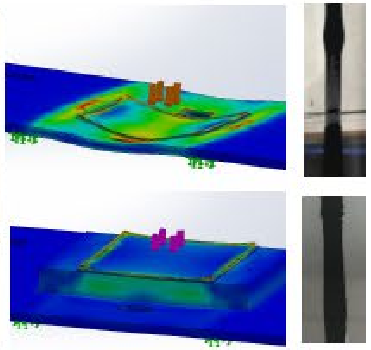


Poor Start Segment – Acceleration: 520 ms Pump Prestart: 900 ms

Optimal Start Segment – Acceleration: 690 ms Pump Prestart: 790 ms

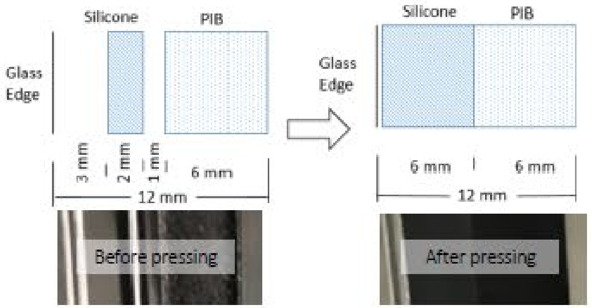
Press Optimization

Automated Press

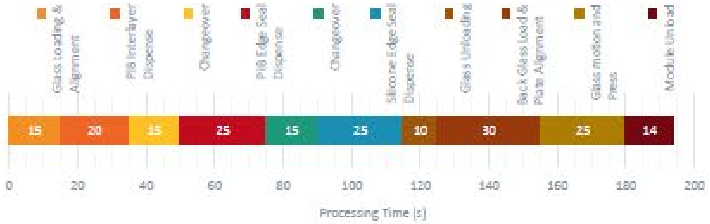


Non uniform seal on top, uniform seal on bottom

Edge Seal



Quality & Speed Milestone



Additional project contributors: Sam Ellis, Tushar Shimpi, Larry Maple

Highlights for PVRD 7551 (CSM, Rockett)

Dramatic improvement in grain structure & device performance

3 stage process:

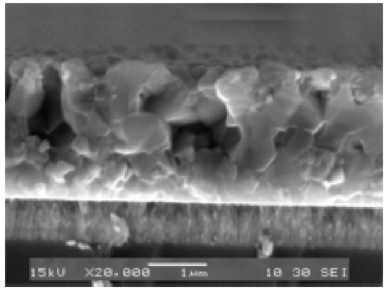
Stage 1: 350°C, III-rich

Stage 2: 400°C, Cu-rich

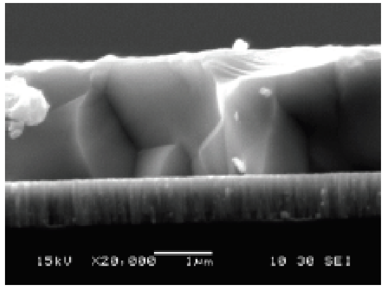
Optional anneal (+5 min)

Stage 3: 400°C, III-rich

12 min total time.



No recrystallization



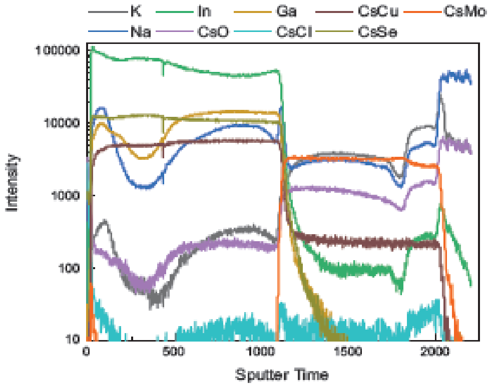
AgBr, 5 min, 400°C

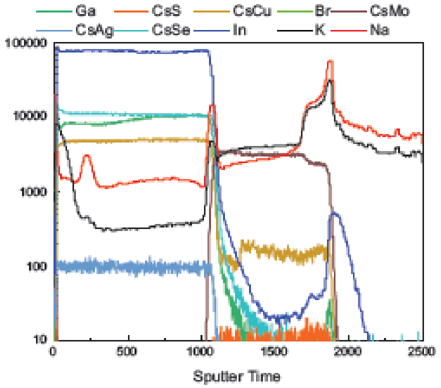
SIMS Profile:

Sharp interfaces retained.

Ga profile lost in recrystallization.

Good results with $AlCl_3$ ex-situ anneal. Also exploring CuCl and $InCl_3$.

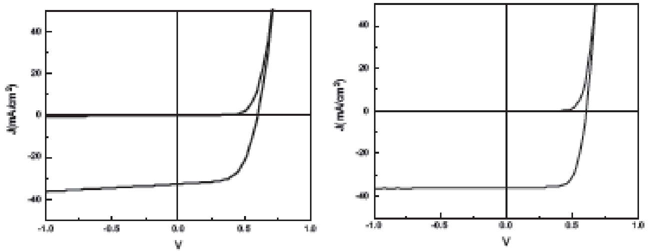




	Voc(mV)	Jsc(mA/cm²)	FF(%)	η(%)
Reference	599	32.6	55.6	12
AgBr	605	35.9	72.2	**15.7**

No recrystallization

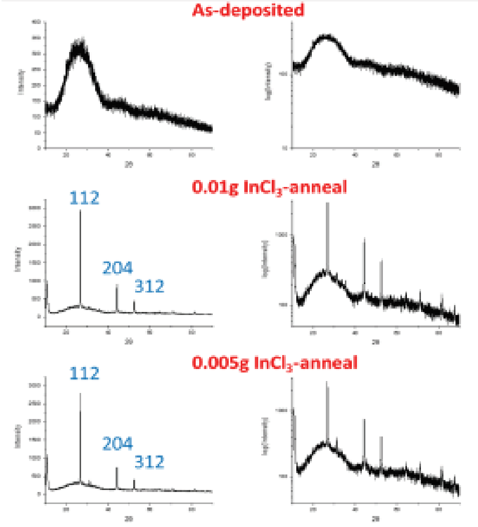
AgBr, 5 min, 400°C



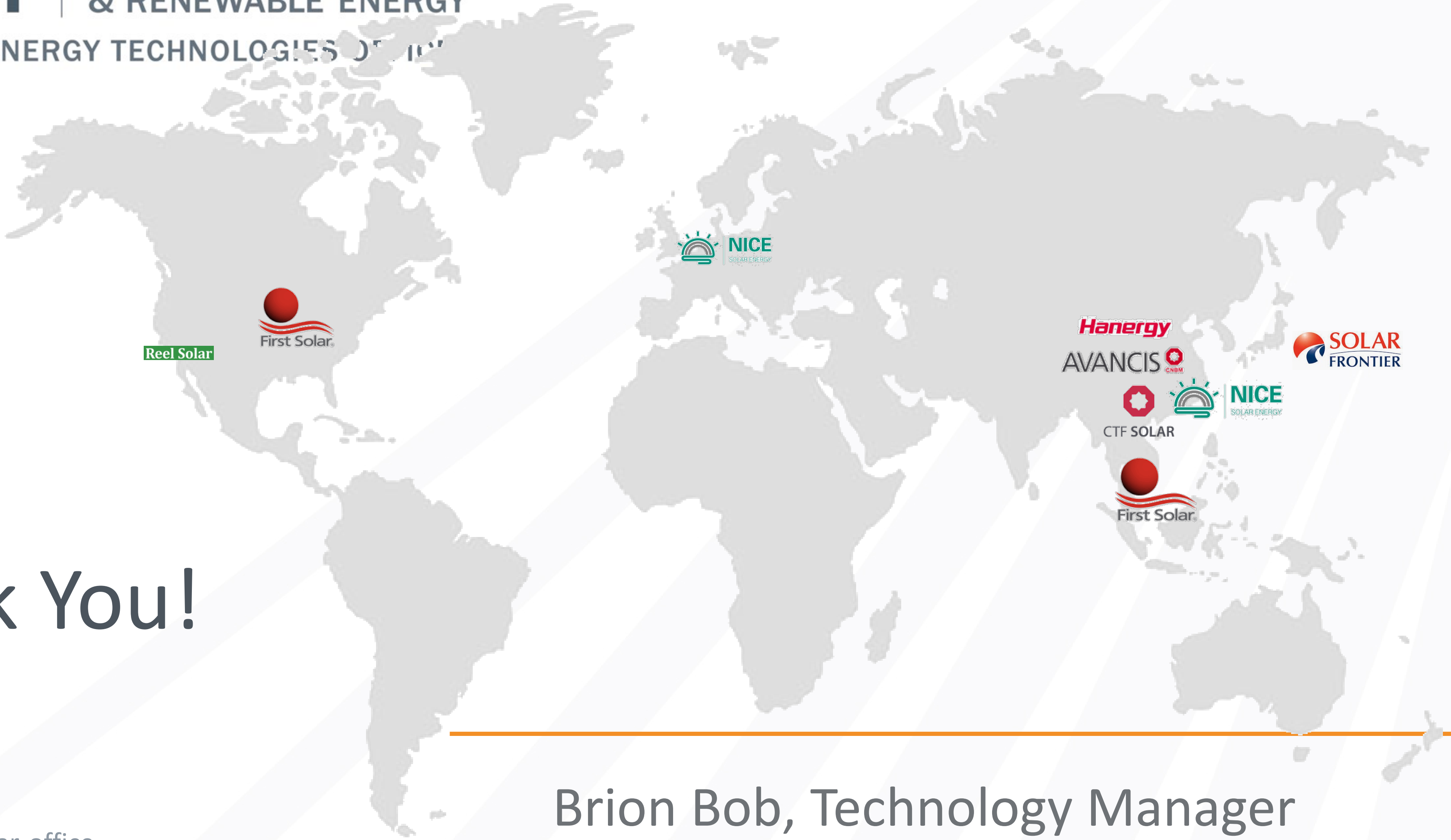
Reduced voltage-dependent collection, reduced series resistance, improved current, improved voltage & fill factor

Further improvements expected with corrected Ga profile & alkali halide PDT.

Recrystallization of initially amorphous material deposited at room temperature shows potential for even higher rates and lower temperatures



Additional project contributors: Sylvain Marsillac, ECE Department, Old Dominion University, Norfolk, VA



Thank You!

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