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US-MAC
Manufacturing of Advanced Cadmium Telluride

CTAC
Cadmium Telluride Accelerator Consortium
U.S. DEPARTMENT OF ENERGY

Welcome to the 7th Annual CdTe PV Workshop

October 25 – 27, 2023

National Renewable Energy Laboratory

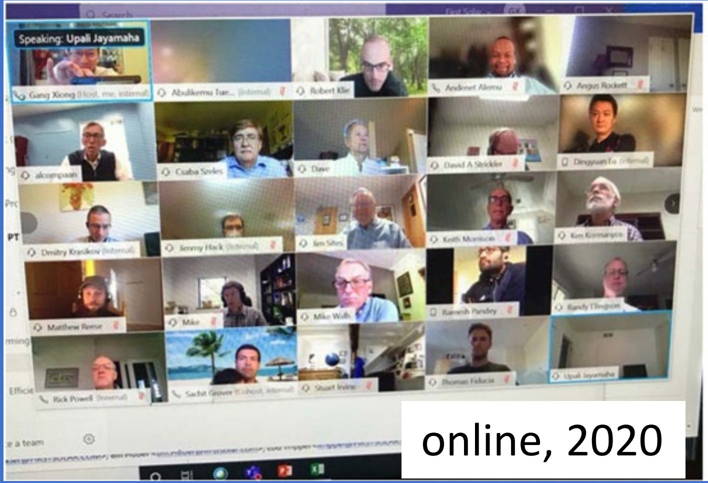
NREL
Transforming ENERGY

U.S. DEPARTMENT OF ENERGY

CTC, 2017


UT, 2018


NREL, 2019


online, 2020


Chicago, 2021

UT, 2022

US-MAC

- ad hoc organization, with the following mission:

- Leverage resources, stimulate R&D investment, and accelerate innovation.
- Cut cost in half in 5 years, extend solar panel life from 25 to 50 years.
- Reduce CapEx and increase rate of production with new processes.
- Meet all U.S. PV demand and enable export across the world.
- New markets for rooftops, building integration, defense applications, & solar everywhere

Self organized in 2018 – 2019, MOU signed in 2021

US-MAC
Manufacturing of Advanced Cadmium Telluride

13 Companies, 5 Universities, NREL

Hot Topics

5N PLUS
ASU
Colorado State University
CONSOLIDATED RESEARCH SYSTEMS, LLC
DIRECT SOLAR LLC
First Solar
JPHB
Lucintech
nexTc
Nious Technologies ...unbounded imagination
NREL Transforming ENERGY
PILKINGTON
Sivananthan Laboratories
Tau Science Process Control for PV
TOLEDO SOLAR
UNIVERSITY OF DELAWARE
THE UNIVERSITY OF TOLEDO
THE UNIVERSITY OF UTAH

CTAC

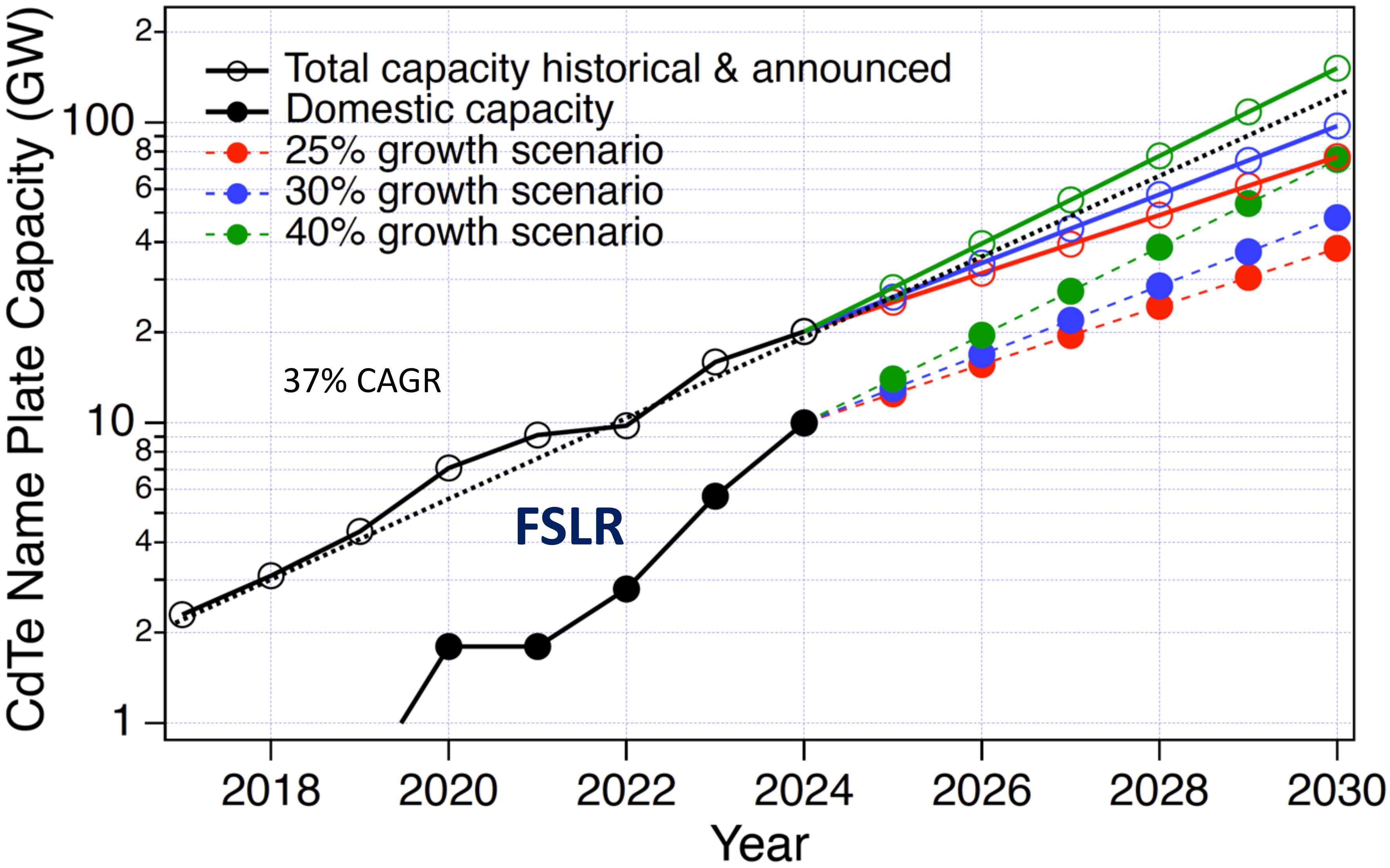
CTAC
Cadmium Telluride Accelerator Consortium
U.S. DEPARTMENT OF ENERGY

- Formed by DOE/SETO's Photovoltaics Program in 2022.
- Managed by NREL :
  - Support the planning/operations of a technology development consortium to enhance U.S. technology leadership and competitiveness in CdTe PV
  - Enable cell efficiencies above 24% and module costs below $0.20/W by 2025 Enable cell efficiencies above 26% and module costs below $0.15/W by 2030 Maintain or increase domestic CdTe PV material and module production through 2030.

➢ - Initial award for $9 M (CSU, FSLR, Siva Labs, Tol. Solar, UToledo + $1.7 M for NREL
- Two additional $2 M supplementary RFPs to date
- Third $2 M RFP is expected soon

➢ Additional R&D funding from SETO's Manufacturing and Competitiveness Program
➢ Overall, CdTe R&D Funding has grown ~3X since 2018

Road to 100 GW_{DC}/yr



First Solar Update

Bill Huber
Head, Advanced Research

October 25th, 2023

First Solar

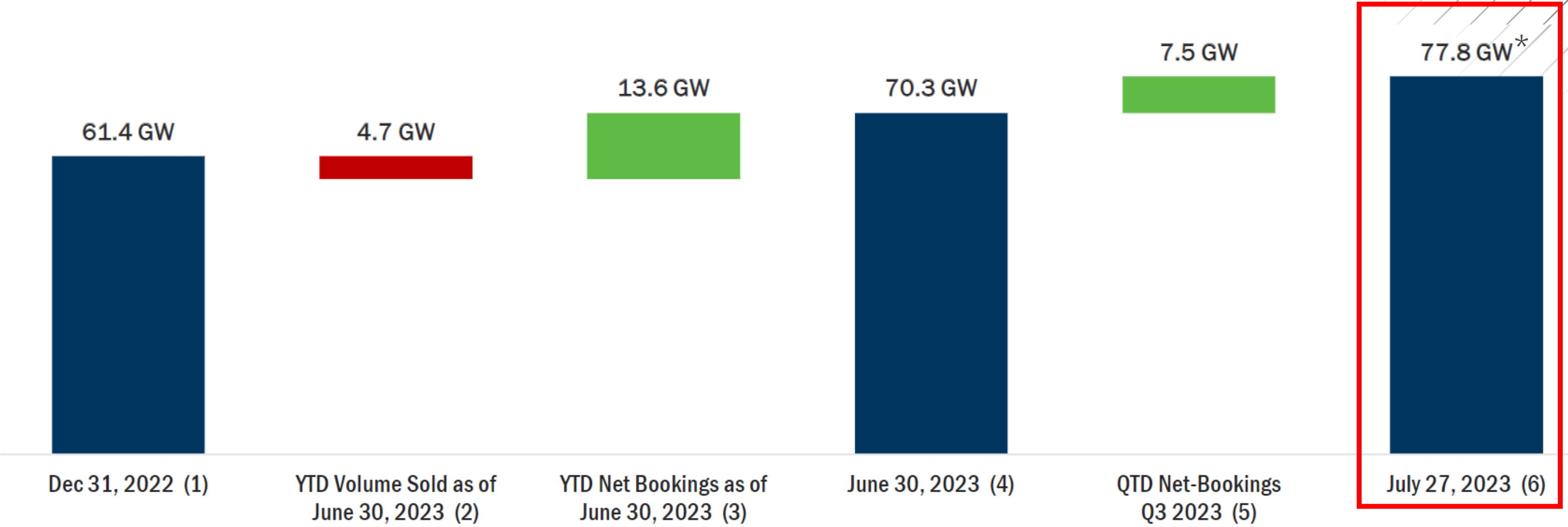
LEADING THE WORLD'S
SUSTAINABLE ENERGY FUTURE

Today

First Solar

- >20 years of thin film PV leadership
- 1st company:
  - < $1/W
  - > 1 GW installed
  - Global module recycling
- Lowest carbon footprint
- 50 GW shipped, to date

Customer Demand



25GW+ of Annual Manufacturing Capacity by 2027

Ohio, USA
Expansion Expected Finished 2024

Kulim, Malaysia
Operational 2008

Dong Nam, Vietnam
Operational 2019

Tamil Nadu, India
Anticipated Opening 2H 2023

Alabama, USA
Anticipated Opening 2024/2025

New! Louisiana, USA
Anticipated Opening 2026

25 GW/yr →  8.3 Million / year

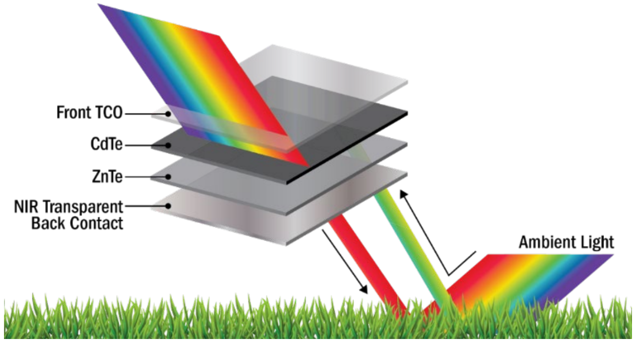
First Solar Proprietary & Confidential - General

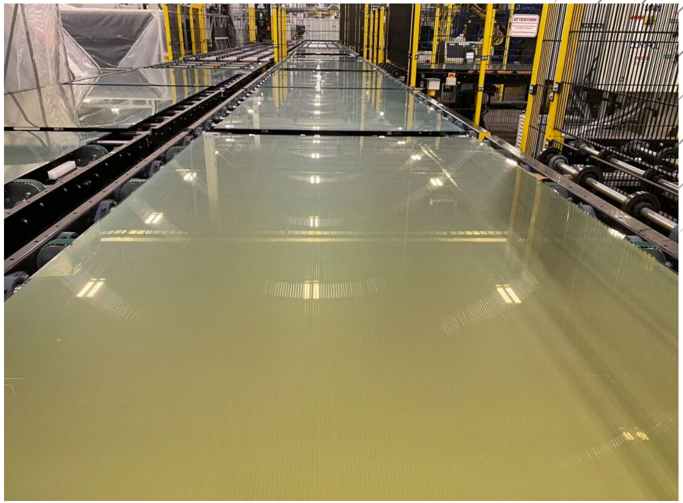
Research & Development Center (RDC)

Under construction (2024)

- Largest PV R&D innovation center in Western Hemisphere
  - 1.3 m ft2 – 15 soccer fields
  - > $300 M investment
  - 24/7
- Fully automated; flexible.
- Supports CdTe roadmap & future tandem.

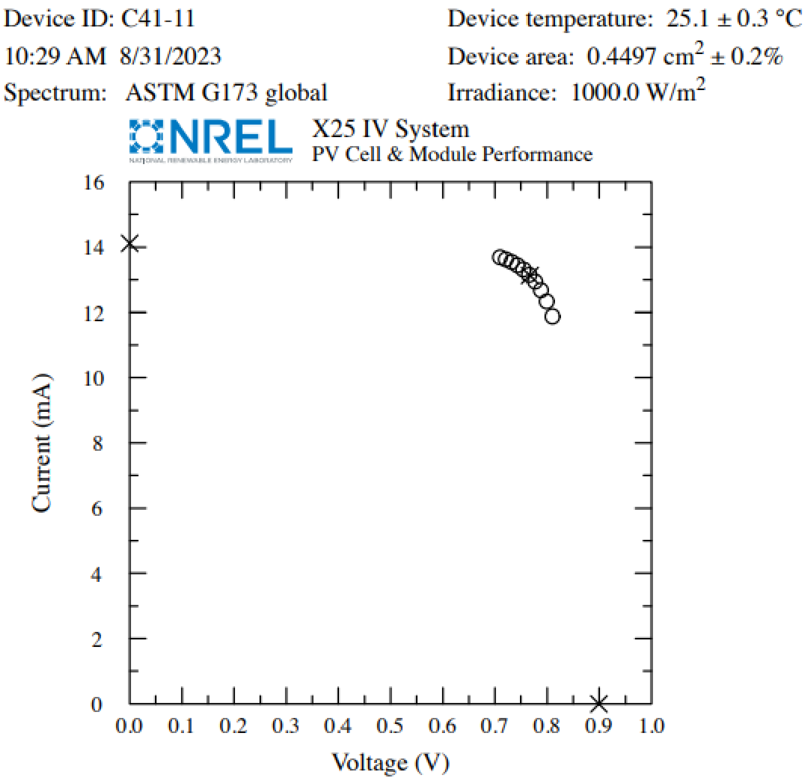
Ramping Bifacial CdTe





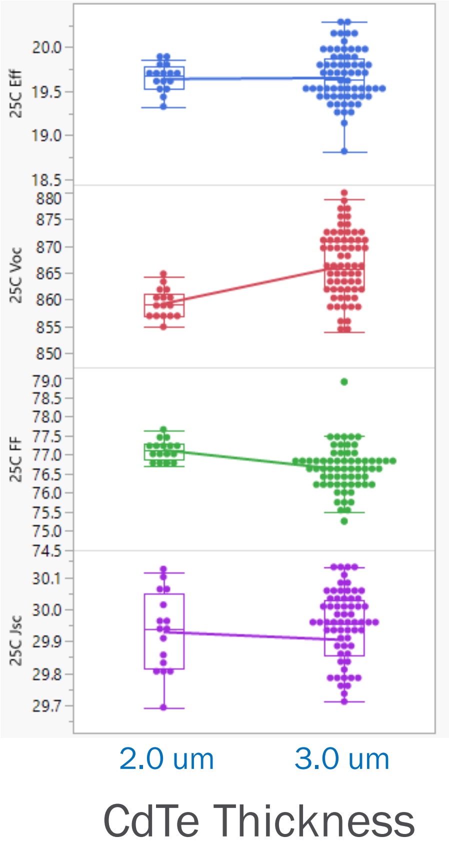
- ✓ 15-20% BiFi at launch.
  - Path to 50+%.
- ✓ Minimal power loss.
  - TCO sheet rho.
- ✓ Lower operating temperature.
- ✓ Same excellent stability/reliability.

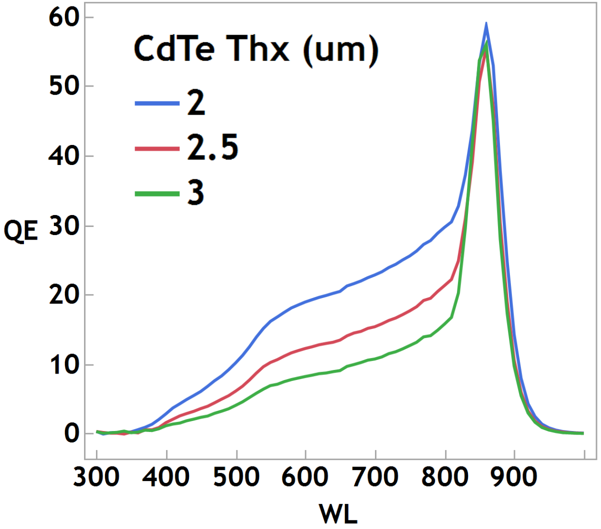
New CuRe Record: 22.4%



Efficiency	22.4%
Voc	900 mV
Jsc	31.4 mA/cm^2
FF	79.3%

CuRe enables thin CdTe

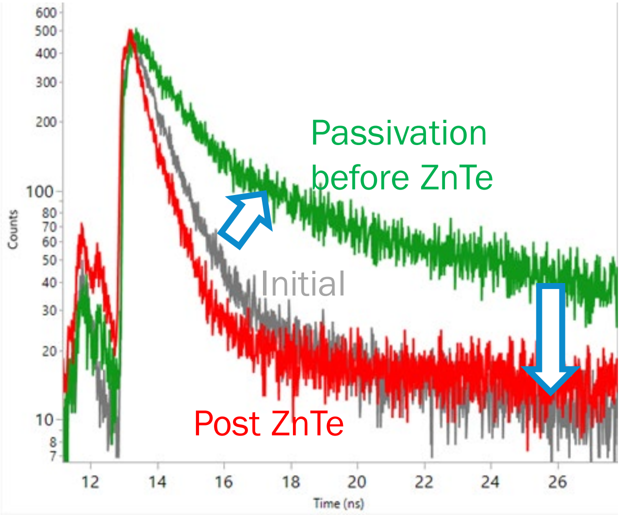




- Comparable efficiency.
- Reduced CdTe thickness.
- BiFi > 30%

Challenges Remain

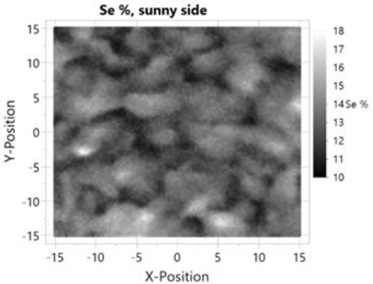
Film side TRPL



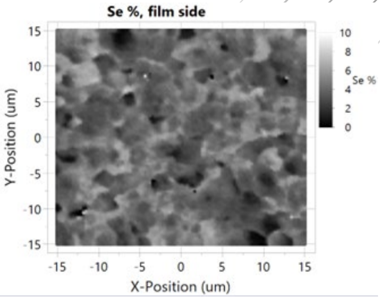
Back interface passivation doesn't survive ZnTe

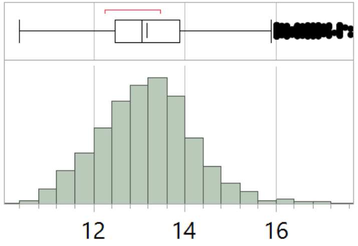
Confocal PL

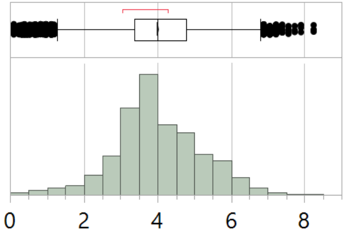
Sunnyside



Film Side







Significant Se, As non-uniformity
even w/high efficiency devices

Needs from CdTe Community

- Passivated back contact.
- Improve understanding of interfaces & Voc loss.
- High As activation in poly-CdTe.
  - Stop working on Cu.
- Leverage FSLR for device integration/testing.
- Grow CdTe community.

LEADING THE WORLD'S SUSTAINABLE ENERGY FUTURE

NSG
GROUP

Introduction to NSG Today

- One of the world's largest manufacturers of glass and glazing
- Principal operations around the world, with sales in over 100 countries
  27 float lines worldwide
- Approximately 26,000 employees globally
- Consolidated Revenue JPY600.6bn (2022/3)

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NSG and Solar Activities

NSG GROUP

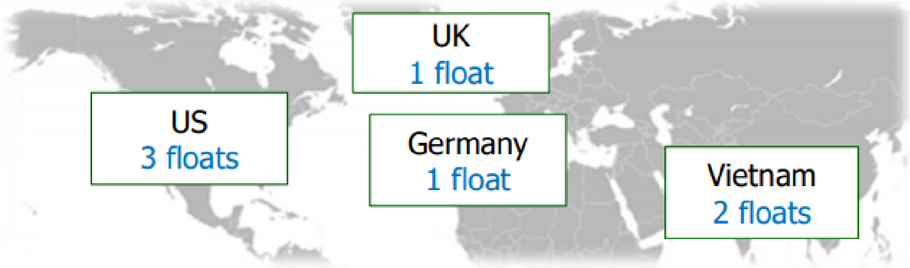
Acceleration of the shift from commodity glass to value-added products

Strengths and Functions of Online Coating

- NSG's proprietary technology
- Seven float lines with online coaters globally
- Thin, uniform metallic oxide film deposited over glass while being formed inside the float bath
  - Cost competitive, available in large size
  - Durable and versatile, suitable for further processing and various applications

Function	Use
Conductivity	Heating glass
	Transparent conductive film for touch panels
	Transparent conductive film for thin film solar panels
Infrared reflection	Heat insulation glass
	Heat blocking glass
	Low e glass

Float lines with Online Coaters



↑ Glass for thin film Solar panels
Courtesy of First Solar Inc.

↑ Glass for electrochromic applications
Courtesy of View Inc.

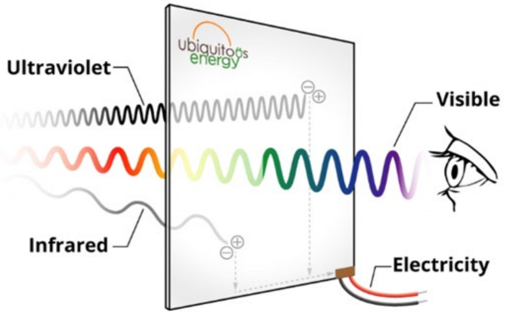
Recently Announced - Installation of online coating capacity to existing float furnace in Malaysia to produce Solar Energy Glass – Operational 2024

Solar Opportunities Outside CdTe

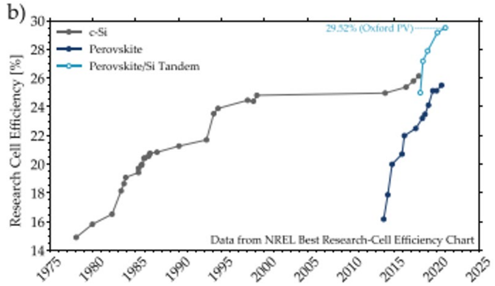
- NSG focusing on a number of Thin Film PV opportunities for TCO/Glass
  - Dye-Sensitized Solar Cells achieve sufficient power from dim/internal lighting to act as battery replacement cells in IoT devices
    - <1.6mm TCO/Glass requirement

Low light harvesting cell

  - Organic PV provides opportunity for Building Integrated PV (BIPV)
    - Tuned to absorb in IR and UV
    - No visual impact from silicon wafer systems
    - Need to further improve efficiency levels



  - Perovskite PV
    - Relatively cheap to manufacture, abundant materials
    - High efficiencies in both single and tandem junction
    - Large market potential for Glass/TCO in both single and 4T tandem junction devices if durability issues solved



A number of Thin Film PV opportunities arising outside of Cad Tel

Roadmap to Carbon Neutrality for 2050

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NSG GROUP

Committing to achieve carbon neutrality by 2050.

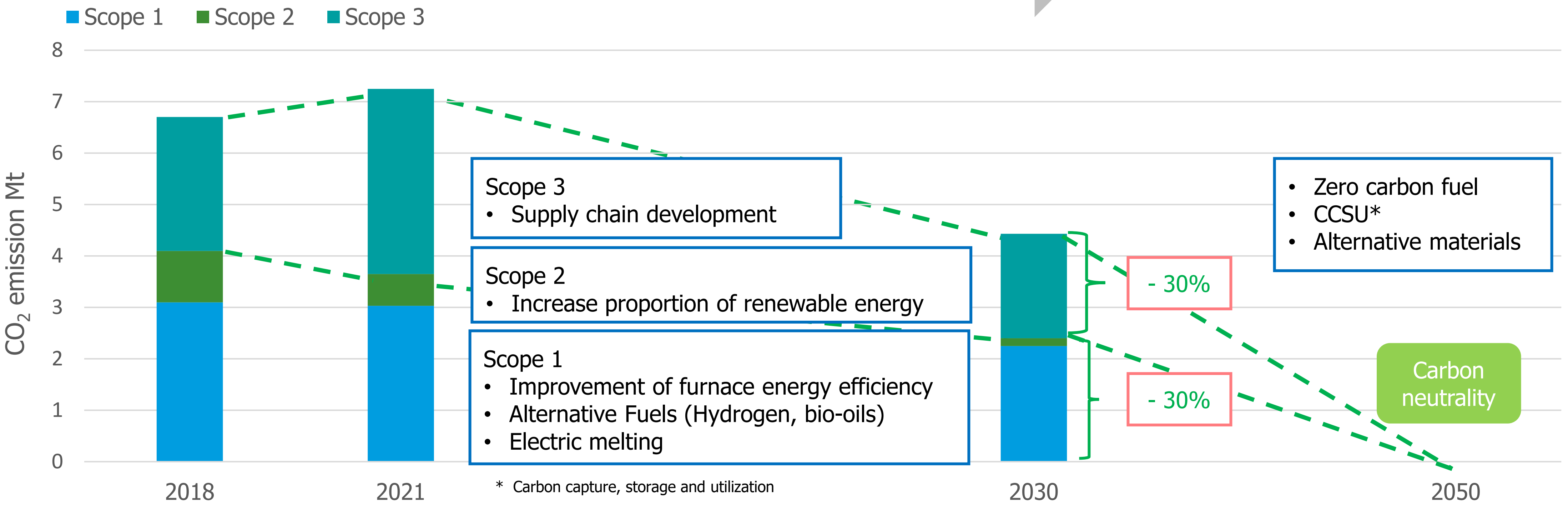
Raising carbon reduction target by 2030 from 21% to 30% compared to 2018

Targets

2021 – RP24 – 2024	2030	2050
Achieve 2 percent reduction of CO_2 p. a. during RP24	2030 targets (vs 2018) ・Scope 1＆2 : - 30% ・Scope 3 : - 30%	Achieve carbon neutrality

Existing technology improvement → Transition stage → Disruptive innovation

Key initiatives



* Carbon capture, storage and utilization

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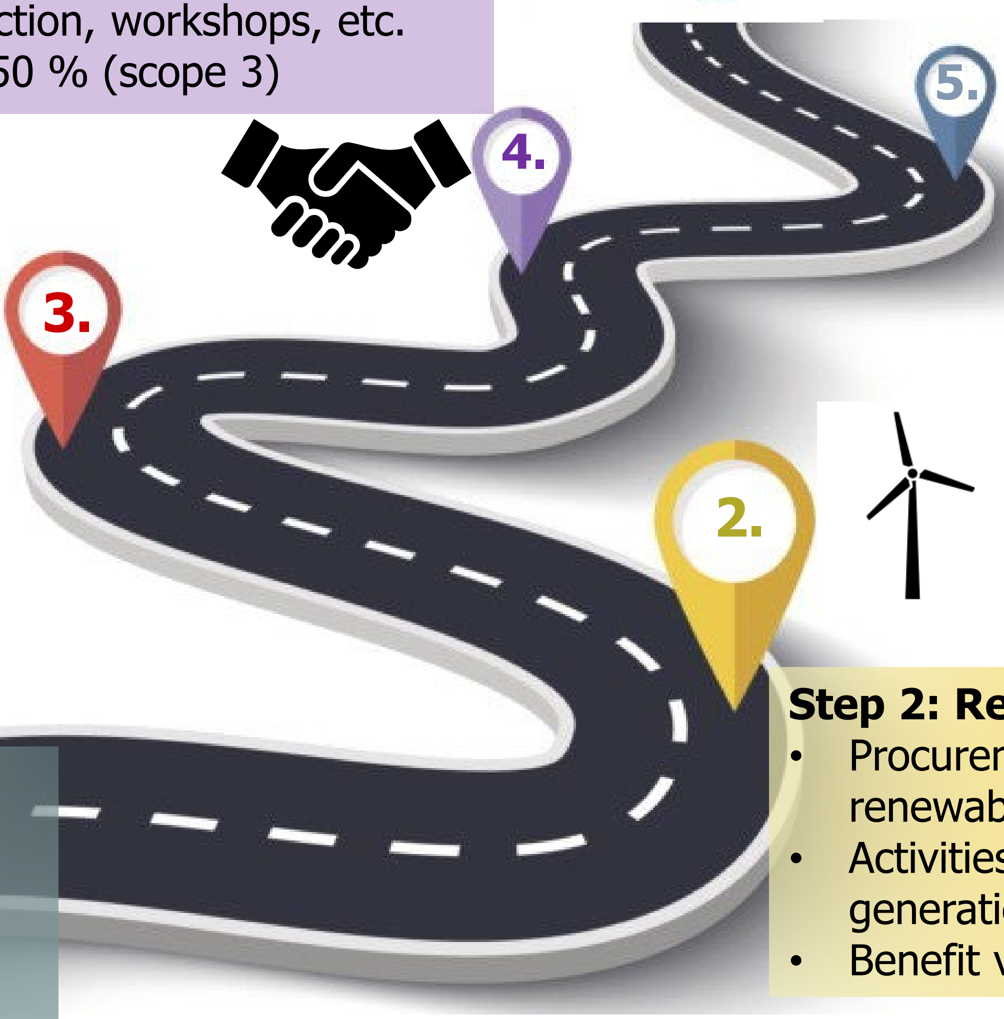
Decarbonisation Roadmap

NSG GROUP

Step 4: Value Chain Engagement
- Understand & reduce scope 3 emissions
- Activities include; data collection, workshops, etc.
- Benefit vs Baseline @ 15 – 50 % (scope 3)

Step 3: Technology Change
- Development & implementation of new technologies
- Benefit vs Baseline @ 20 – 70 %
- Activities include; Carbon capture, Low carbon fuels, electrification, alternative materials, etc.

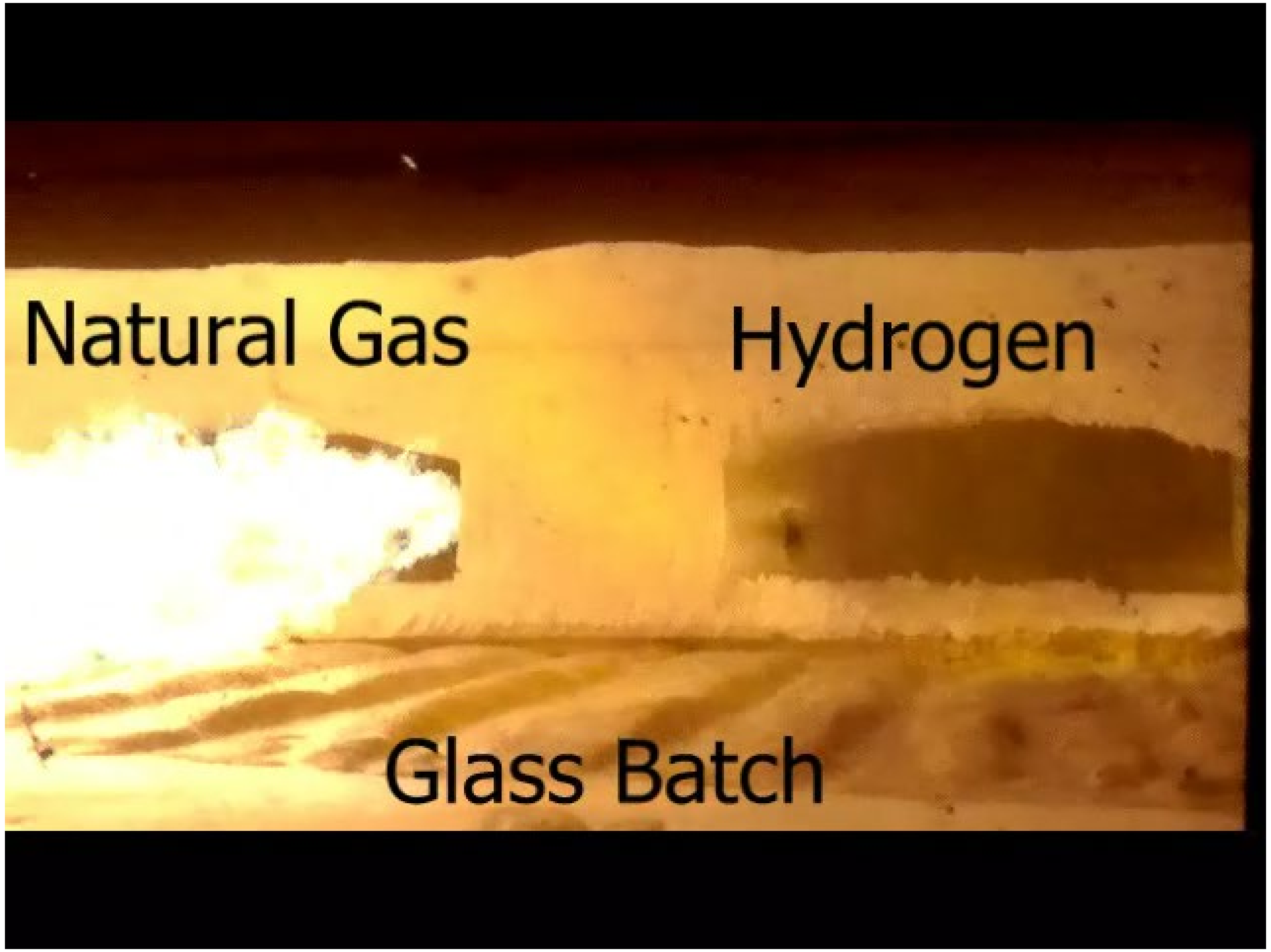


Step 5: Carbon Offsets
- Final step to achieve carbon neutrality

Step 2: Renewable Energy
- Procurement/generation of renewable energy
- Activities include; PPA, on site generation, heat recovery
- Benefit vs Baseline @ 5 – 15 %

Step 1: Operational Efficiency
- Effective dissemination of energy/CO_2 efficiency measures across all Group operations
- Activities include; infrastructure upgrades, waste glass (cullet) management, etc.
- Benefit vs Baseline @ 5 – 15 %

NSG Group achieves World First Float Glass production with Hydrogen Fuel

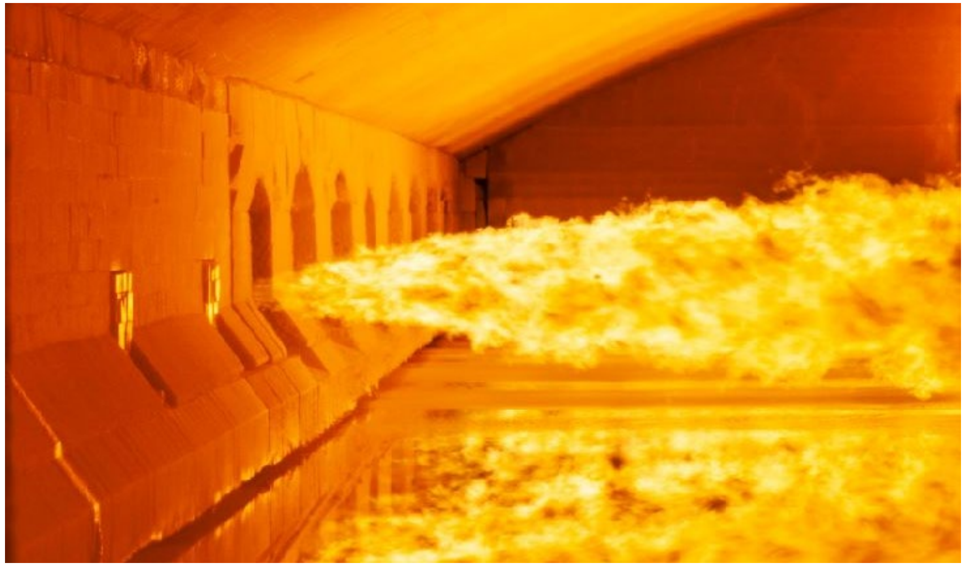


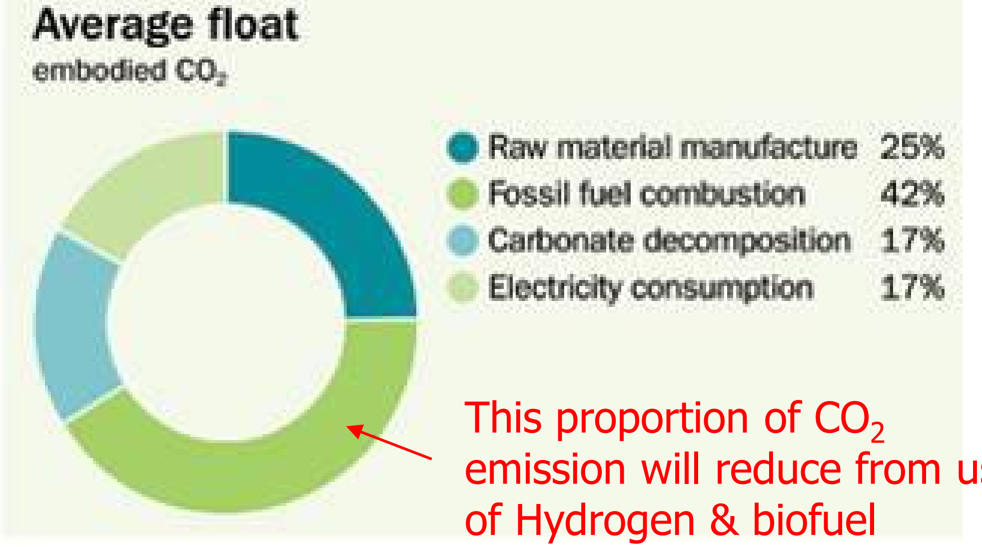
- Aug-2021 – Flame appearance with increasing hydrogen
- @7% reduction in overall CO_2 footprint of glass produced during the trial

World's first float line to use Hydrogen as a fuel

NSG Group Achieves Another World First – Float Glass production with 100% Biofuel

- 14th – 17th February 2022
- Excellent fuel for glassmaking – technical properties very similar to traditional fuel oil
- High level of confidence that liquid biofuel is a viable alternative to fossil fuel
- @40% reduction in overall CO_2 footprint of the glass produced
- Technical challenge overcome – Commercial & Logistics challenges remain





This proportion of CO_2 emission will reduce from use of Hydrogen & biofuel

Lowest carbon float glass ever produced in the world

PILKINGTON

Pilkington **Mirai™**

- Mirai, meaning 'future' in Japanese, was developed to mark the start of the next generation of low carbon glass products to help meet stricter sustainability requirements in the built environment.
- 50% less embodied carbon* compared to our standard float glass
- A low Global Warming Potential (GWP**) of less than 5.5 kg CO2 per m^{2*}
- Manufactured using a combination of alternative fuel, high recycled glass content and 100% renewable electricity
- Identical neutral aesthetics, exceptional quality and performance as our standard product, manufactured in accordance with EN 572-2

Pilkington **Mirai™** can currently be offered as a low carbon base substrate or in combination with our high performance low-e and solar control coating ranges such as Pilkington **Optitherm™**, Pilkington **Suncool™** including laminated and acoustic variants and has been designed for both commercial and residential segments.

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NSG GROUP

Summary

- NSG continuing it's shift from commodity to value added glass
  - Solar sector is a key part of this strategy
  - Further expansion of our use of On-Line Coatings to supply sector announced

- NSG working in parallel on key carbon reduction activities
  - Proof of concepts successfully conducted for H_2 and Biofuels
  - Significant work now on evaluating commercial viability of these routes for all market segments

NSG

GROUP

Juntos, Vemos Más Allá

Vitro Flat Glass, LLC
Company Overview and 2023 Update
Solar Program

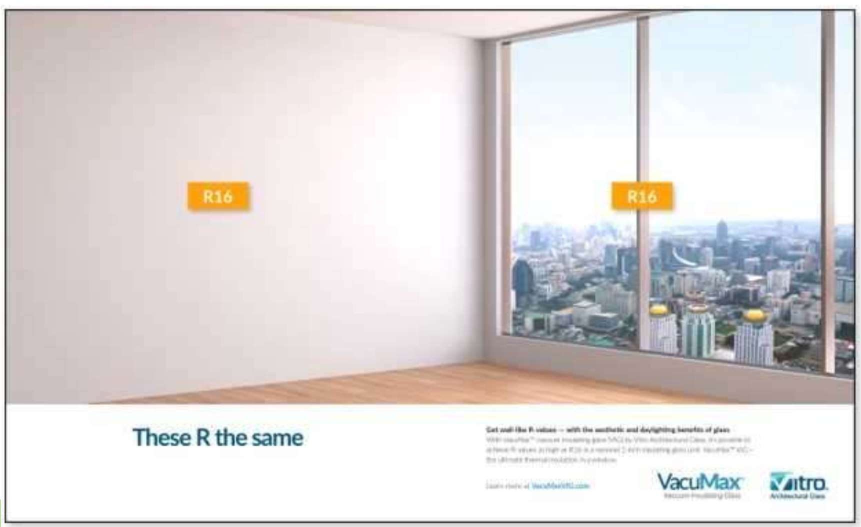
October 2023

Company overview

- Vitro is the largest **glass manufacturing company** in North America and one of the largest in the world.
- **+110 years of experience**. Founded in 1909 in Mexico, the company offers quality products and reliable services to serve 3 segments: **Flat Glass, Glass Containers and Chemicals**.
- In 2016 and 2017, Vitro **acquired PPG & PGW** respectively, to consolidate, expand and strengthen the architectural and automotive businesses.
- Vitro's companies produce, process, distribute and market a wide range of glass products to multiple markets like **architectural and automotive glass**, **cosmetics, fragrances, pharmaceuticals and liquors**. It also supplies **chemicals and raw materials**, **machinery and equipment** for industrial use.

Architectural Glass Business

- Vitro manufactures and distributes glass for the **construction, residential, industrial** and **automotive** segments.
- We supply a wide range of value-added glass products, such as Solarban®, Starphire®, Intercept® IGU Spacer, VacuMax®, Solarphire® PV, Solarphire® AR, SolarVolt®



Vitro®

Juntos, Vemos Más Allá

Solar Program

New Products

- SolarVolt® BIPV modules for the architectural market
- Glass and fabricated backplates for CdTe modules for the utility market

Generate clean energy. Replace building envelope materials. Give glass something new to do.
Produce CO_2-free power. Customize aesthetics and performance with any Vitro Glass product. Potentially replace typical building enclosure and exterior elements. Next-generation, energy-efficient design is inevitable with new *Solarvolt*™ BIPV modules by Vitro Architectural Glass.

For more information, contact an architectural representative. Find yours at vitrosolarvolt.com.

SOLARVOLT™ Building Integrated Photovoltaic

Vitro. Architectural Glass

New Projects – Focus on CdTe

- Initiated development with partners to deliver technology to increase the performance of CdTe modules with potential applications to perovskite PV

- Project partners aligned to provide complementary technology strengths to target improvements in the superstrate component
  - Device and materials physics
  - Materials development
  - Component process
  - Device fabrication

- Goal is to develop technologies with path to supply commercial products to the CdTe market

NREL CRADA Project

Develop novel front contact layers for CdTe photovoltaics

- Partnered with NREL Thin Film Material Science & Processing group
  Deborah Mcgott, Craig Perkins, Matt Reese

- The goal is to develop theory and processes to identify and incorporate front junction materials into CdTe based photovoltaic devices to enable higher open circuit voltage and efficiencies. This will include investigation of front junction partner band alignment, doping density, oxidation catalytic activity, and stability.

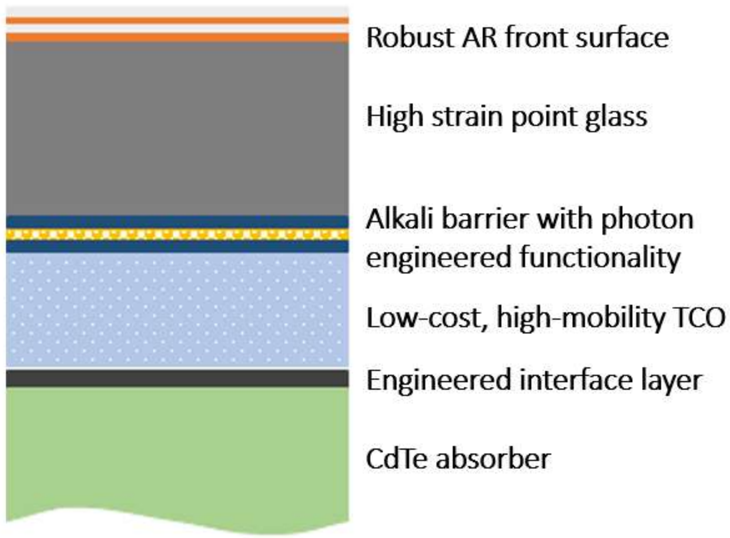
- Project framework:
  - Front junction materials selection and experiments
  - Front junction materials evaluation experiments

- Status…nine candidate materials identified, ranked and investigation underway

SETO Solar Manufacturing Incubator Funded Project

High Performance Superstrate (HPS) for CdTe Modules

- Partners
  - Dr. Amit Munshi, Colorado State University
  - Dr. Cory Perkins, nexTC Corporation
  - Dr. Michael Heben, University of Toledo
- Goals
  - Increase CdTe module efficiency through multicomponent improvements to the HPS
  - Provide scholarship funds for STEM research opportunities through programs at University partners
- Project framework:
  - Budget Period 1- Identify materials and processes for each component; demonstration of existing high strain point glass composition, decision review milestones for each component
  - Budget Period 2 - Integrate two or more components into the HPS with measured gains in improvement



SETO Solar Manufacturing Incubator Funded Project

High Performance Superstrate for CdTe Modules

- Status

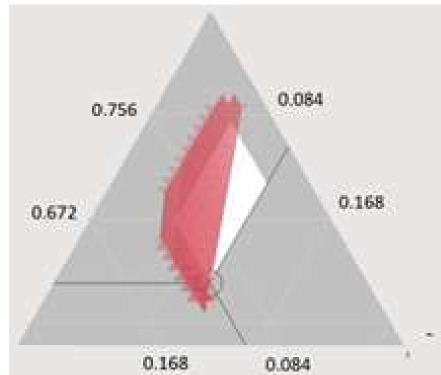
Project logistics in place

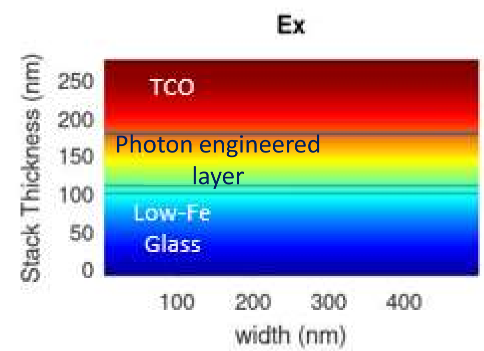
Modeling using physics- and ML-based tools to drive design and materials development

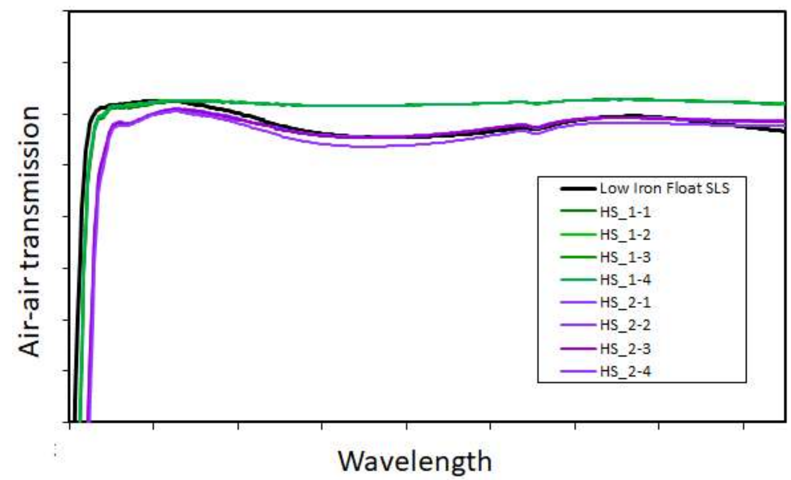
Initial combinatorial materials research begun

Fabrication of individual components underway

- Glass substrate
- Transparent conductor
- Photon engineered layers







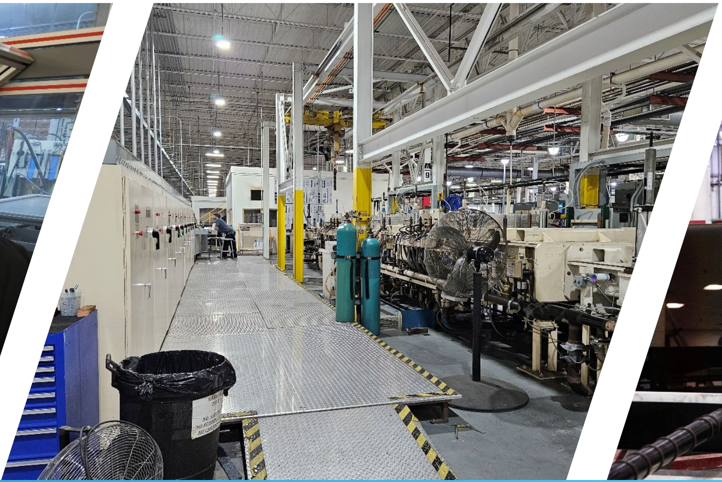
Vitro®

Juntos, Vemos Más Allá

Thank You

Update on the Status of

TOLEDO SOLAR



Change of Management

- Back in July 2023, the majority of TSI stakeholders decided a change in executive management was necessary to ensure the long-term success and viability of Toledo Solar

- Sean Fontenot was elected as the new Chairman of the Board

- Tom Pratt was installed as the interim President, Treasurer, and Secretary to guide TSI during this transition

Toledo Solar's Future

- The board remains committed to Toledo Solar's mission of expanding CdTe adoption and usage worldwide, as well as strengthening US based manufacturing in general

- To this end, the board is also committed to providing the resources necessary to make TSI successful
    - Interim funding secured
    - Implement new systems
    - Hire personnel
    - Equipment/materials

- Plans for future funding in the works

Administrative Changes

- Settlement reached with First Solar in September
  - Swift resolution speaks to the new management's commitment.
  - Opens the door for a more collaborative relationship with FS moving forward

- New management team

- EHS system implementation
  - Ross Environmental
  - St. John EHS Consulting

Production/ Process Changes

- Re-commissioning of a proven VTD system
- Inline metrology
  - XRF
  - $CdCl_2$ Heat Treatment Pyrometers
  - Plans to expand inline metrology further
- Centralized Database
  - SQL/JMP Based
  - Freely accessible internally
- Project Planning/Project Management Systems

Growing the Team

- C-suite
    - Interim COO (by EOY 2023)

    ↓

    Remainder of C-suite (Q2 2024)

- Operations
    - Added an operator in October
    - Added a laser technician in October
    - Adding a controls engineer end of October/early November
    - Expecting a 2nd operator added in November
    - Continued review of personnel needs and hiring as needed

TOLEDO SOLAR

Moving Forward

- Collaboration with University of Toledo and Colorado State University
- Greater engagement in CdTe industry via CTAC and US-MAC

- Non-Utility and rooftop Markets
- Continued focus on product development, specifically semi-transparent modules
    - BIPV
    - Agrivoltaics
    - Automotive
    - Other niche sectors

Looking Ahead

Q4 2023

- ✓ Interim COO
- ✓ Produce complete modules
- ✓ Meet internal targets
- ✓ DOE 9330

Q2 2024

- ✓ C-suite
- ✓ Start of UL certification process
- ✓ Completion of DOE 9330
- ✓ Long term capital investment secured
- ✓ Planning/initial orders for new production lines

2025/2026

- ✓ Installation of new lines
- ✓ Plans for new factories to further increase production capacity

TOLEDO SOLAR

CTF Solar GmbH

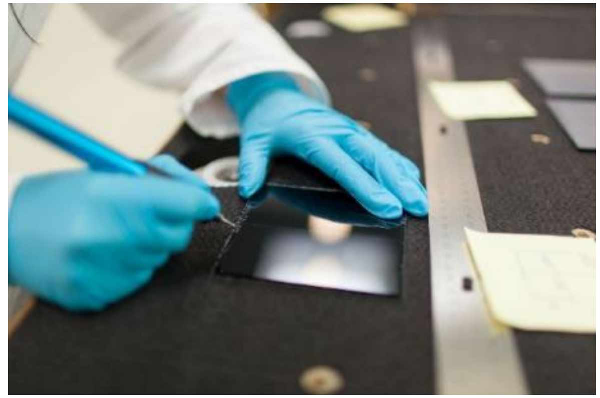
7^{th} CdTe workshop at NREL (USA)

Anna Kindvall, October 2023

Outline

- History of CTF SOLAR
- Production technology and factory projects
- Research and development

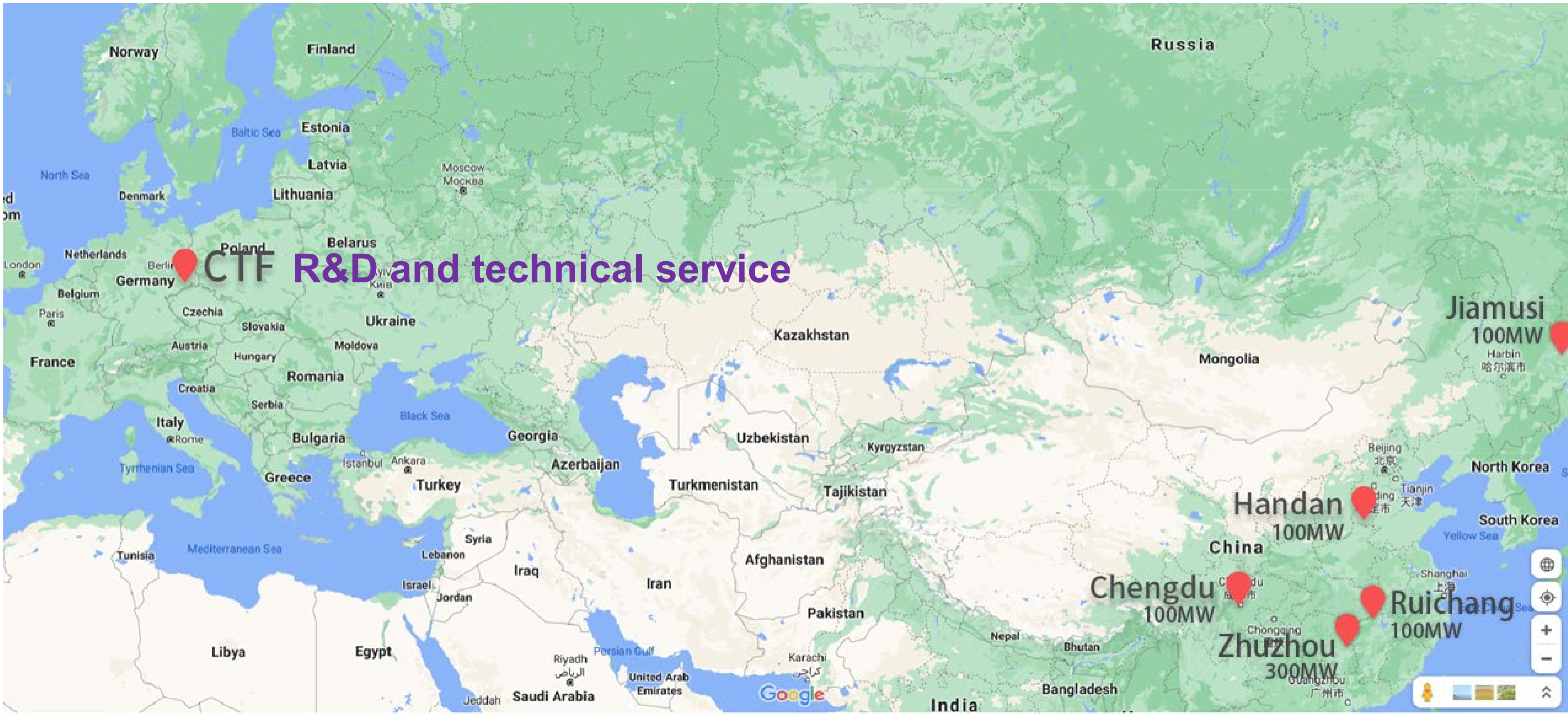
CTF Solar – CdTe Solar glass innovation with a long history, a CNMB company



1969	World's first working cadmium telluride (CdTe) cell by Dr. Dieter Bonnet
1993	Start of industrialization; predecessor ANTEC GmbH
2012	Take-over by CTIEC, part of CNBM group
2015	Dresden R&D Center established, 15,2% cell efficiency
2017	Start of production in first Factory Chengdu
2020	Upgrade of Dresden pilot line at new location, > 50 R&D staff
2022	Start of production in Handan factory
2023	Start of production in Ruichang factory

CTF SOLAR
CNBM

CNBM CdTe business



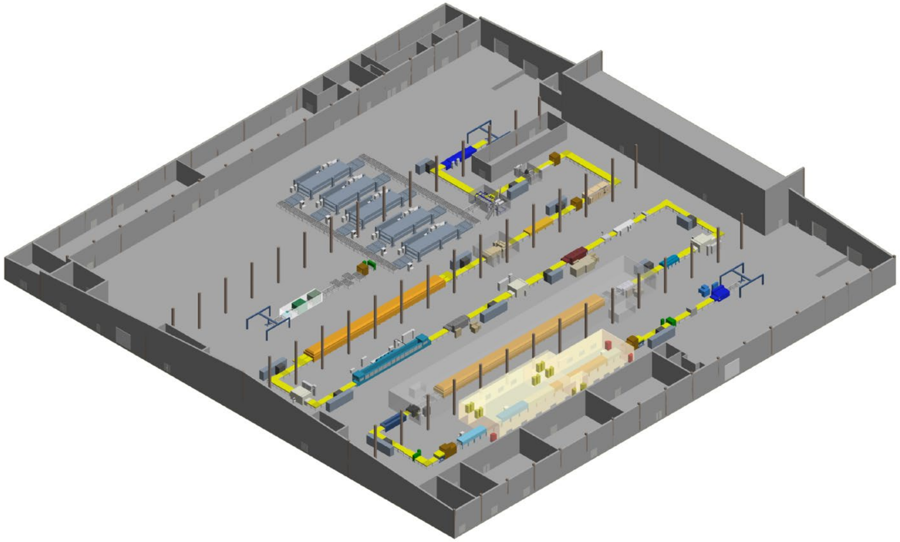
CTF SOLAR
CNBM

CTF Process & Equipment Technology

Production Facility

- Proprietary CdTe module technology
- 100 to 300 MWp production capacity possible
- 288 Wp modules at 15 % efficiency

  (as a starting point)
- 1200 mm x 1600 mm x 7 mm modules
- coating technology by CTF Solar
- 24/7 operation, 1 production line
- 65 modules per hour
- 95 % yield
- zero-emission design



CdTe factory, internal view of site with one production line

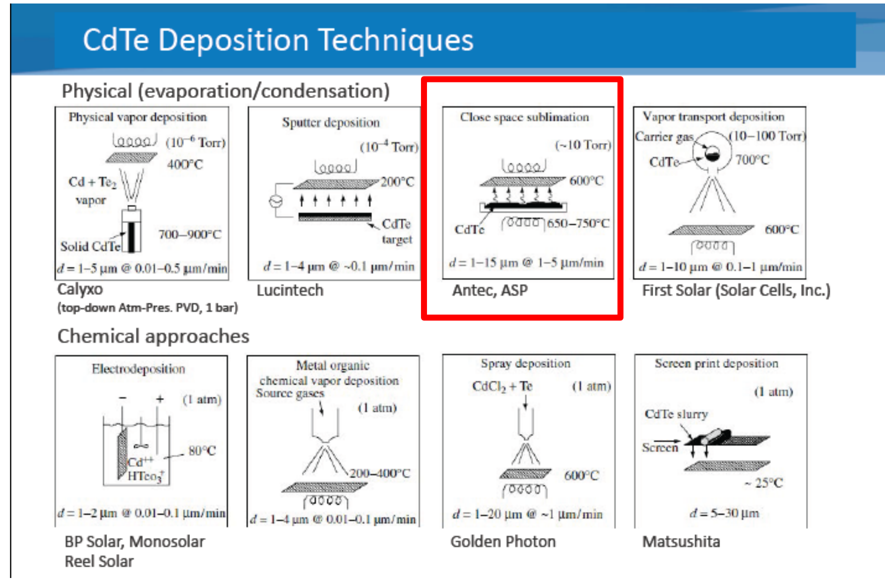
→ **Cell research to development of full factories**

→ **CTF does not own factories**

→ **Factories are offered world wide**

CTF SOLAR CNBM

Proprietary CSS semiconductor deposition technology on glass



Source: M. Reese NREL

- CSS (Close Spaced Sublimation) deposition technology in <u>pure</u> vacuum compared to others
- Fully automated and reliable – less than 5 hours from glass to solar glass
- 1,92 m² glass-glass module design
- > 60 joint patents CTIEC / CTF

Company proprietary

CTF SOLAR
CNBM

Factories

Jiamusi –100 MW

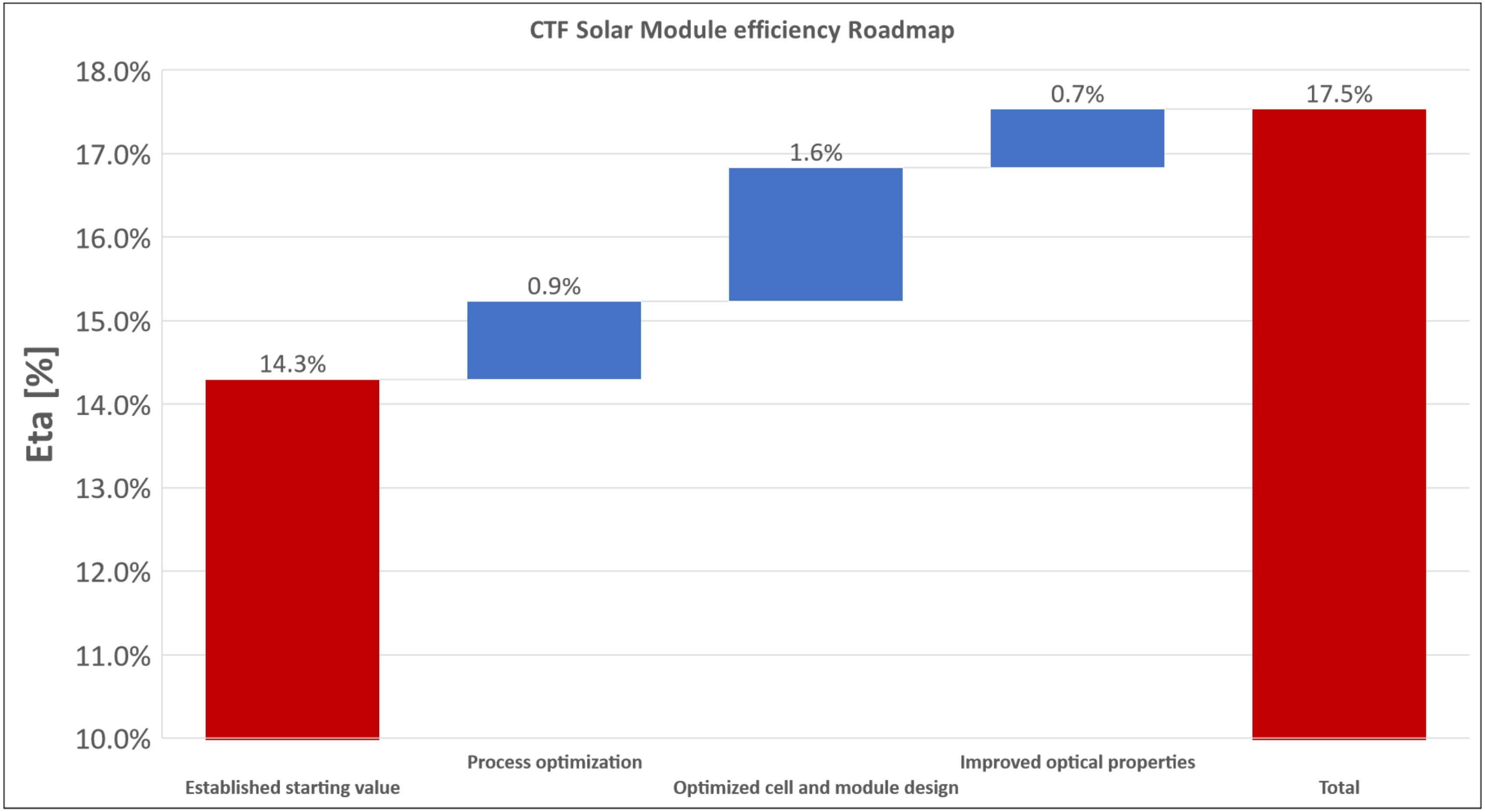
Chengdu – 100 MW

Handan – 100 MW

Zhuzhou – 300 MW

Ruichang – 100 MW

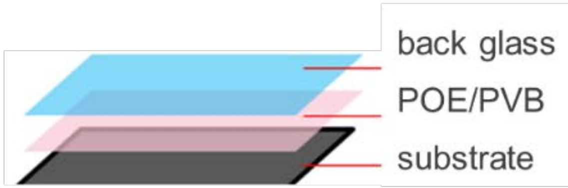
Efficiency Roadmap next production lines



Company proprietary

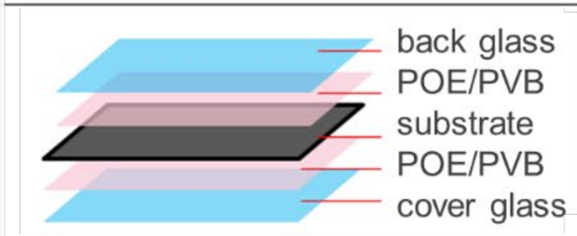
CTF SOLAR
CNBM

BIPV products – glass windows

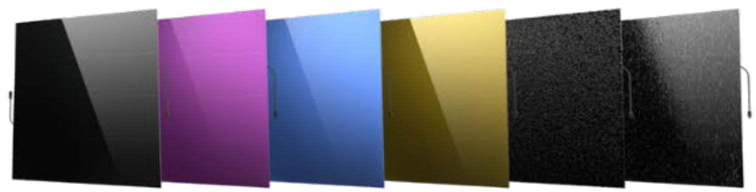


Double glass module

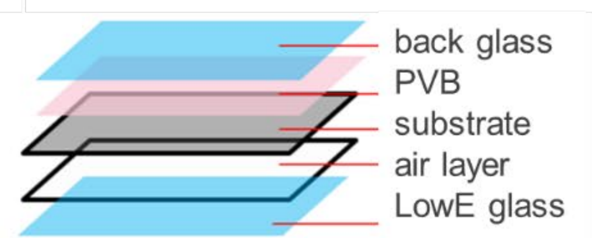
Black, semi-transparent



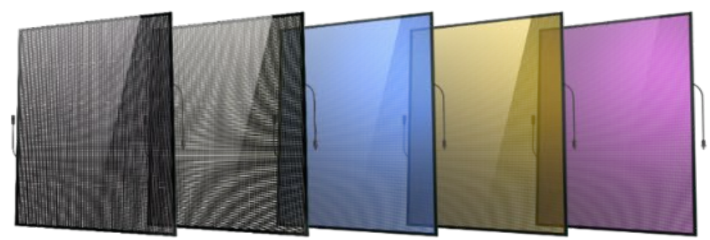
Triple glass module



Black, colour



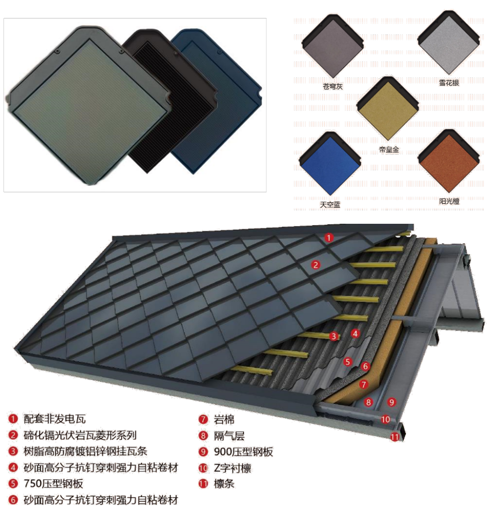
Double glazings



Semi-transparent, colour, black

BIPV products – examples

Colorful Applications

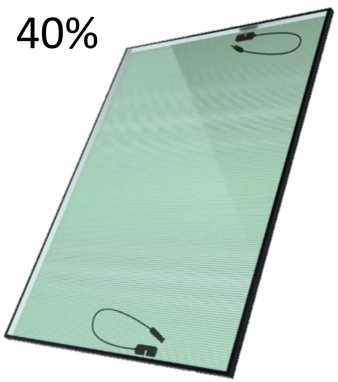


Company proprietary

BIPV products – examples

Transparent Solar Glass
for Window-Applications and Fences

40%

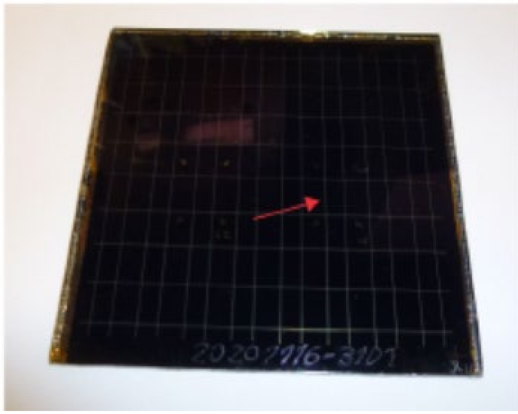


60%

CTF SOLAR
CNBM
Company proprietary

Current lab cell efficiency and CTFs R&D Pilot Line

Lab-Cell Eta-Developement:



Source: ISFH measurement report: 12520Z_05,2

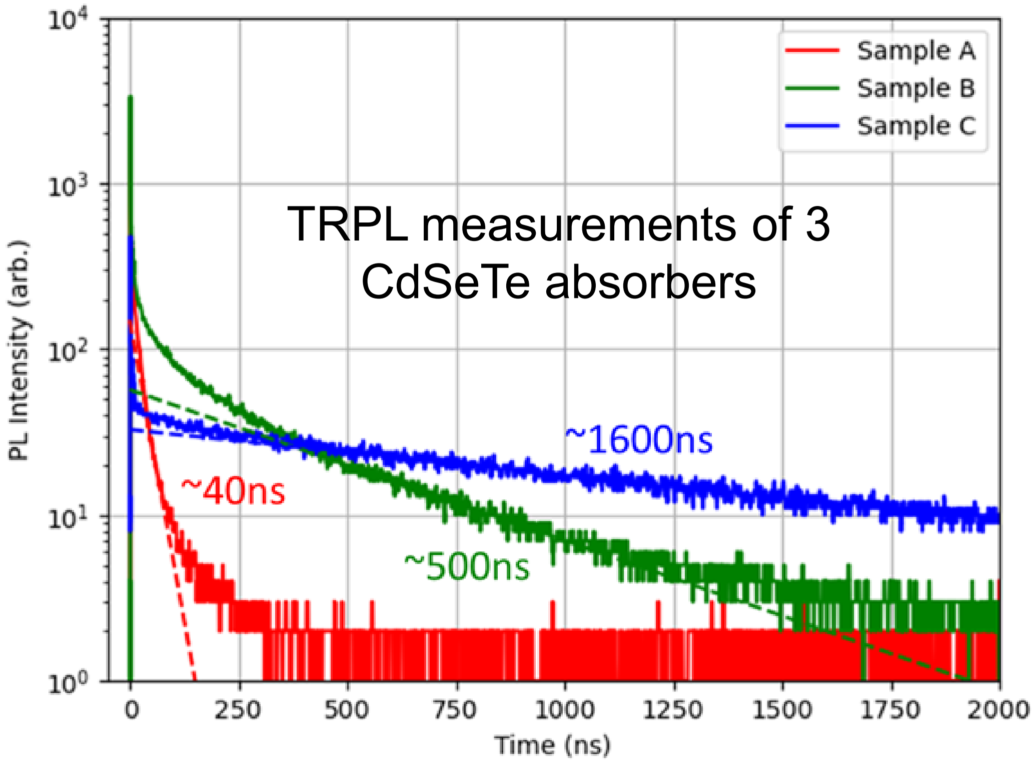
- 20.1% power conversion efficiency
- based on 0,495 cm² rear metallization area
- Internal cell record 20.84% (2022/10)

Pilot Line:

- Format: 30x40 cm²
- Dynamic CSS coating
- Similar to full size production process

Company proprietary

CTF R&D: Analytic department PL and TRPL



By changing absorber deposition and passivation treatment configurations and conditions, a wide range of lifetimes can be attained

PicoQuant FluoTime 300

- Steady-state and time-resolved PL
- 640nm excitation source
- UV/VIS PMT
- Soon to be upgraded with additional IR PMT for long-wavelength detection

CTF SOLAR
CNBM

R&D demands to the CdTe community

- Fundamental research of new processes towards 25 % cell efficiencies
- Development of advanced characterization methods
- Aligned certified IV measurements (optimized for CdTe thin film cells)

Internship at CTF solar

RISE Professional offers summer research internships in Germany

Rise: Research Internships in Science and Engineering

The German Federal Foreign Office (DAAD) enables an internship in Germany to Master's and Ph.D. students from USA, Canada, Great Britain or Ireland at companies and non-university research institutions with strong relations to industry.

Procedure:

- The internship database opens between **October 15th and November 30th**. The students need to submit their application documents to the RISE portal.

https://www.daad.de/rise/en/rise-professional/

Thank you!

Contact:

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Job applications to:
HR@ctf-solar.com

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Anna Kindvall
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CNBM CTF SOLAR

CFV Labs
Albuquerque, NM

Jim Crimmins, CEO
CdTe Workshop

2023-10-23

Thin Film Testing at CFV

CFV Labs

CFV Labs

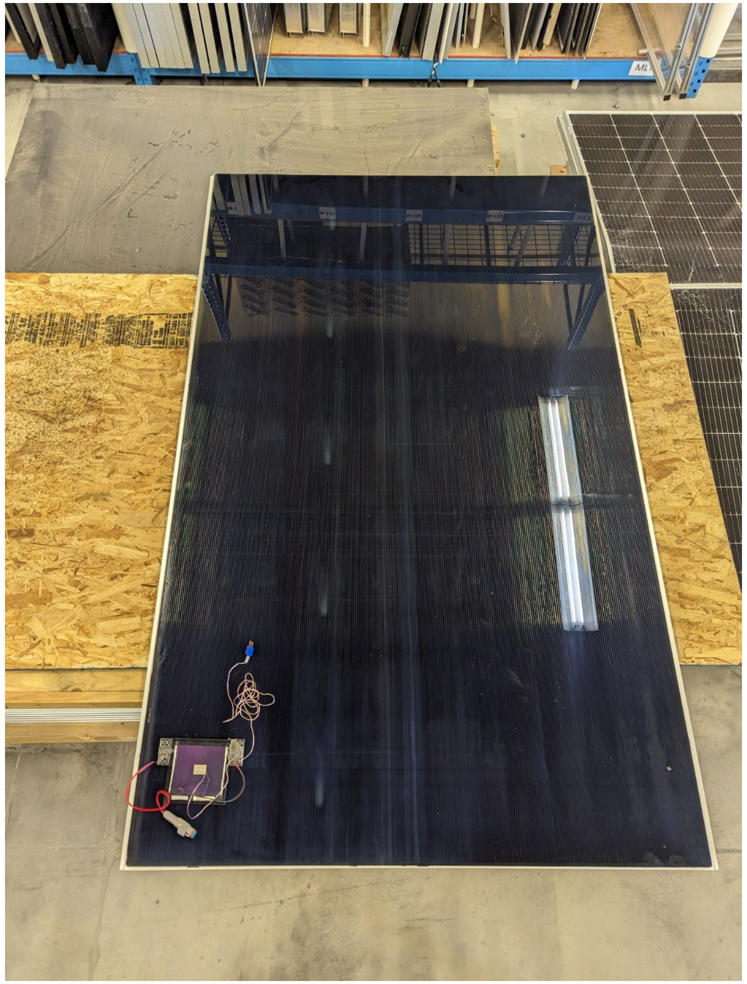
- PV Test and Research Lab in Albuquerque, NM.
- Specializes in custom performance and reliability testing.
- Largest market share of commercial thin film testing in US
- National Lab Collaborations:
  - PACT Center – Perovskites – Sandia/NREL/Los Alamos
  - Hail Testing – Duramat – James Hartley
  - CSP Mirror Reliability – Sandia
  - Tracker Reliability – Sensor Direct-to Cloud - Sandia

CFV Labs

CFV has been testing thin-films since 2011

Thin-film testing at CFV is happening with different technologies and at very different scales

- Thin-film testing ranges from lower TRL Perovskite cell and mini-module samples to large format commercial CdTe products
- Imperative to have different equipment and techniques for different TRLs and product sizes.
- Tested technologies include CIGS, CdTe, bifacial CdTe, PSC, tandems.
- Modules are getting bigger!



CFV Labs

Wide spectrum of possible testing scenarios depending on TRL

CFV Labs

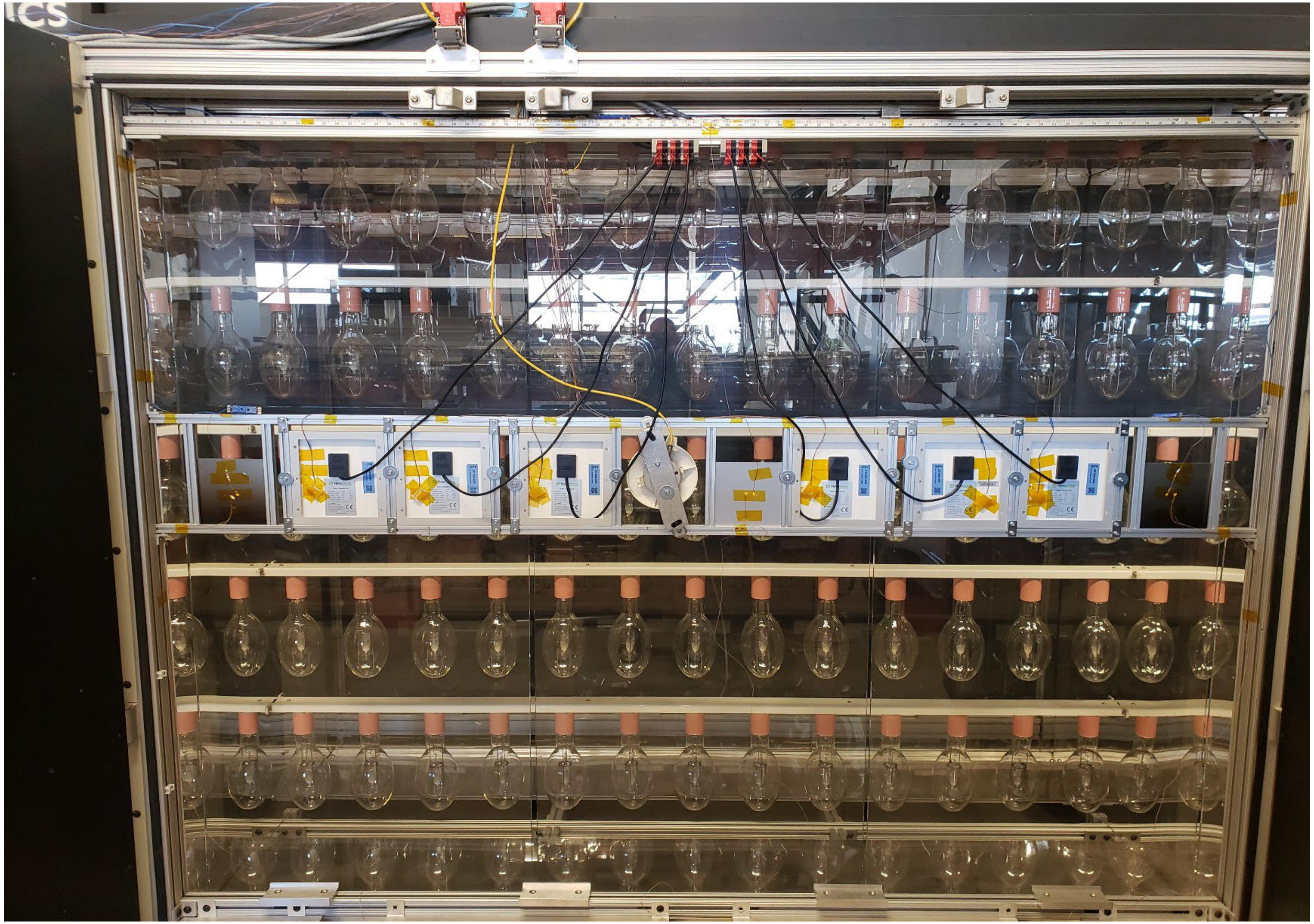
- Types of thin film testing done at CFV:
  - Preconditioning/Stabilization
  - Performance Characterization
  - Outdoor Testing
  - Reliability Testing
  - Certification/Bankability Testing
  - Subsidized testing through PACT and American Solar Prize

Small scale devices are typically being preconditioned with light soaking

Atonometrics chamber can support many smaller devices

CFV Labs

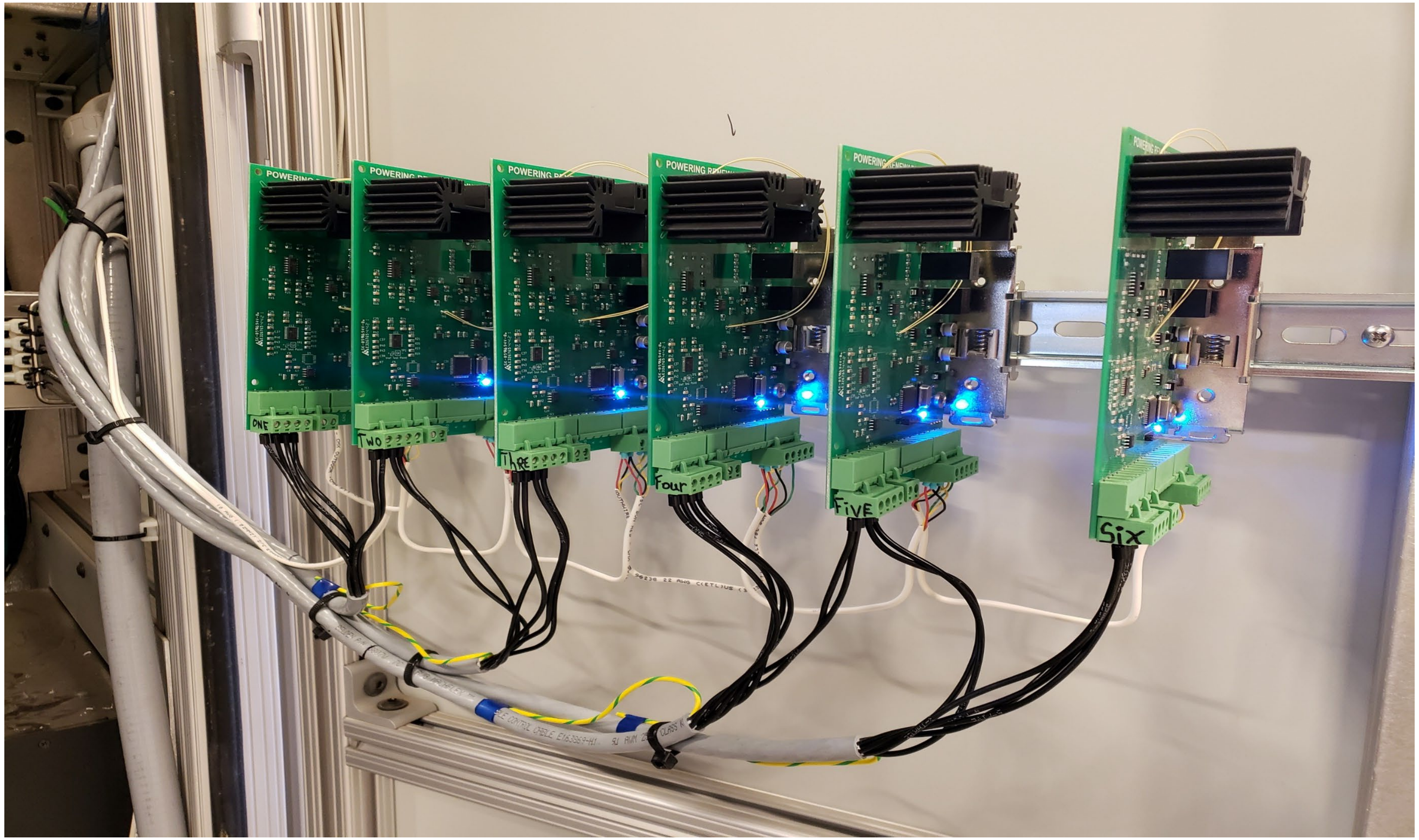
- Preconditioning – Small Scale Devices



Can be hard to find commercial electronics for smaller samples – we make our own.

CFV Labs

- Custom load boards (<10W) for preconditioning at MPPT, IV tracing indoors and outdoors.



Large scale thin film devices are typically preconditioned using elevated temperatures and current injection

- Preconditioning – Large Scale Devices.

CFV Labs

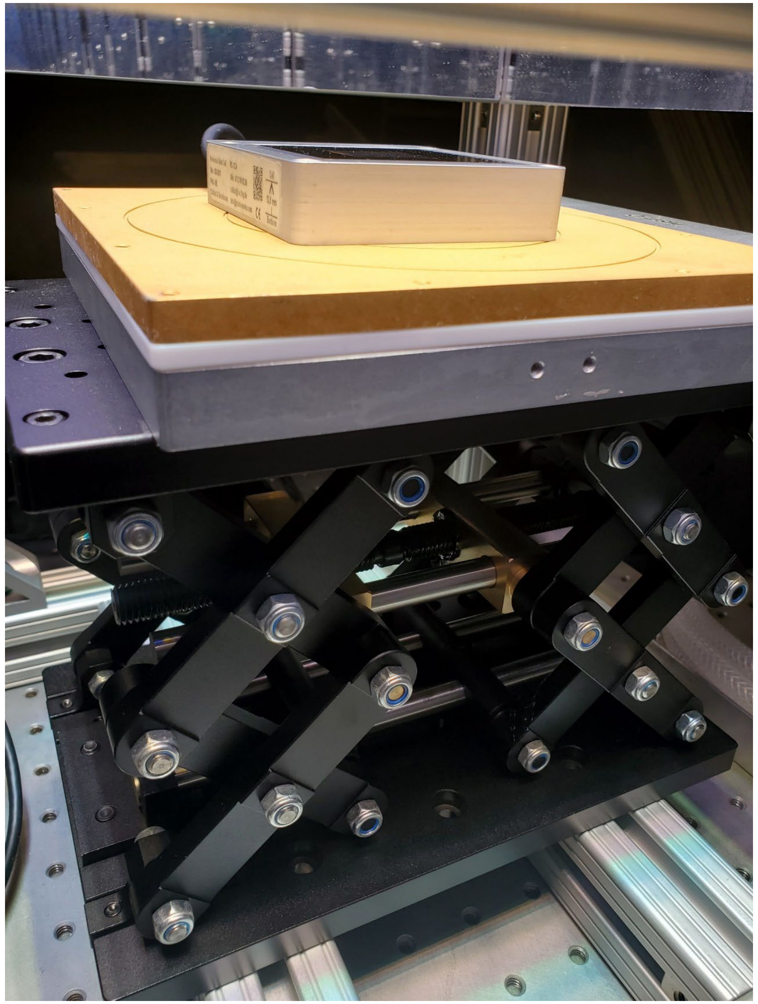
G2V LED light source set-up for small scale samples, up to 250mm x 250 mm

Temperature controlled chuck.

Custom< 10W Electronics.

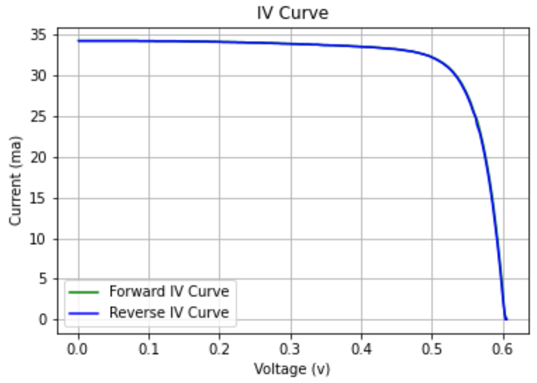
CFV Labs

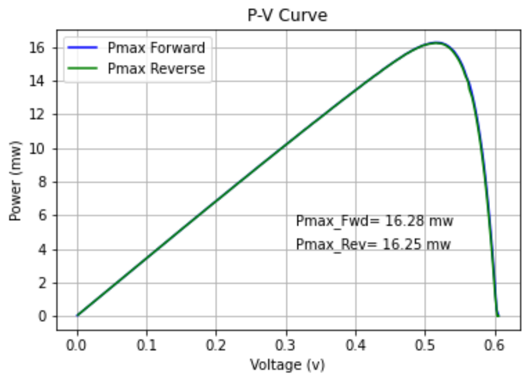
- Performance Characterization – Small Scale

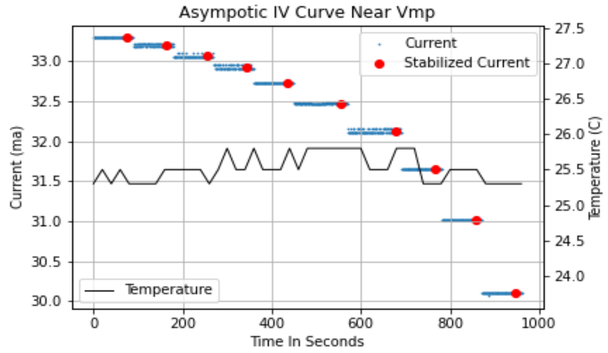


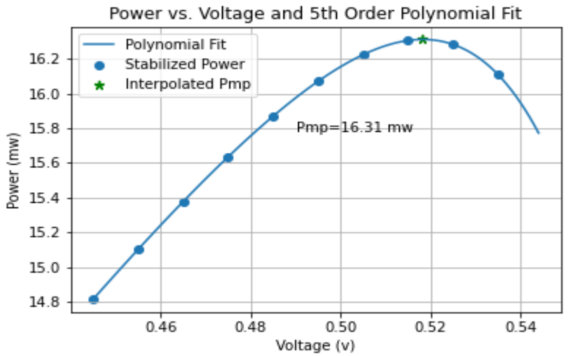
- Performance Characterization – Small Scale

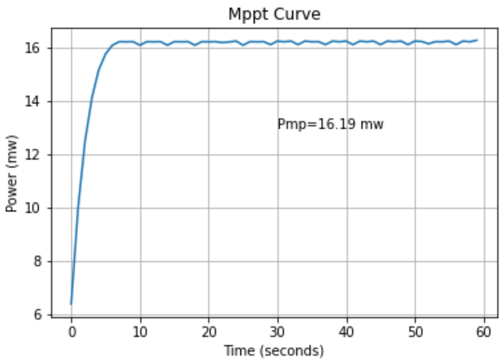
Custom electronics and software can run various workflows including asymptotic IV curves











PSC Workflow - Measured at CFV Labs

CFV Labs

halm A+/A+/A+ flasher with attached temperature chamber

Able to measure modules up to 2.5m x 1.4m

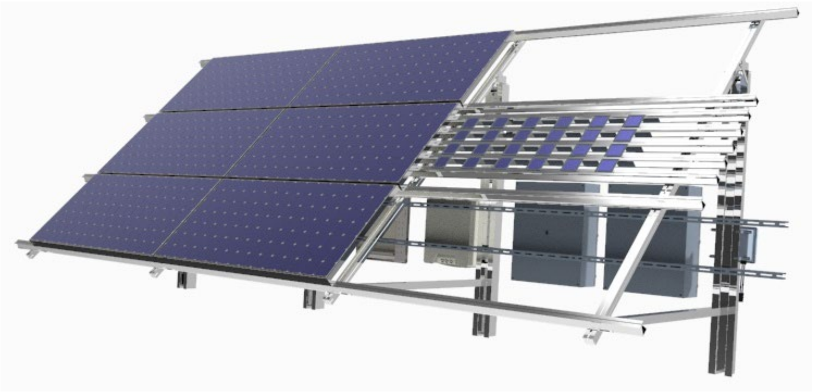
G-T matrices, tempcos

CFV Labs

- Performance Characterization – Large Scale

Moving the system outdoors

16 measurement/load channels per enclosure, integrated power supply, and computer will provide a complete testing unit.



CFV Labs outdoor test rack equipped with irradiance sensors, weather station, and electronic loads specifically designed for mini-modules and cells.

Specification	Parameter 1	Parameter 2	Parameter 3	Parameter 4
I,V Ranges	150ma/250ma/ 500ma/ 1A	3V/6V/12V/24V	16-bit A/D converter	Accuracy +/- .2% typical
Temperature Measurement	Type K-, J-, N-, T-, S-, R-, or E- thermocouple	18-bit A/D converter	0.05 °C resolution	+/- 1 °C accuracy typical
Card Interface	16 channels	Modbus	16 registers/ch.	115.2 kbps
Operational / Data Logging Options	Campbell – simple functionality	Raspberry Pi – complex functionality	Ethernet/Wi-Fi MQTT	NV data backup Battery backup

CFV Labs

Chambers are large and multi-purpose and can be used for DH, TC, HF, UV, etc.

Frequently this testing used in support of certification or bankability

CFV Labs

- Environmental Stresses – All Scales

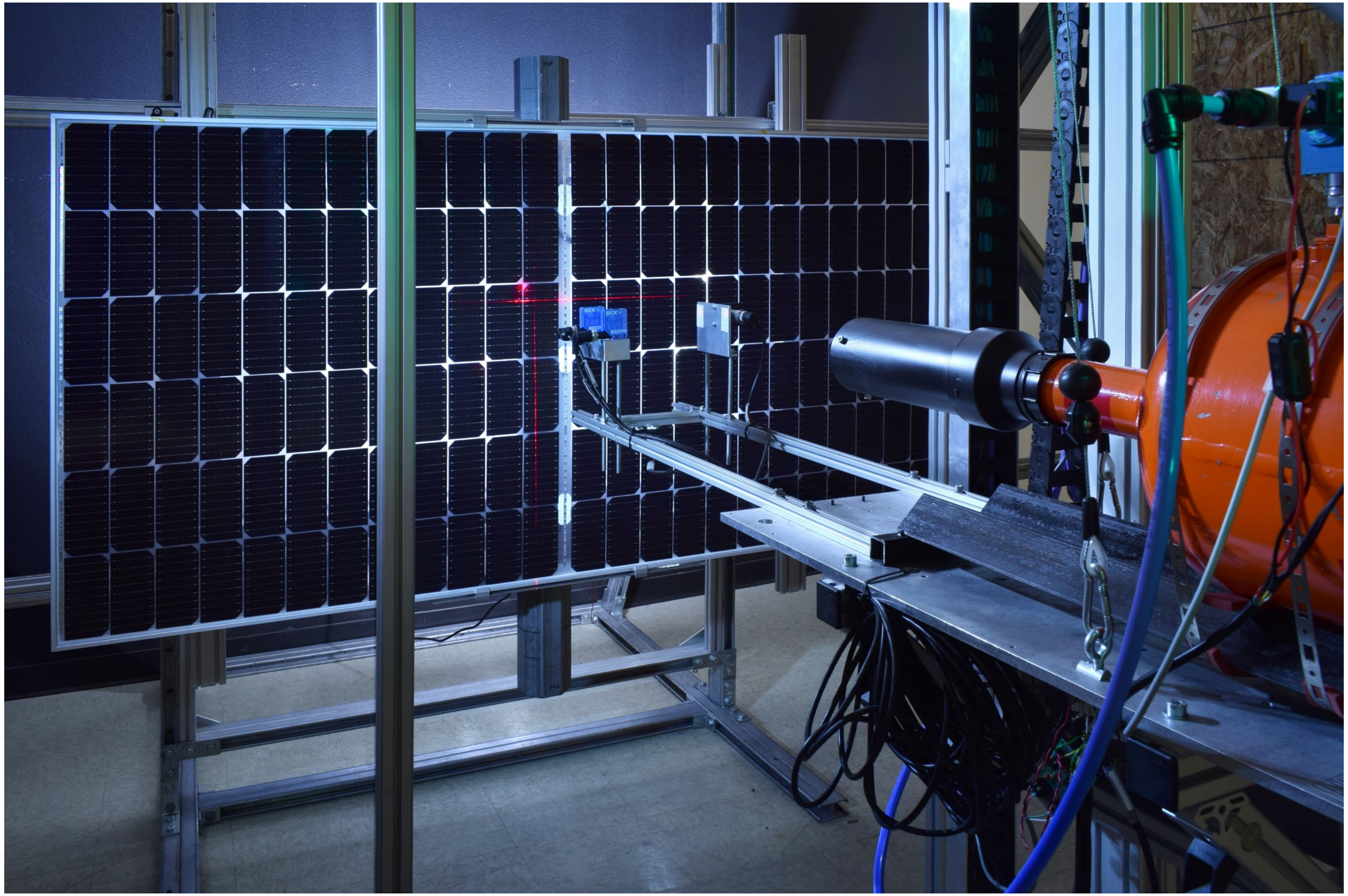
Envirotronics Triple DH Chamber

SLZ UV Chamber

ESPEC Temperature and Humidity Environmental Chambers

Hail testing in high demand for certain deployment locations

- Hail Testing – thin films potentially have advantage here



CFV Labs

MLT testing an increasing concern as modules become larger – both cell cracking and total package failure can be a problem

CFV Labs

- Mechanical Load Testing – thin films potentially have advantage here

CFV is a Connector for and can accept prize vouchers for testing services

- American Made Solar Prize

CFV Labs

PACT center launched in 2021

Product mix still in flux commercially

PACT
Perovskite PV Accelerator for Commercializing Technologies

- Accelerator for commercializing Perovskite products.
- Development of technology specific preconditioning, characterization and reliability testing protocols.
- Subsidized testing for commercial participants.
- Indoor and outdoor test stands at NREL, Sandia and CFV.
- Tandem capabilities starting to be developed.
- New products being added to testing portfolio as market matures.

Contact

Jim Crimmins, CEO

Email: jim.crimmins@cfvlabs.com

CFV Labs
5600-A University Blvd.
Albuquerque, NM 87106

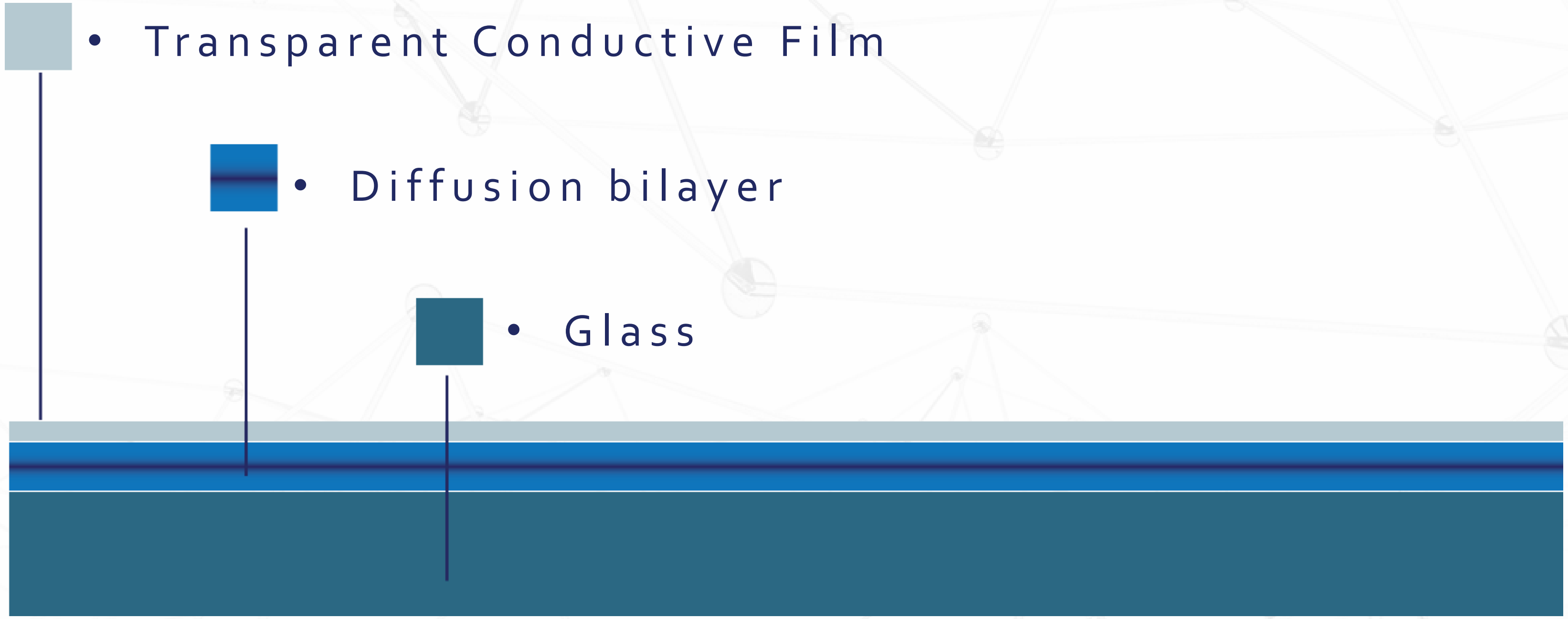
CFV Labs


nex·tc™

Headquartered on HP Campus in Corvallis, OR

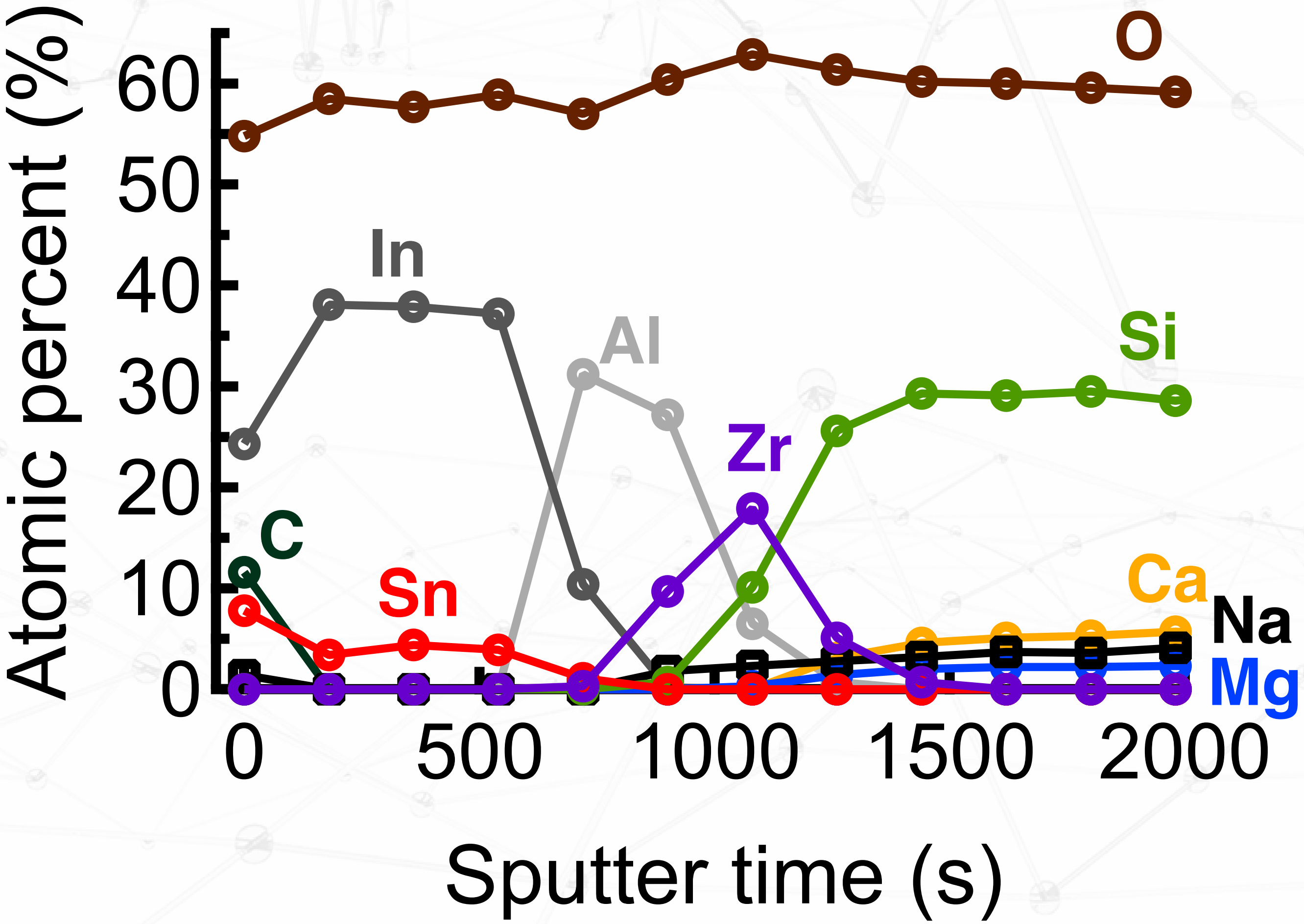
- Spinout from OSU
- Chemical startup
- 5 full time employees

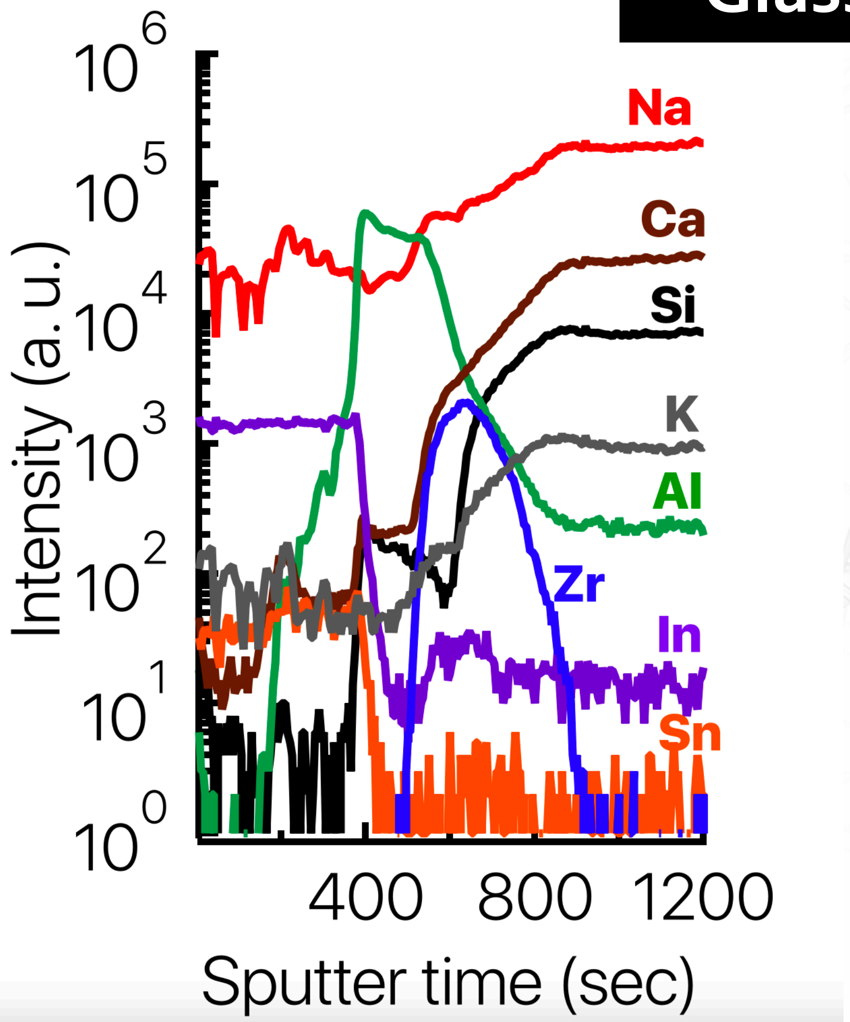
nexTc™ Solution



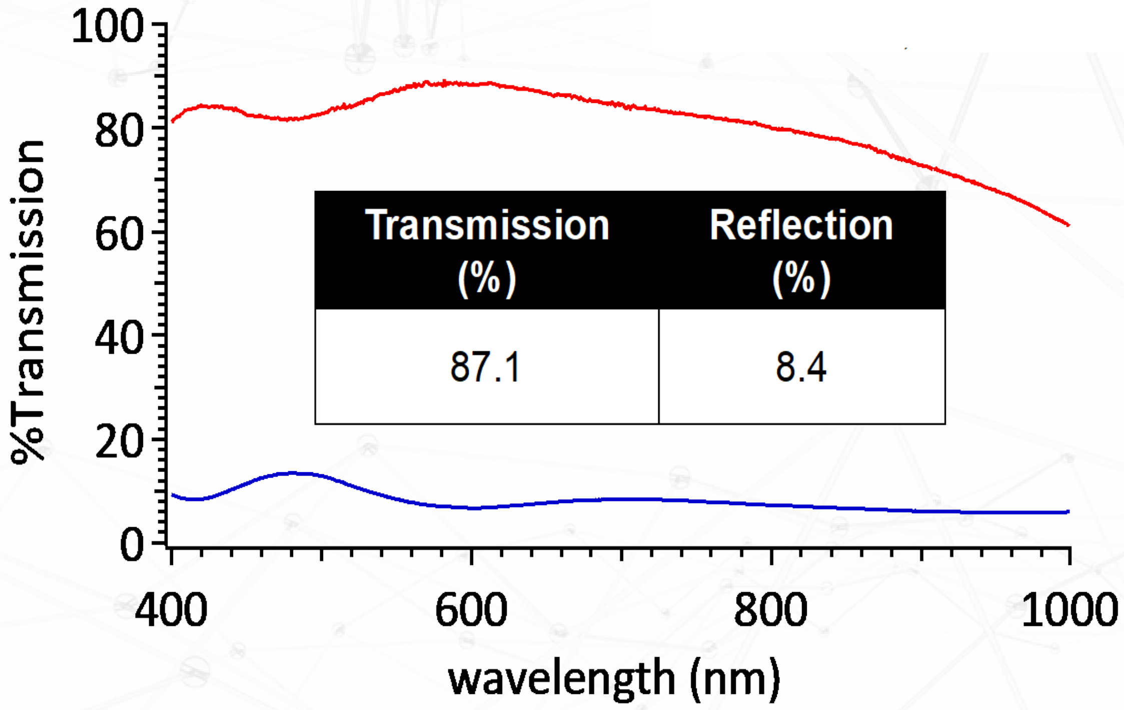
Diffusion bilayer

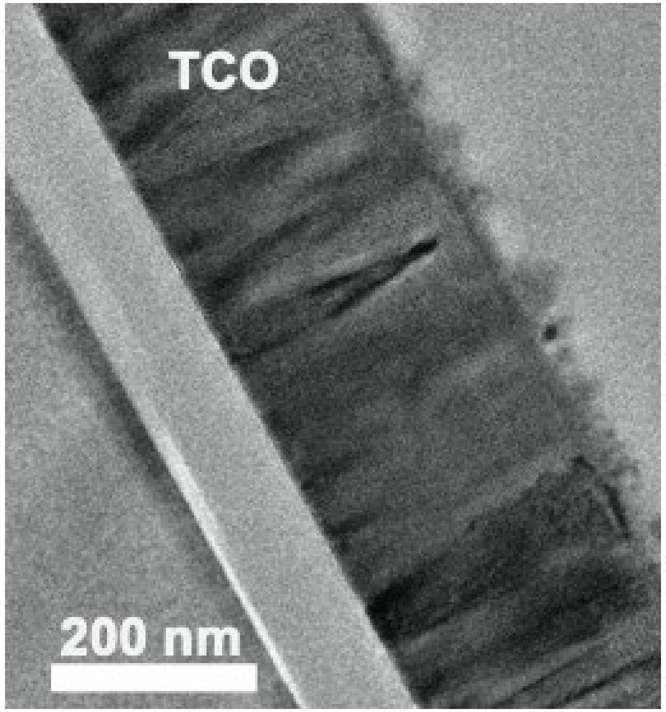
TCO
Bilayer
Glass





TCO



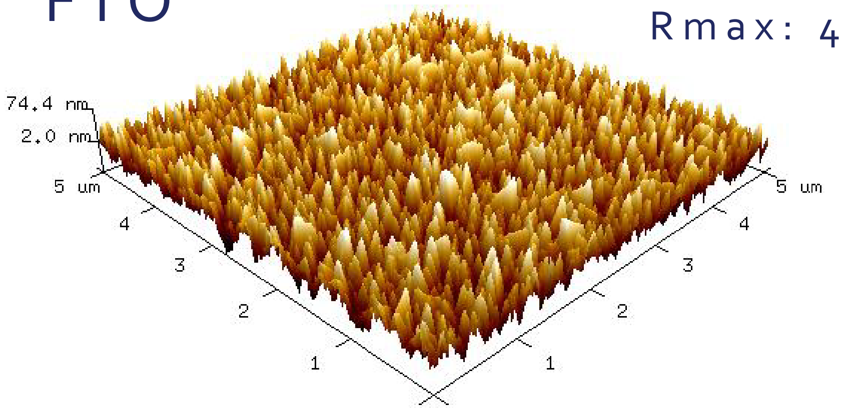


Sample	Thickness (nm)	Resistivity (ohm • cm)	Carrier Concentration (cm^{-3})	Mobility (cm^2/VS)
Commercial ITO	250	1.99×10^{-4}	9.46×10^{20}	33.2
nexTC	305	2.89×10^{-4}	1.02×10^{21}	21.2

Functional coatings

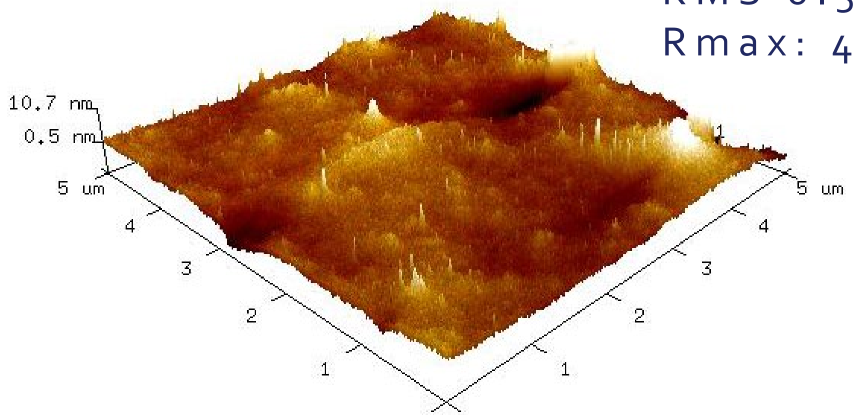
FTO

RMS 21.4 nm
Rmax: 49 nm



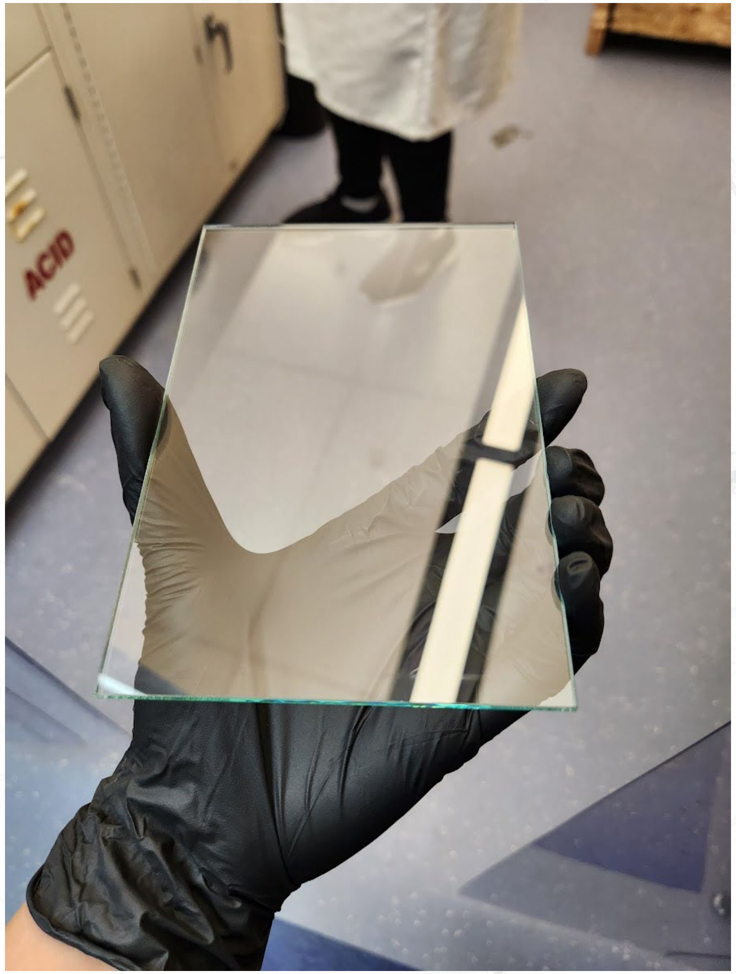
nexTC coated FTO

RMS 0.37 nm
Rmax: 4 nm

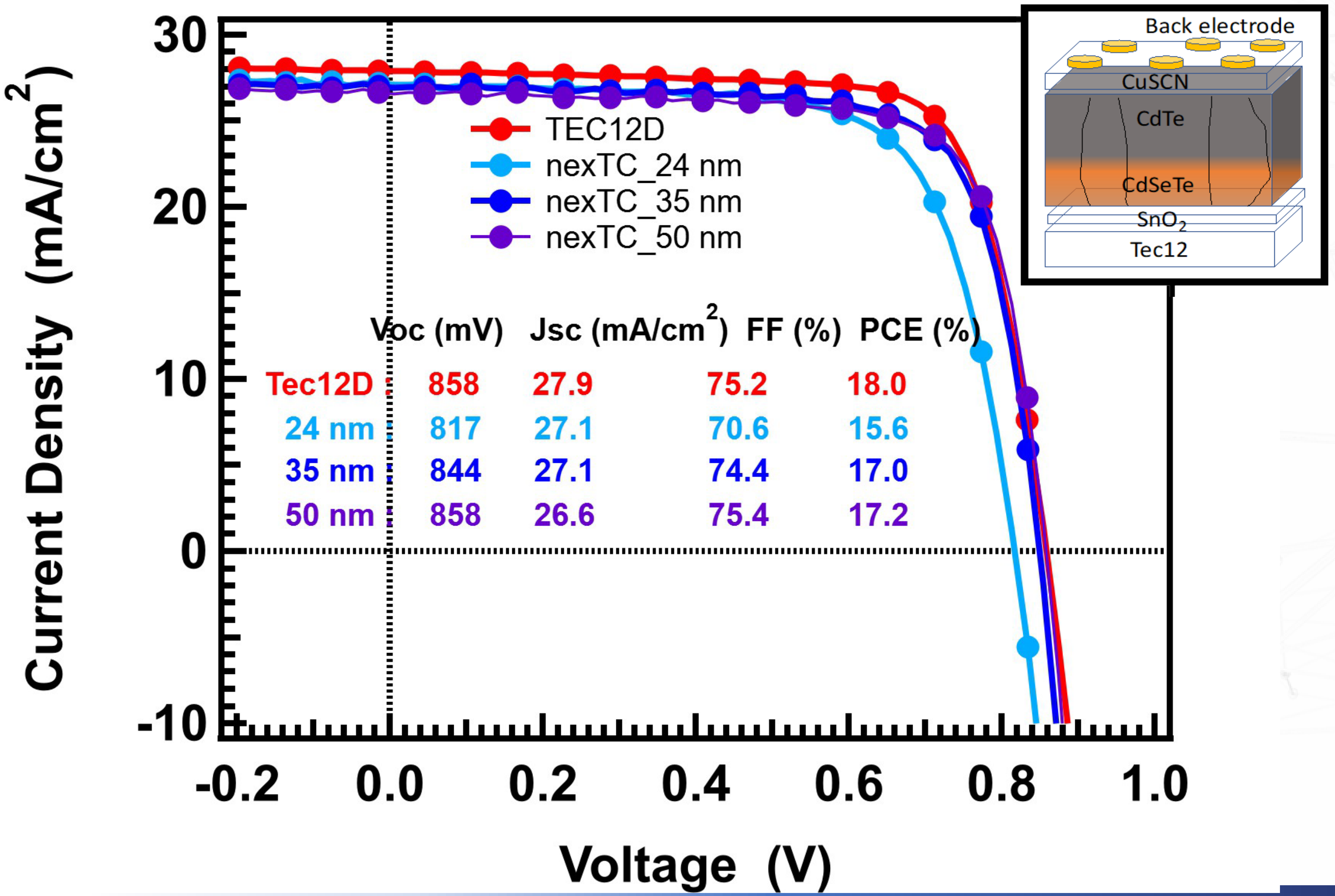


- Improved sheet resistance
- Low-surface roughness
- Advanced materials sets

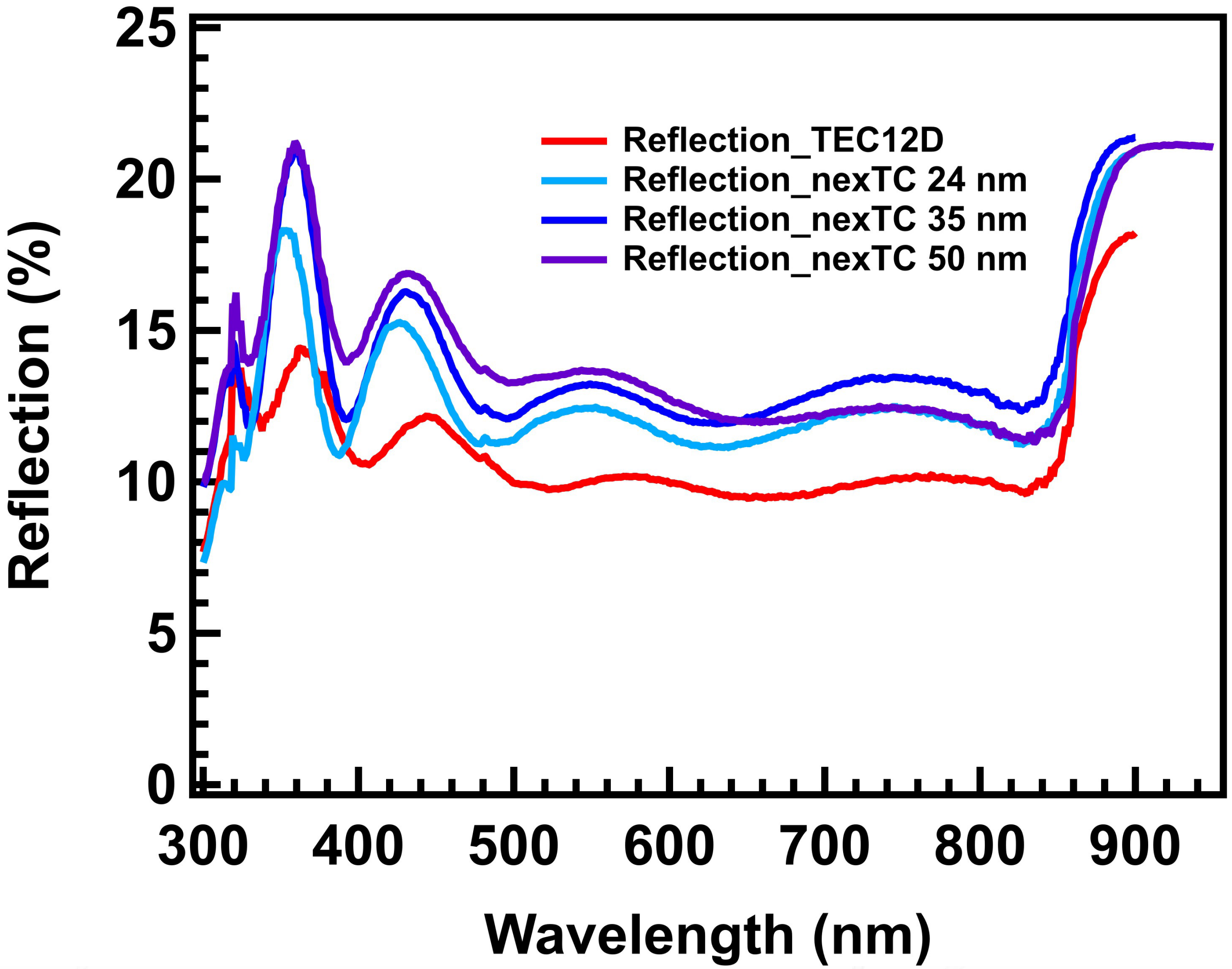
Since last meeting…



New: Emitter films



New: Emitter films



Thank you!

nextc™

Cory Perkins, PhD – Founder/CEO
Email: cory@nextcmaterials.com

JPHB CleanTech

Disruptive Solar Energy Innovations

Proud member of -

NSBA
National Small Business Association
Leadership Council Member

US-MAC
Manufacturing of Advanced Cadmium Telluride

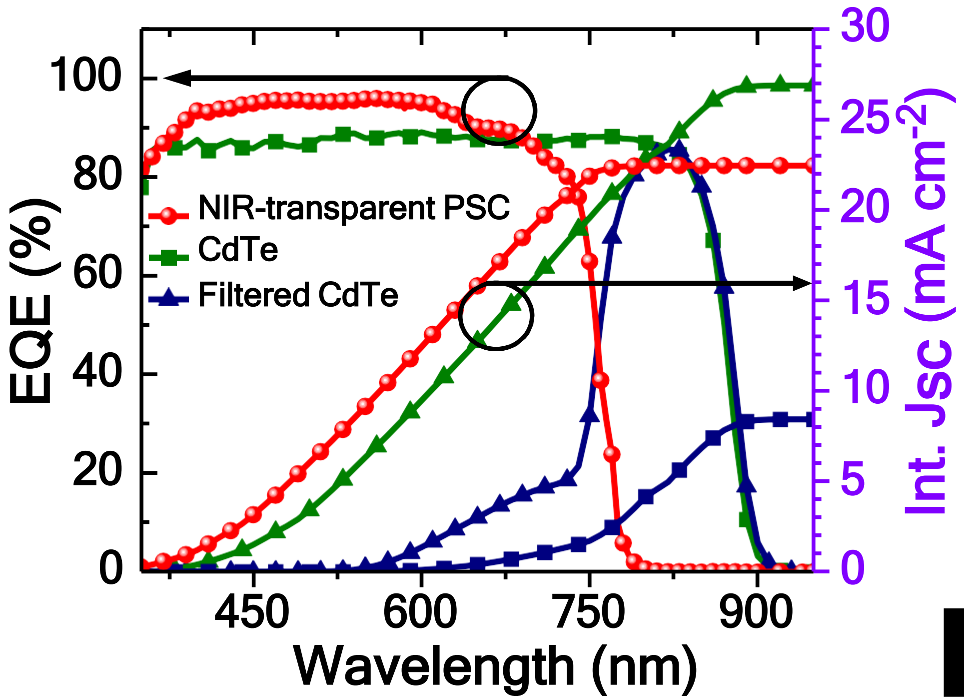
https://www.usa-cdte.org/

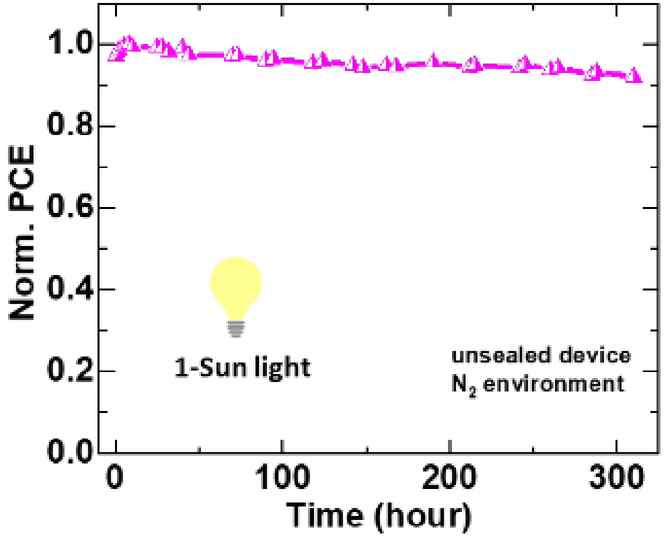
About JPHB -

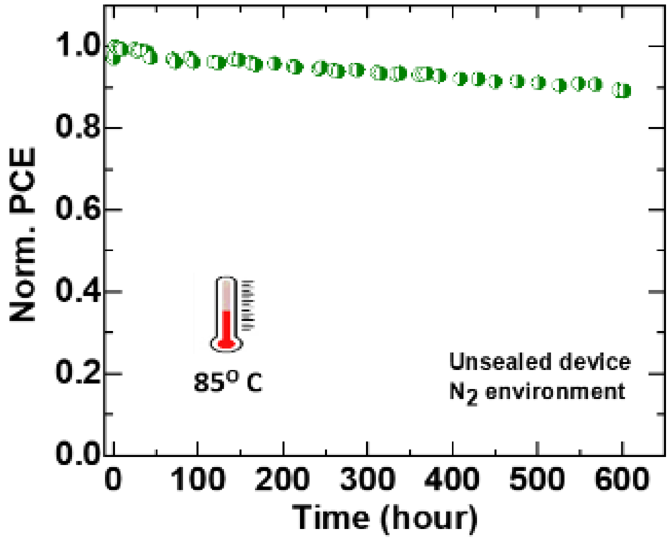
- JPHB Solutions LLC/JPHB CleanTech LLC is a spin-off from CSU founded by Amit Munshi

- JPHB is aimed at investigating some of the high-risk, high payoff technology ideas; develop and license the technology to partner organizations

Update #1 –CdTe/Perovskite PV



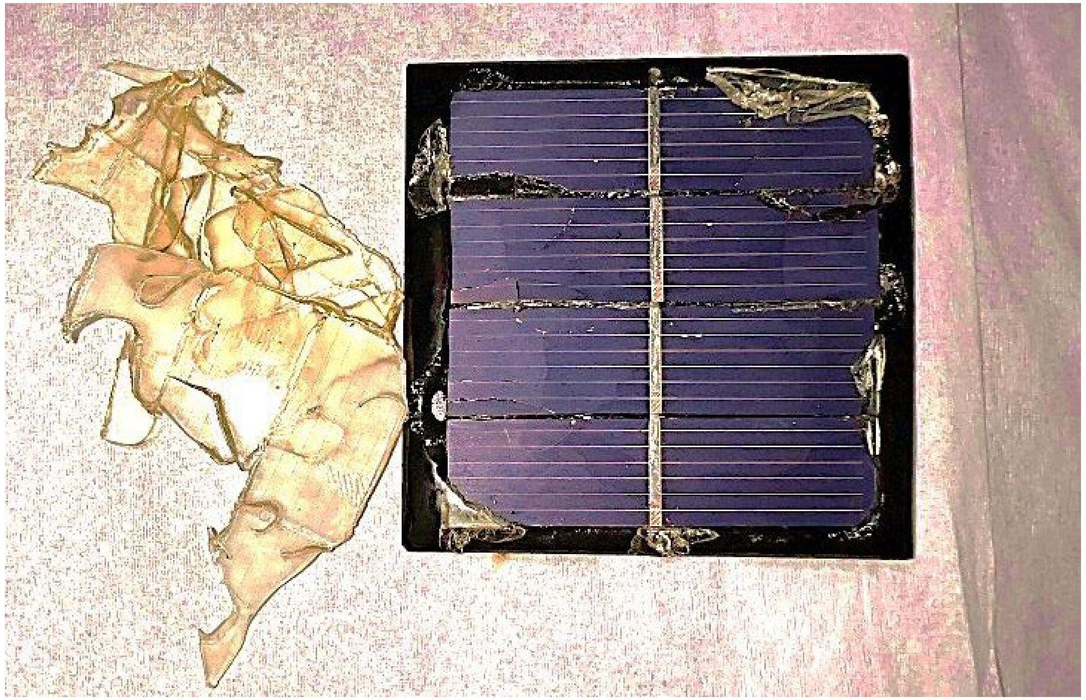




Device	J_{sc} (mA/cm²)	V_{oc} (V)	FF (%)	η (%)
Perovskite PV	22.36	1.156	73.39	18.97
CdTe PV	27.1	0.854	80.5	18.71
4T with CdTe + 0.175 cm2 NIR-T PSC (E_g ~1.39)				23.98*

Preliminary work in collaboration with Indian Institute of Technology at Bombay

Update #2 – High Value c-Si End-of-Life Recycling



- >90% recovery of glass intact (without crushing or breaking)
- >80% recovery of c-Si solar cells
- >50% recovery of high value materials viz. silicon, copper and silver

Preliminary results; Patent pending
Total process time - ~10 seconds; No corrosive chemicals used

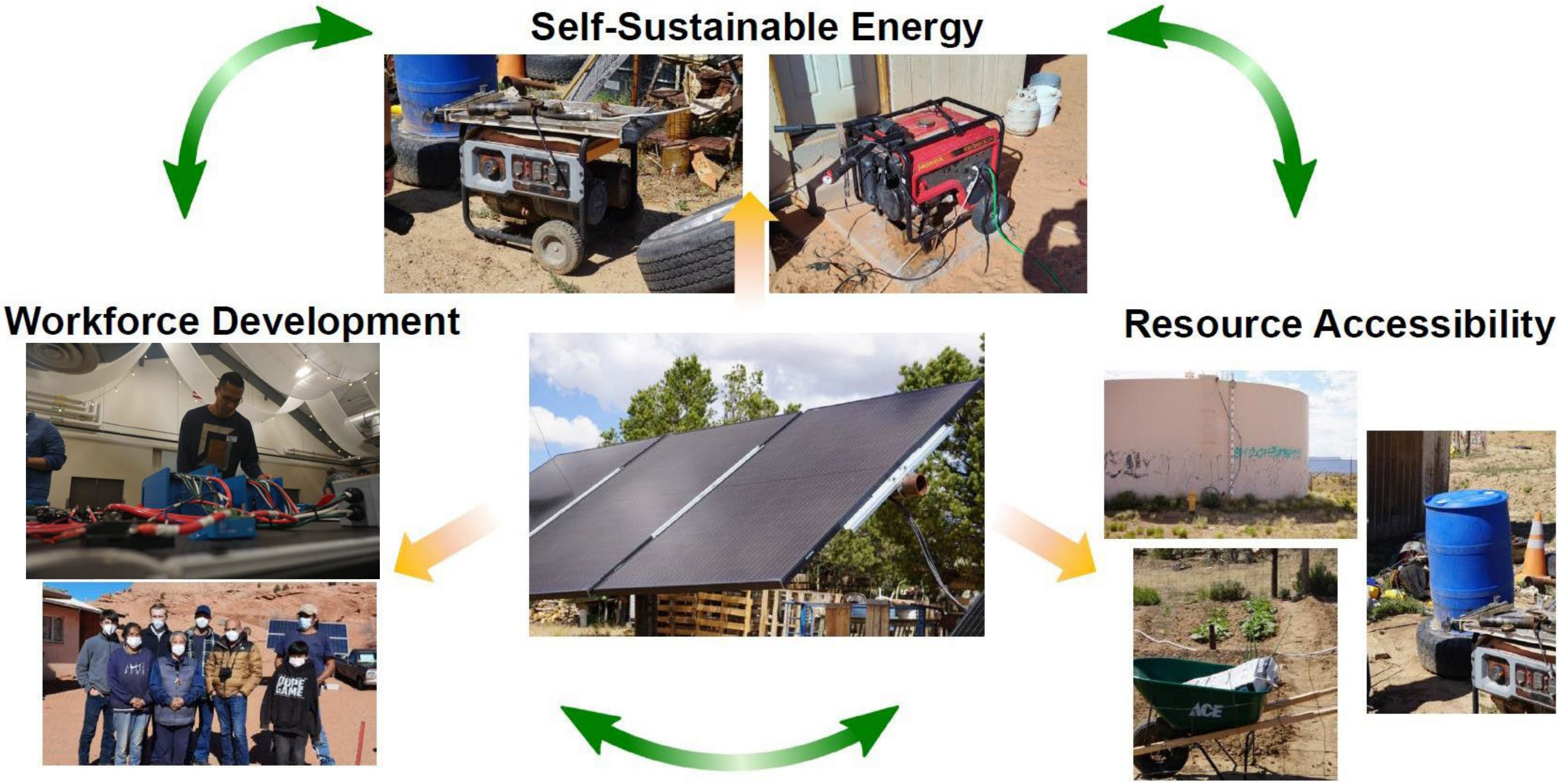
Update #3 – Navajo Nation Off-grid Resilient PV

Test setup successfully completed, planning for installation in the reservation in progress

Update #3 – Navajo Nation Off-grid Resilient PV

Test setup successfully completed, planning for installation in the reservation in progress

Update #3 – Navajo Nation: Potential Impact



Test setup successfully completed, planning for installation in the reservation in progress

Acknowledgement -

- Anthony Nicholson, William Nichols, and JPHB team
- JPHB advisors – Douglas Schatz, Jay Munshi, Walajabad Sampath
- Radiation Detection Technologies Inc.
- First Solar Inc.
- Colorado State University
- Victron Energy
- National Science Foundation
- Indian Institute of Technology at Bombay
- Clean Energy Group
- Wallis Energy Corporation
- GRID Alternatives and TSAF
- And many many others…

Motivation – To make solar energy an obvious choice for all domestic and commercial applications

Contact us –

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www.jphb.us

+1 970 215 4116

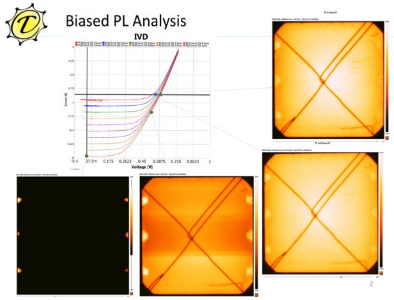
Product Update

Greg Horner, Kyle Lu, Leonid Vasilyev,
Ethan Ignatovich, Phillip Miller, Tom Dirriwachter

- New features for released products
- New machines for 2023
- Plans for 2024

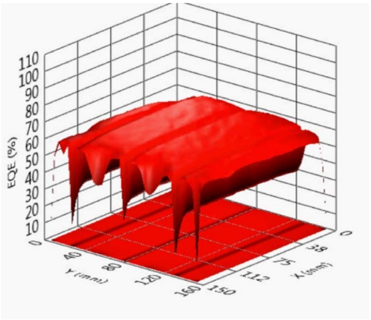
Hybrids

Released Products



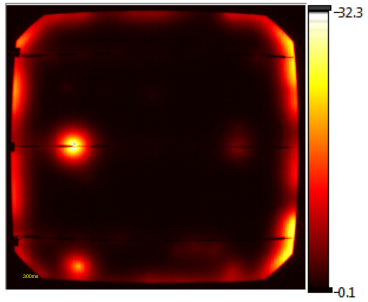
PixEL™

- Cell & module EL/PL imaging for R&D, Inline process control :
  - Customized for Silicon, CdTe, III-V’s, PSC’s
  - External processing runs customer code



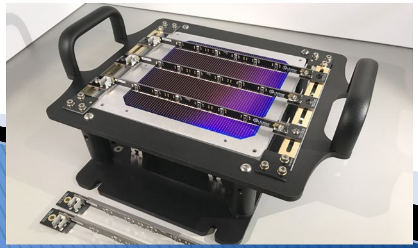
PulseQE™

- World’s fastest EQE/IQE system measures full spectrum in seconds: full cell or small spot scanner
  - Silicon, thin-film and bifacial configurations



IRIS™

- Time-resolved hotspot detection
  - 100-300 ms / cell

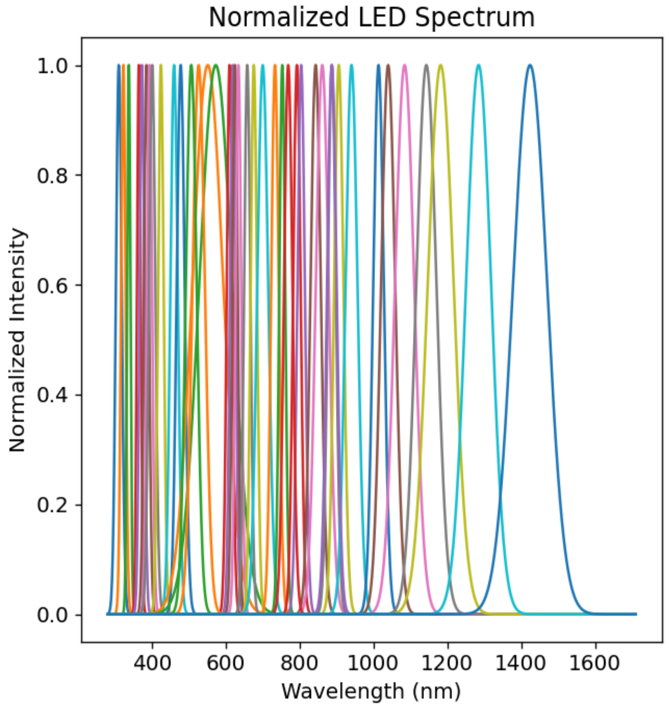


Chucks

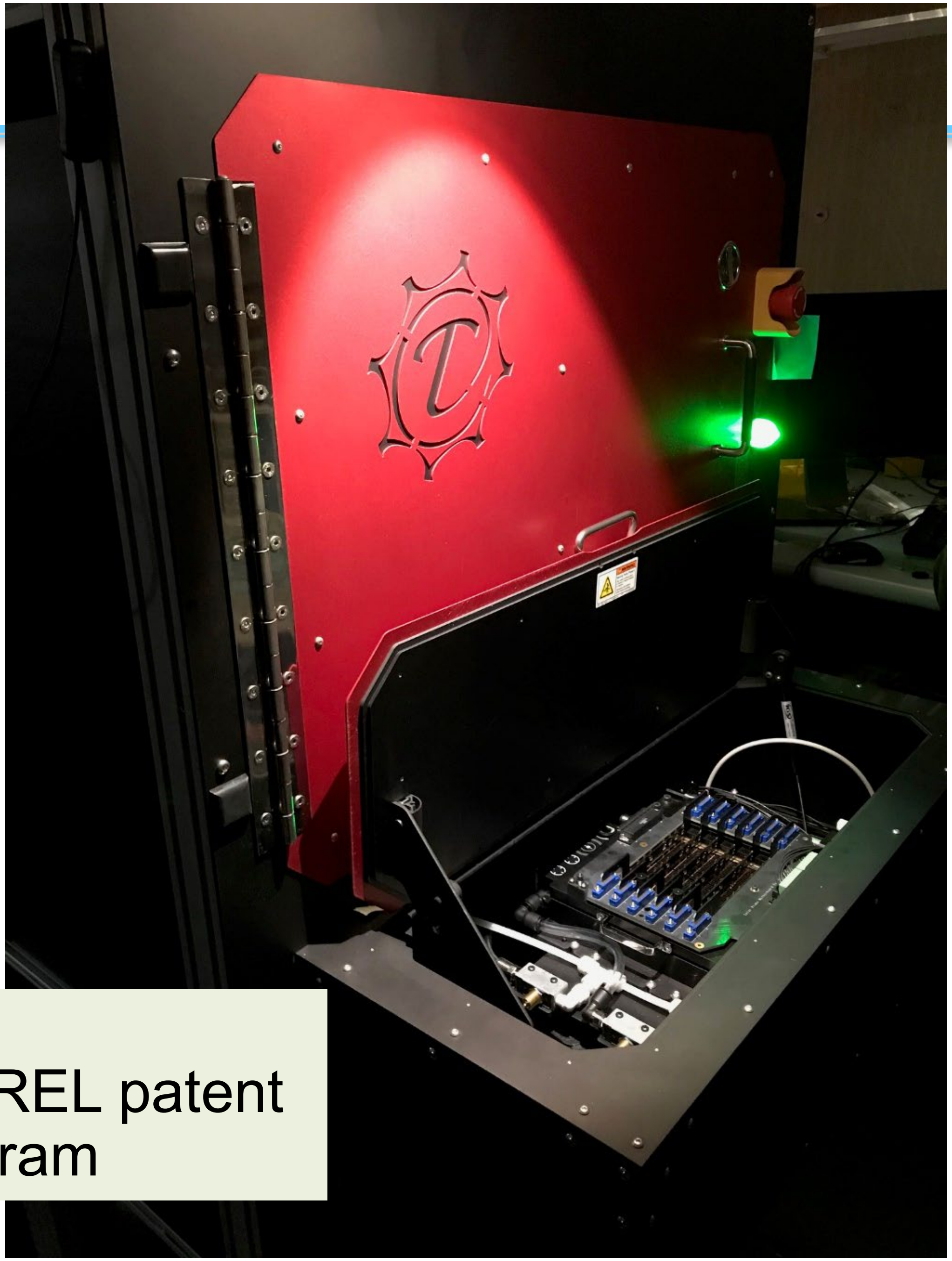
- Cooled & uncooled, conventional and ibc

Thin Film QE Scanner

- XY Stage
- N cells/coupon
- MUX
- ~5 sec / cell



Origin:
- David Young, NREL patent
- DOE SBIR program

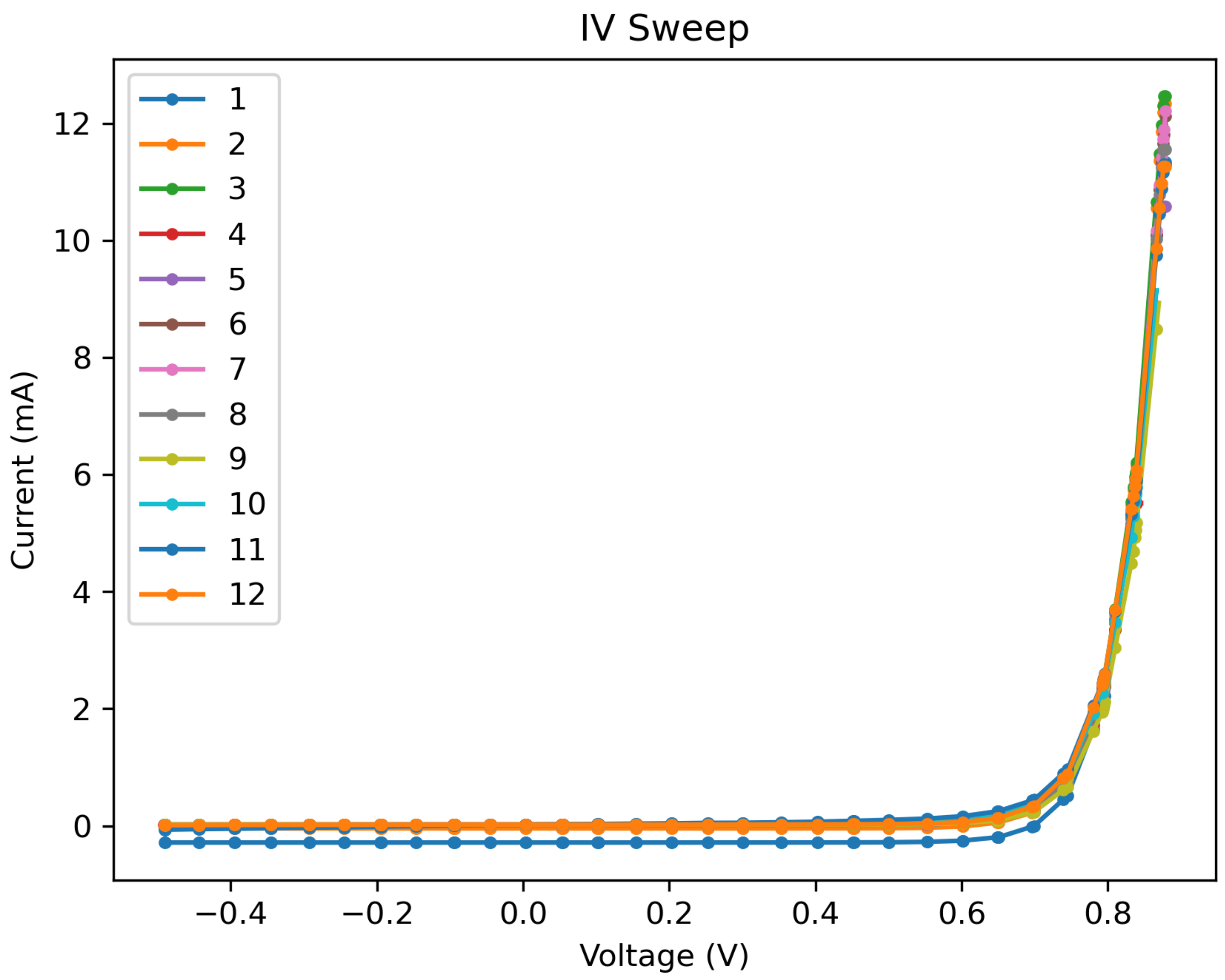


New: I-V Sweep Integrated into QE

Screen for shunted cells

- Dark or Illuminated I-V
- Bias w/ discrete LED λ's
- Diode parameter fit

- Future?: AMx.x lightsource

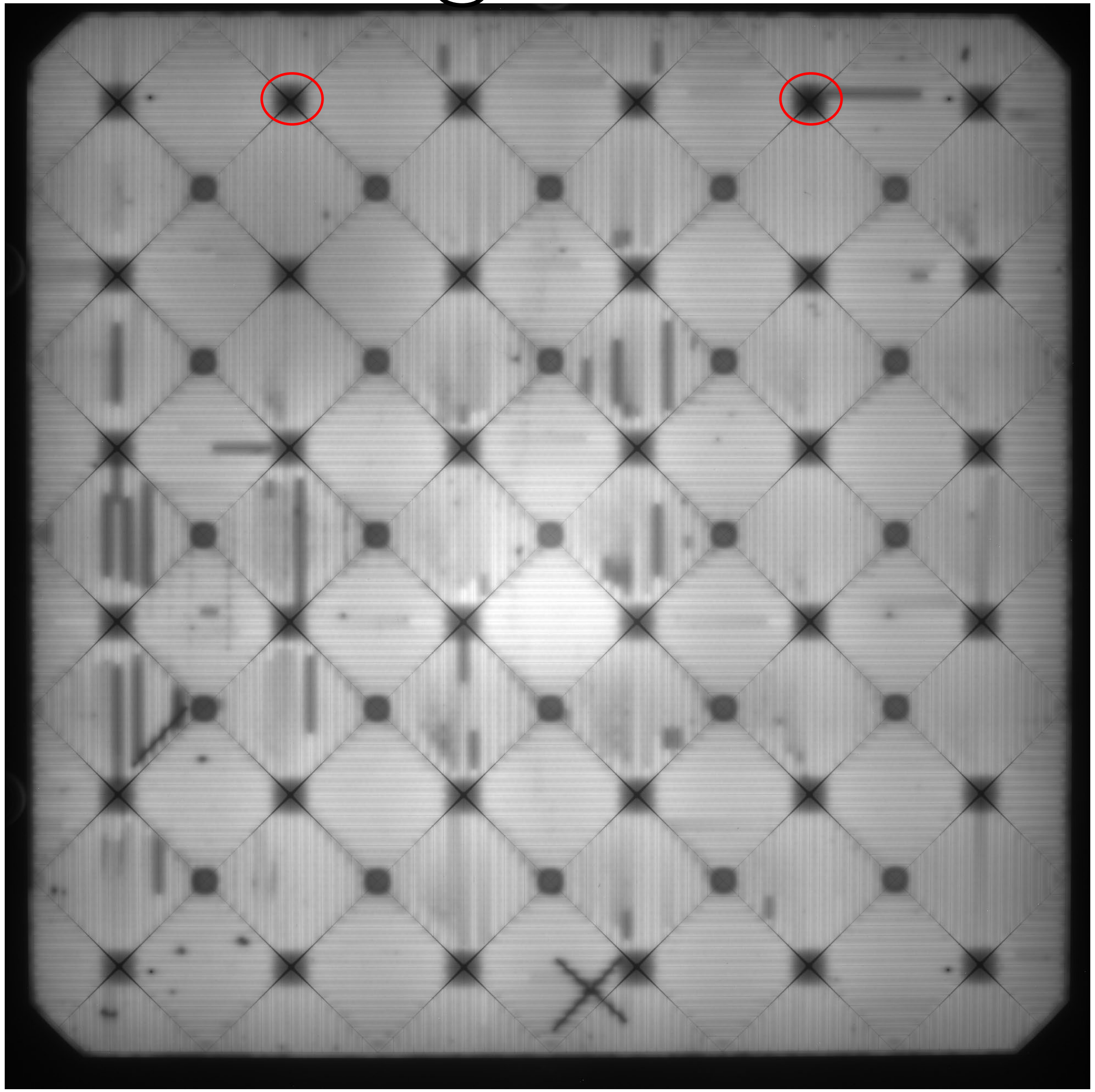


PL/EL Imaging: Back Contact Cell Example

Bias Strategy can highlight defects

Looking for shortcuts to speed detection

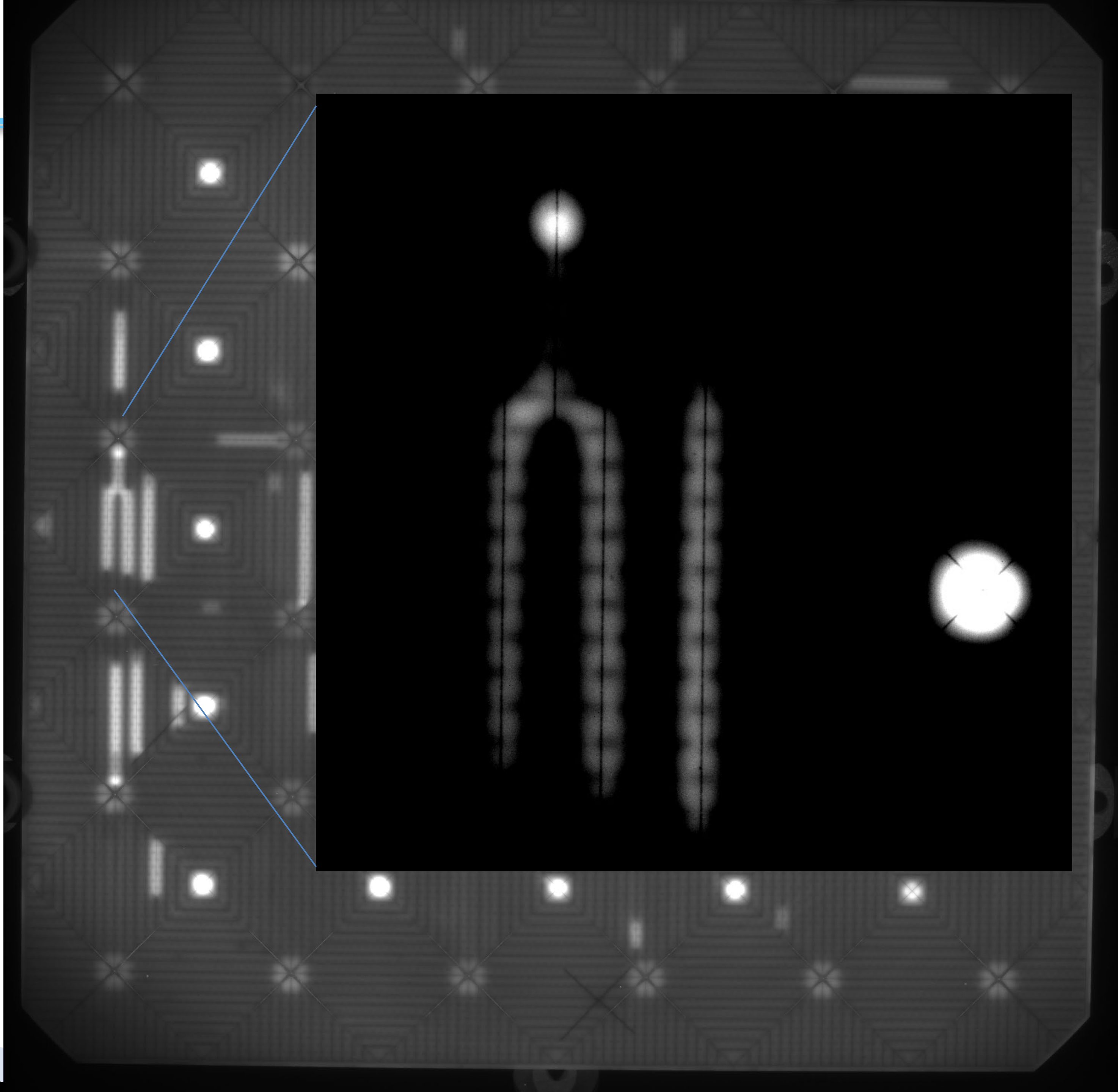
EL @10A FWD



Collection Efficiency

1-sun Illumination
+ hold cell @+0.2V

→high optical injection, and most carriers are extracted, but regions w/ ‘incomplete extraction’ are bright.

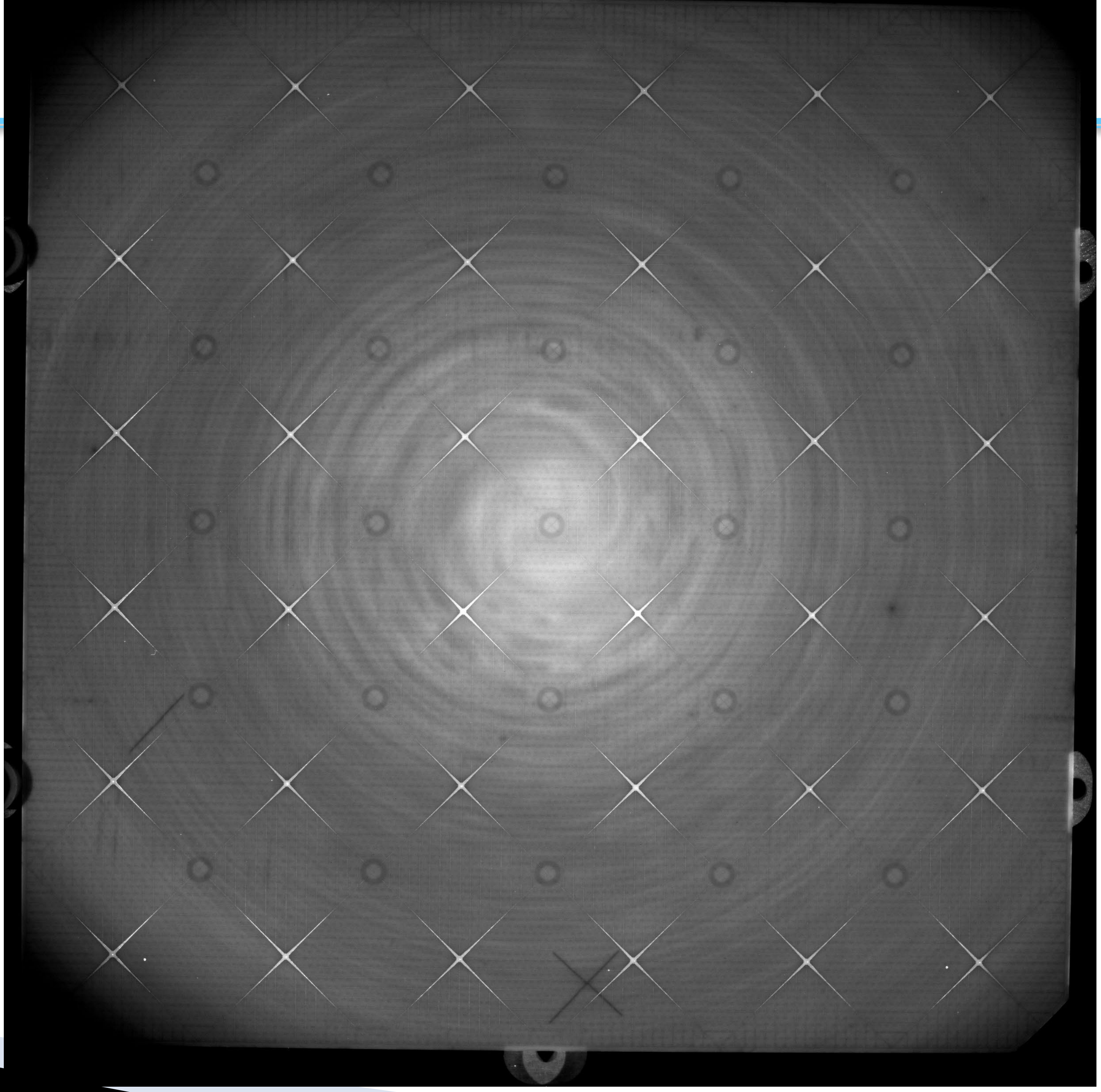


Bulk Imaging

1-sun Illumination
+ hold cell @0.0V

Same sample→high injection, but hold it at short circuit so the only remaining minority carriers are stranded in the bulk (‘diffusion limited’)

Because they’re deep bulk, we start to see ingot features. In this case, oxygen precipitate rings are visible.



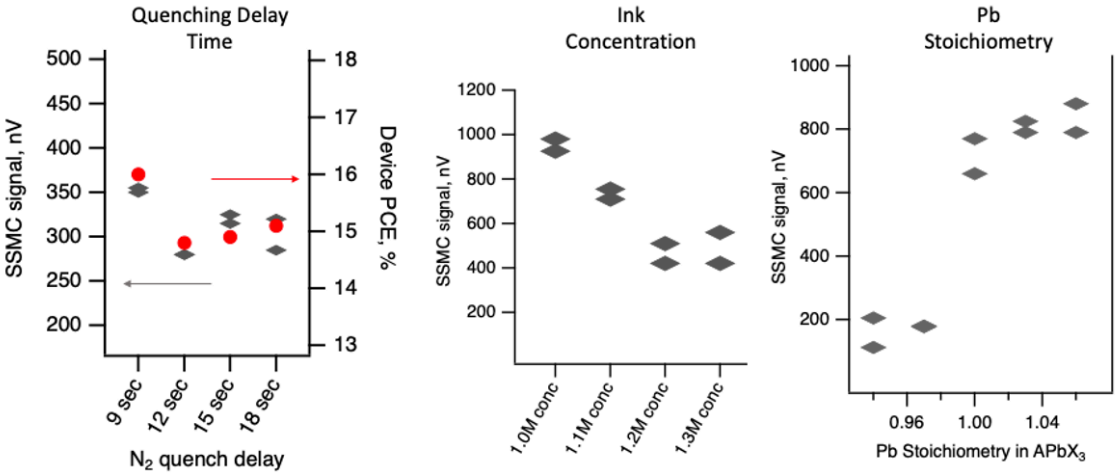
New for 2023: SSMC

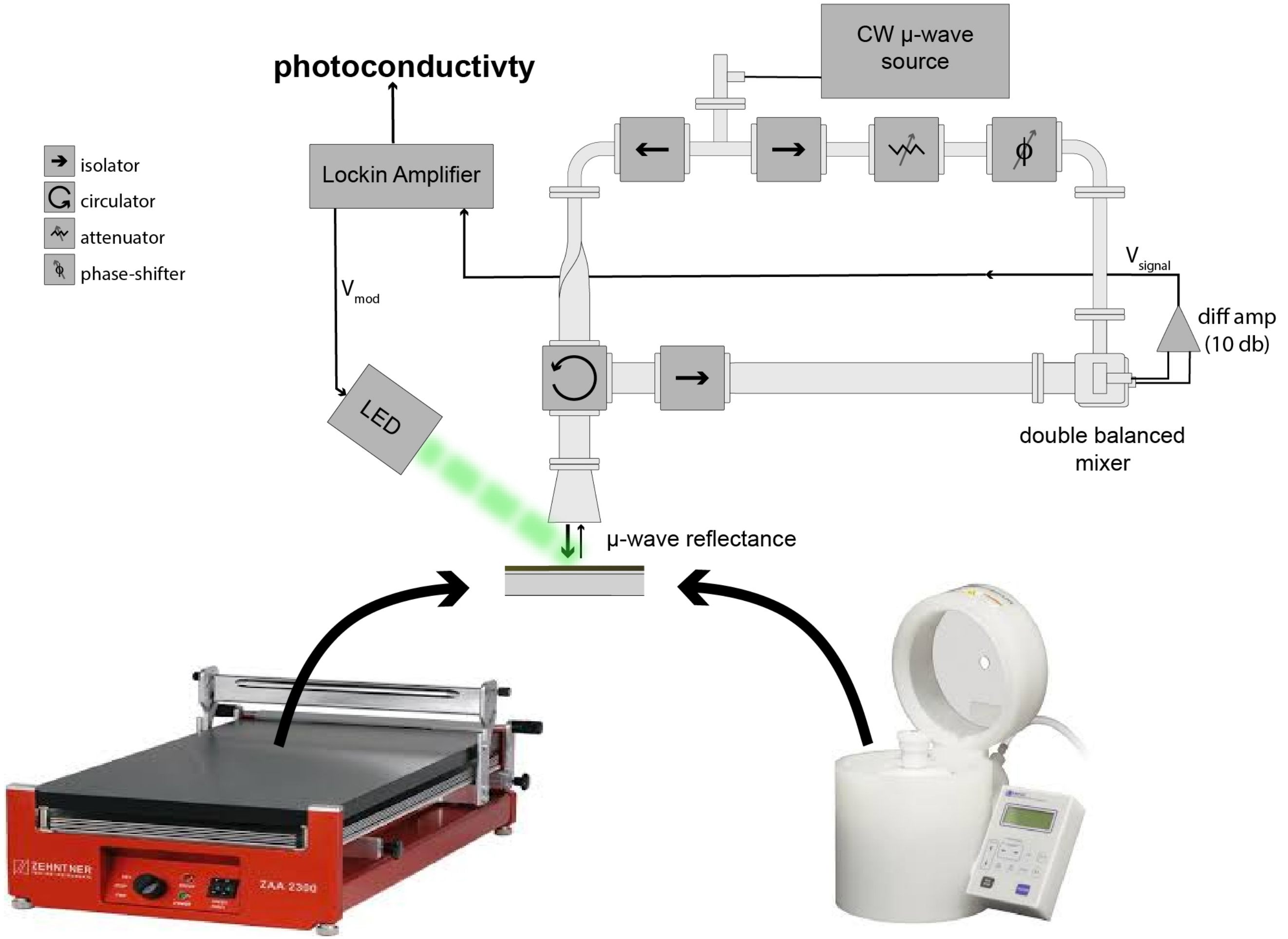
Steady State Microwave Photoconductivity (SSMC)

Bryon Larson, Obadiah Reid (NREL), Kyle Lu (Tau)

NREL Patent, SBIR Phase 2 DE-SC0020718

SSMC Signal ~ QE*μ*τ





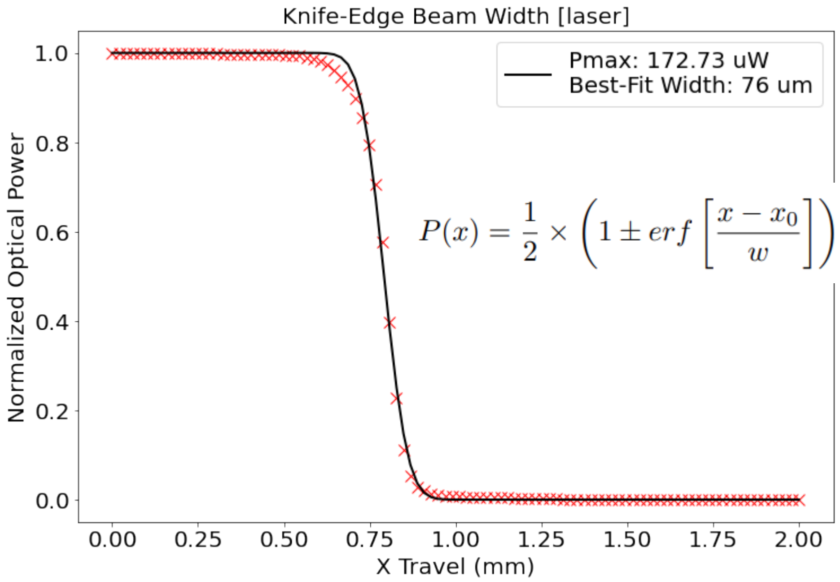
2024 Goal: test on CdTe

New for 2023: TRPL Mapper

- XY scanner
- Auto spotsize
- 500ps or 2ns response time
- Si avalanche detector
- Report Generator

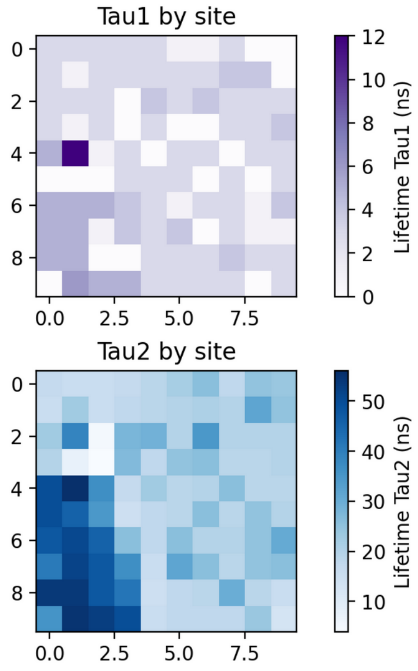
DOE SBIR DE-SC0020718

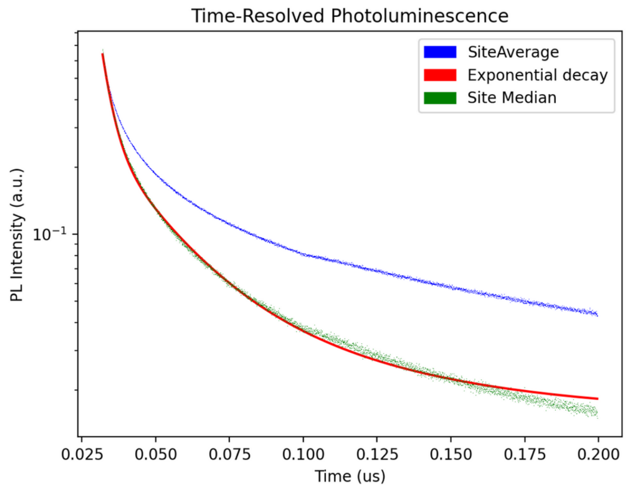
Kyle Lu, Tyler Brau, Abasi Abudulimu, Jared Friedl, Mike Heben, Randy Ellingson, Adam Phillips, Greg Horner



Sample ID:BV2 | Average power (uW): 176 | Laser beam diameter (um): 76 | Pulse repetition rate: 10.0 MHz | Datetime: 9/26/2023

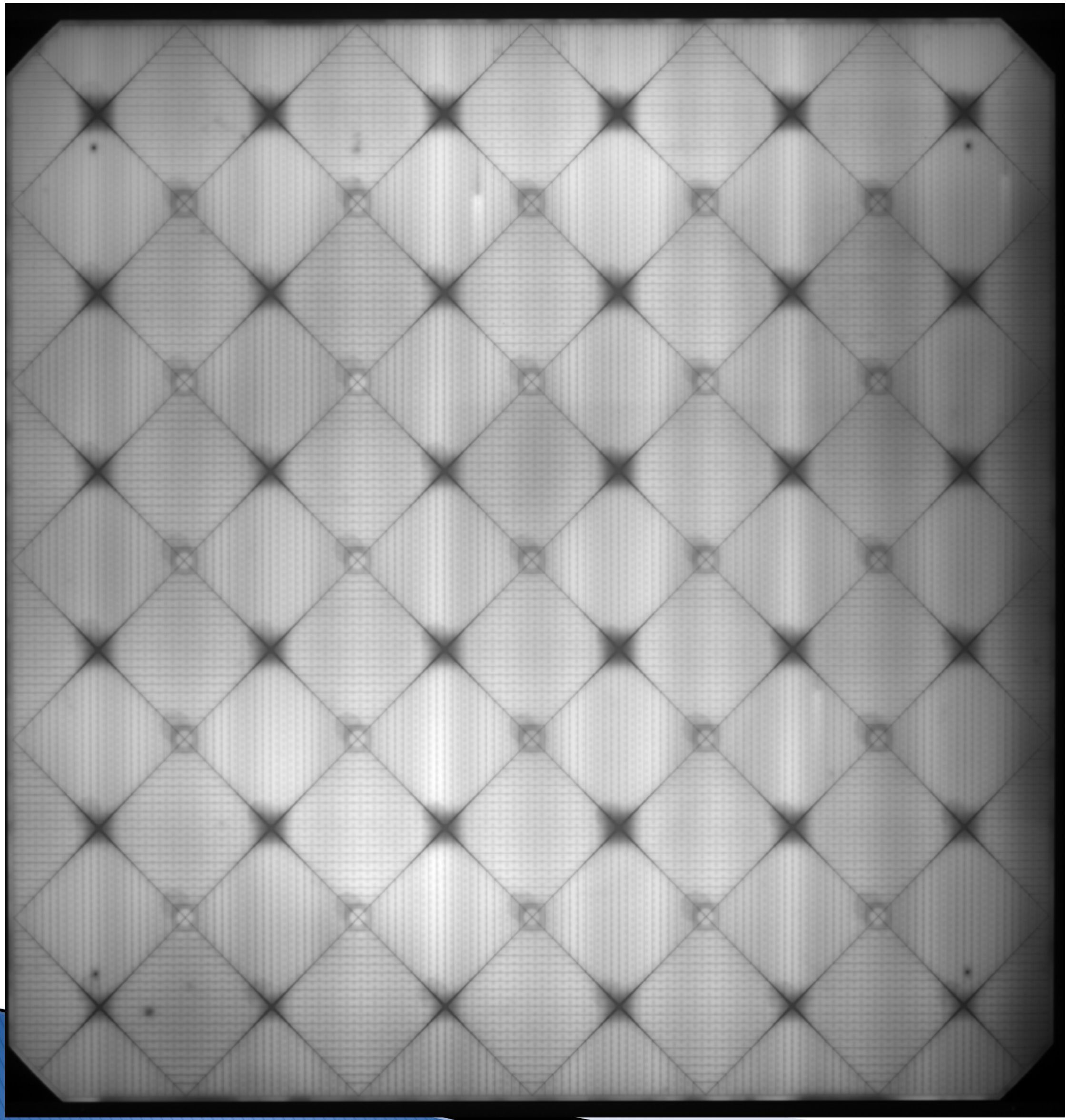
	Tau1	Tau2	Tau3	Raw Counts Max
mean	2.65	26.43	44.92	2590.59
std	1.85	12.25	23.10	1364.56
min	0.00	4.00	1.00	227.00
25%	1.00	18.75	25.00	1829.75
50%	3.00	21.50	50.00	2428.00
75%	3.00	31.25	56.00	3044.25
max	12.00	56.00	100.00	7191.00

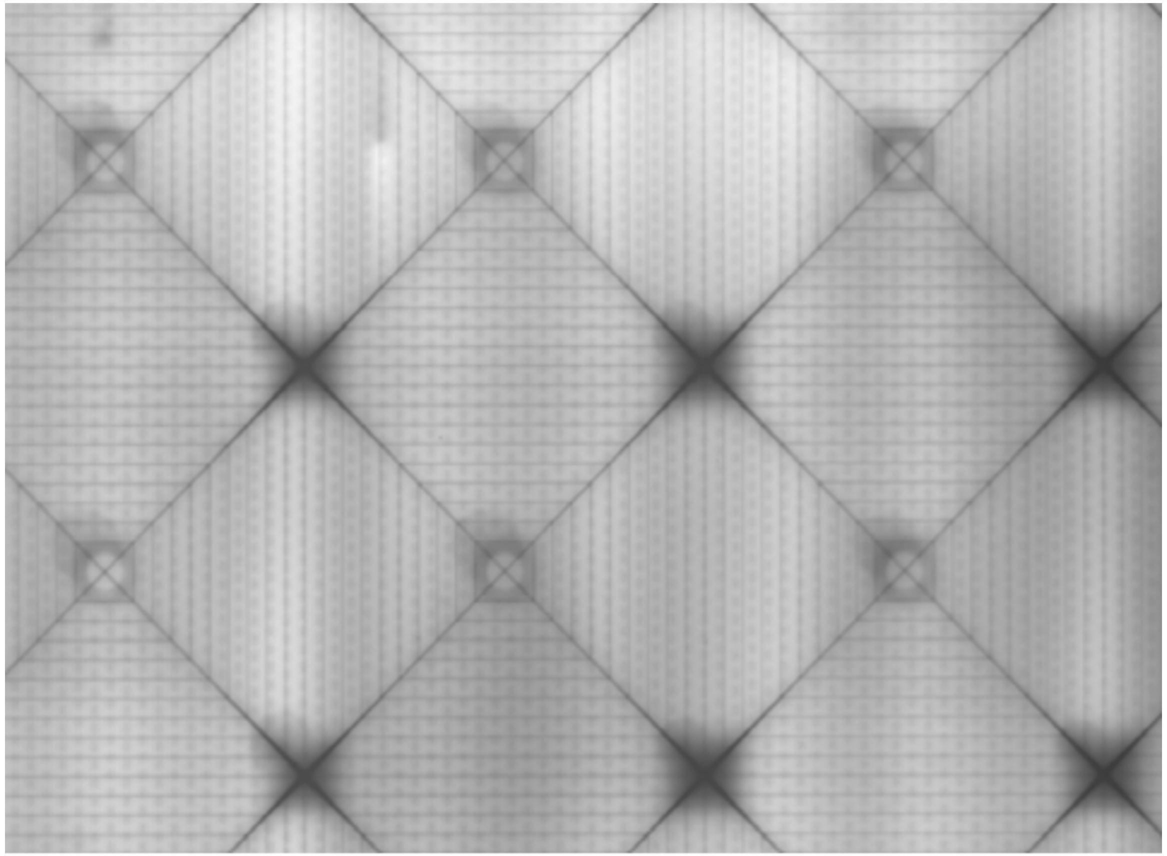


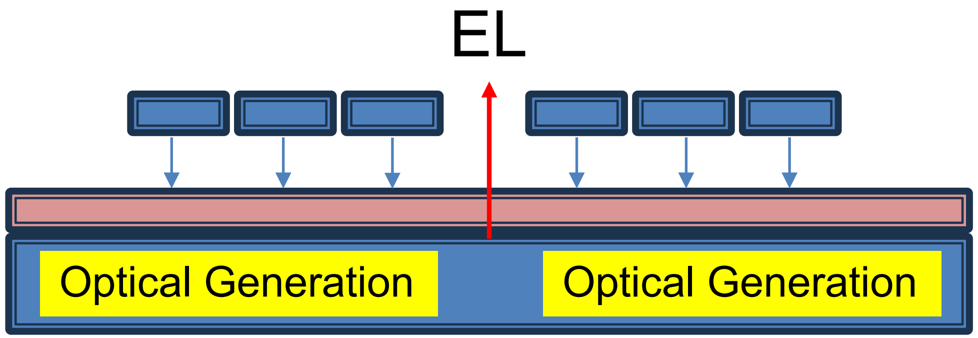


Typical dwell time, CdTe: ~5s/site

2024: Linescan non-contact EL, SETO DE-EE0009635



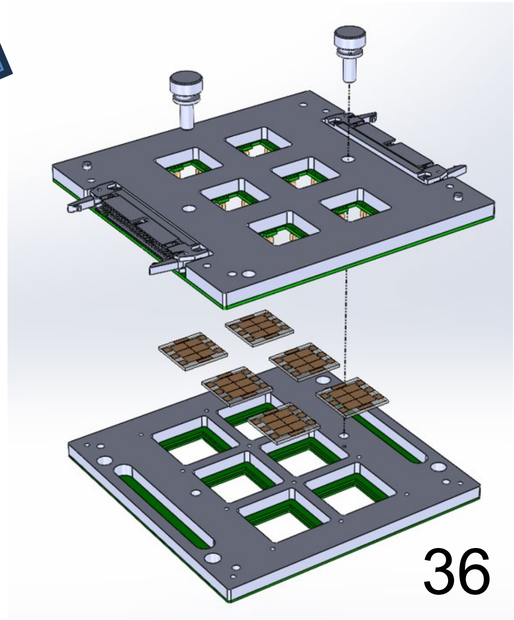


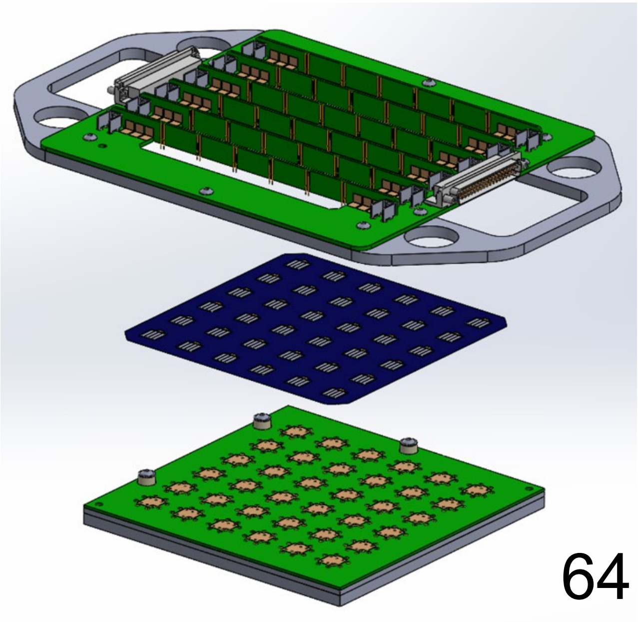


Steve Johnston, NREL Patent, non-contact EL

2024 Plans

- ERE and PLE imaging with Holman Group, ASU
- More contactors and chucks!
- N-channel I-V sweeper
- Indoor & Outdoor WiFi versions
  - Wireless: self powered
  - Hold at MPP
  - Periodic IV sweep
  - WiFi datalogger to central database





Comments, Questions, Collaborations are welcome!

Greg Horner
Ghorner@tauscience.com

Company Activities and Capabilities

Kurt L. Barth Ph.D.
President
kbarth@direct-solar.com

Contributors (Past and present):
Direct Solar: Larry Maple, Sam Ellis

CSU: Tushar Shimpi, Sampath, Ryan Ruhle, and Davis Hemenway

Arizona State Univ.: Ashwini Pavgi, Mani Govindasamy

NREL: Mike Kempe, A. Watts

Direct-solar.com

Direct Solar LLC

Experience

- Research and commercialization
- Members have multiple equity financing rounds, government R&D funding over $28M
- Extensive partnerships and industry contacts extend capabilities

Competencies

- Technology due diligence
- IP legal support
- Manufacturing techno-economic assessment
- New module designs / reliability

Technology Due Diligence

Confidential, independent consultation and analysis

- Commercial and technical

Target areas

- IP evaluation
- Techno-economic / costing
- Reliability / testing

Recent engagements / clients

- Capital providers / VCs: Pre-investment analysis
- Third party review of federal agency reports: costing analysis
- O&M, and asset deployment: Market analysis (early stage)

above

IP Legal Support

Patent, IP and expert witness services

Target areas

- c-Si thin film module construction
- Thin film processing and hardware

Past engagements include

- Patent landscape / freedom operate analysis
- Multiple engagements for PV expert witness (including for CdTe)
- Negotiated the acquisition of a multi-patent IP package for a large university

IP Legal Support: Patent Lawsuit Expertise

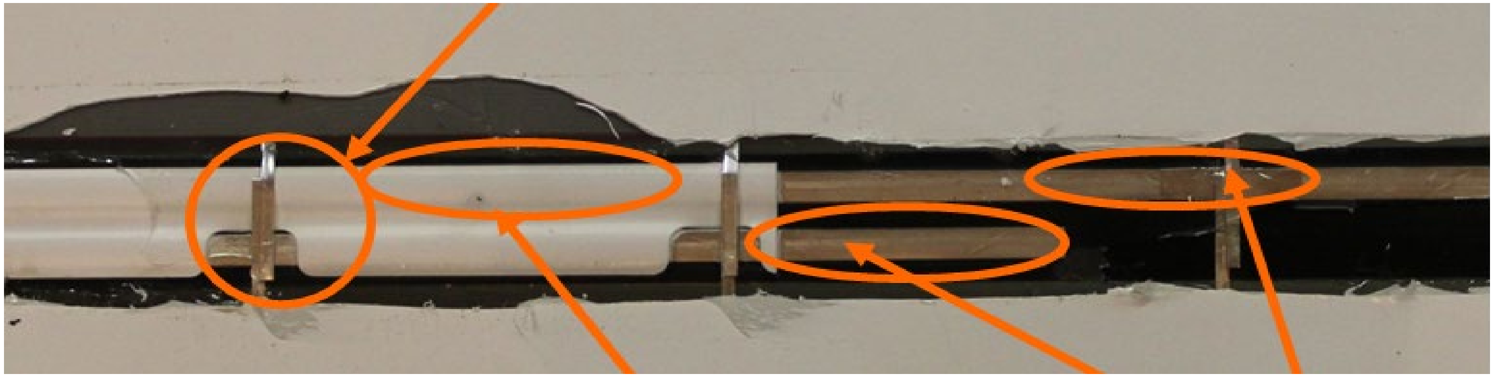
Expert Witness: Direct Solar retained 2021-present by an international law firm

Litigants: "Well known" international PV manufacturers

Area: Silicon solar module design

Direct Solar activities

- Patent prior art review
- Deconstructed competitor modules
- Drafted technical report used for IPR hearing at US Patent Trial and Appeal Board (PTAB)



Outcome: PTAB cancelled all the challenged claims based Direct Solar analysis

Manufacturing Techno-Economic Analysis

Business plan development (early stage)

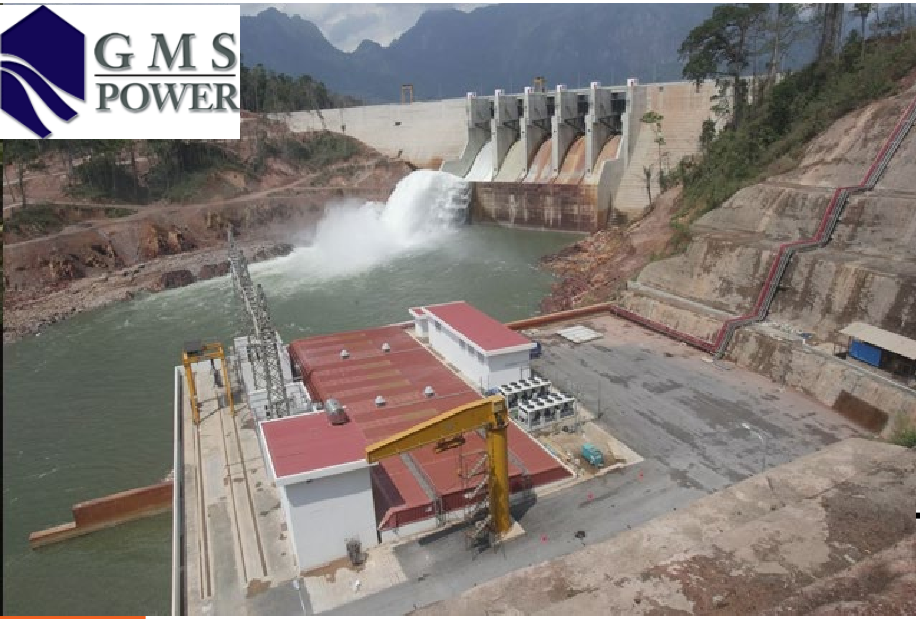
- Developed initial business plan for equity funding
- Multiple rounds eventually totaled to $300M

GMS Power, Thailand

- Hydro, gas and solar generating assets

Retained Direct Solar

- Investigated research, design and manufacturing requirements for CdTe product introduction
- Direct Solar recommendations adopted



New Module Designs / Reliability

Members of Direct Solar developed a new module architecture to improve reliability and reduce manufacturing costs

Development

- 3 DOE projects (Barth PI)
- Proto hardware installed at CSU

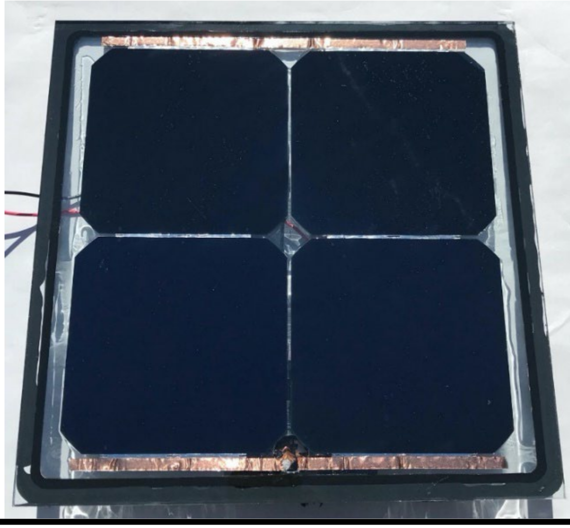
NREL NATIONAL RENEWABLE ENERGY LABORATORY

ASU Arizona State University

COLORADO STATE UNIVERSITY

Processing

- No lamination or batching required
- Recycling: Able to separate glass sheets intact
- < 150C processing temp



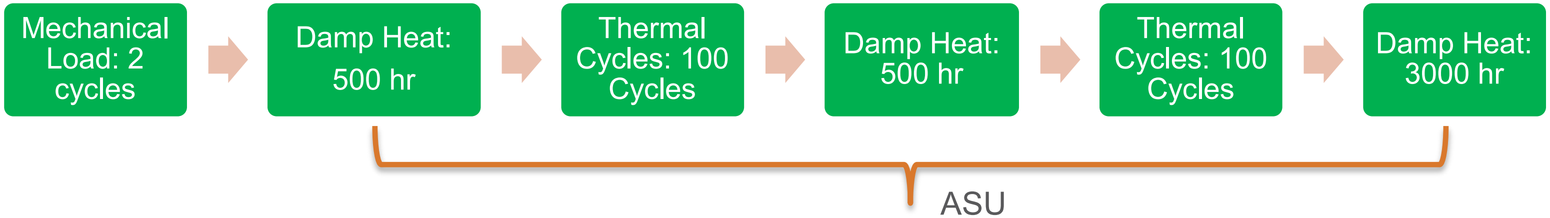
Designs for CdTe, Perovskite and c-Si

Barth, K. et al. 2014 PVSC, Barth, K. et. al. 2018 WCPEC,. Barth, K. et. al. 2019 PVSC.

New Module Designs / Reliability

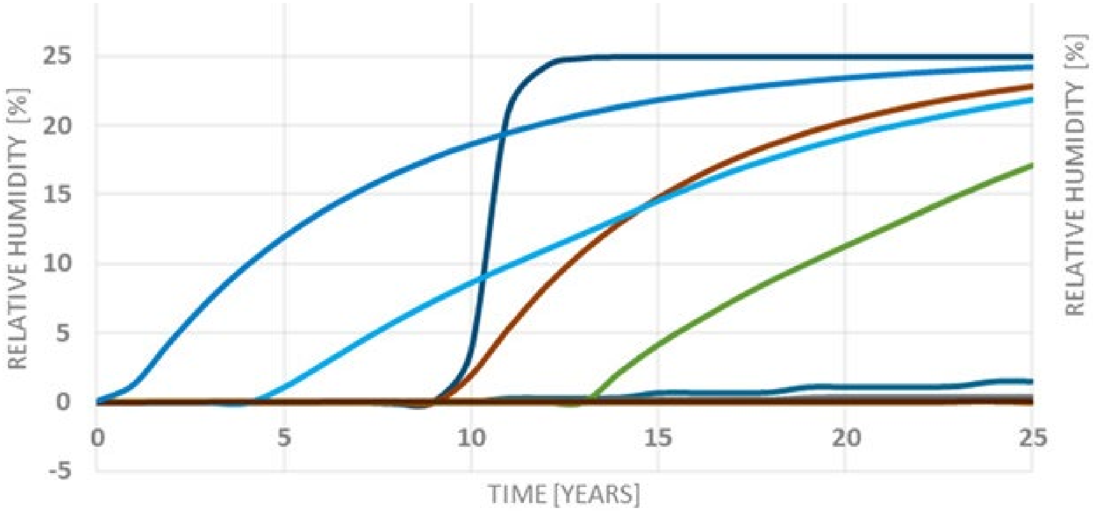
Aggressive testing

- Furnace creep testing: 105 C for 200 hrs.
- Humidity Freeze 40 cycles
- Sequential stress (Thresher style)



No delamination or moisture ingress by visual, UVF, or Spectral reflectance

Modelled moisture ingress



Kempe et al. 2023 "Energy Sci. & Eng. doi.org/10.1002/ese3.1455

- 4x Smaller factory footprint
- Ultra low moisture capability (perovskites)
- ~ 20x reduction in cycle time
- Better than 50% reduction in Cap-Ex

DIRECT SOLAR

Ellis et. al. 47th PVSC, 2020

Direct Solar

- Research and commercialization services
- Members experienced obtaining both private equity and government funding

Competencies

- Technology due diligence
- IP legal support
- Strategic consultation and Techno-economic assessment
- New module designs for cost reduction and reliability

Contact

- Kbarth@direct-solar.com
- US: 970-217-9434
- UK/Europe : 44 07513 370535

Flexible and thin-film CdTe solar cells

Yong-Hang Zhang

(Team members: J. Ding, C.-Y. Tsai, C. M. Campbell, Z. Ju, X. Qi, S. Schaefer, T. McCarthy)

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Tempe, Arizona 85287

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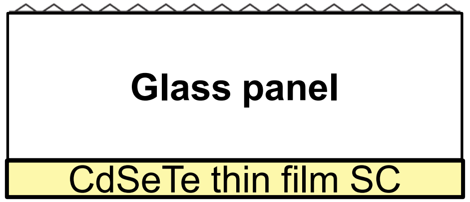
AFRL & AFOSR SCIENCE foundation ARIZONA INNOVATION AT WORK BAPVC PVRD **F-PACE II** NSF

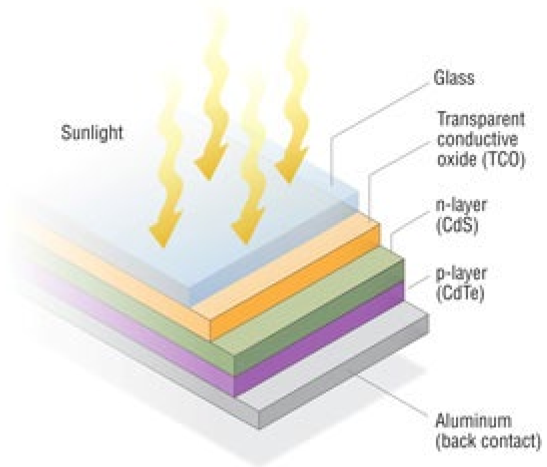
ASU

Motivations for the study of Ultra-thin CdTe solar cells

Low material consumption

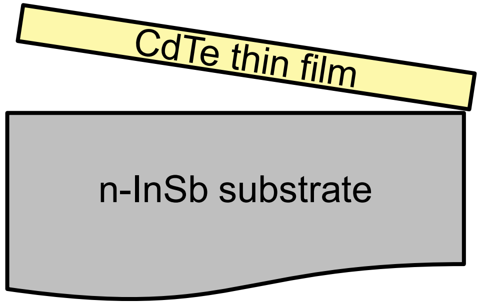


0.5 μm vs 3 μm



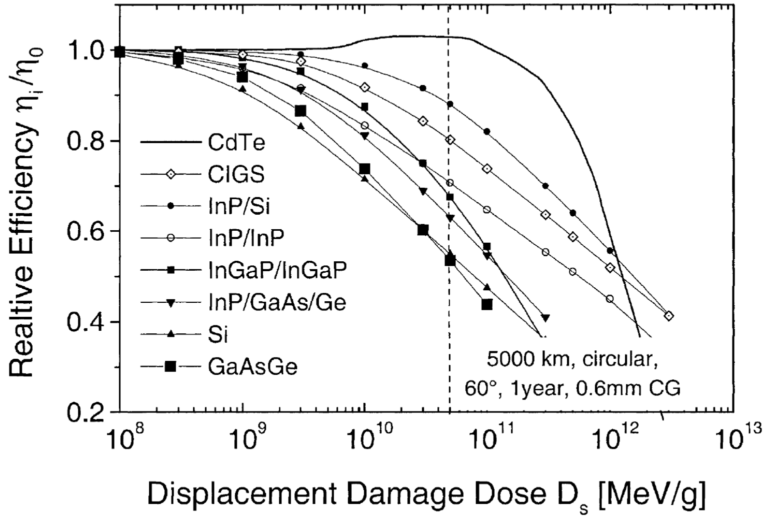
https://www.energy.gov/sites/default/files/graphic_cdte.jpg

Light-weight, high-efficiency thin-film solar cells for space applications



0.5 μm ~ 1 μm

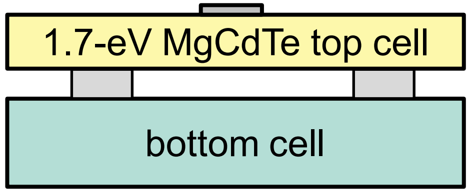
≥ 500 μm

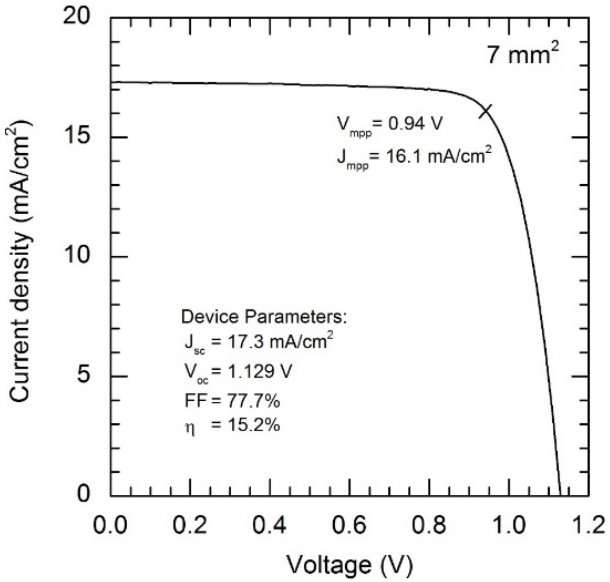


D.L.Batzner *et al, Thin Solid Films* 451-452 (2004) 536-543

1.7-eV MgCdTe/Si tandem solar cell

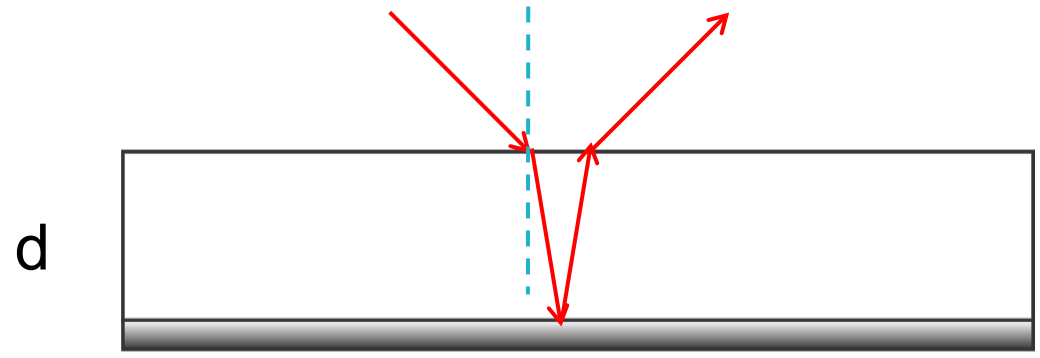
15.2% efficiency





J. Ding, J.J. Becker, C.M. Campbell, C.-Y. Tsai and Y.-H. Zhang, *PVSEC 2019*

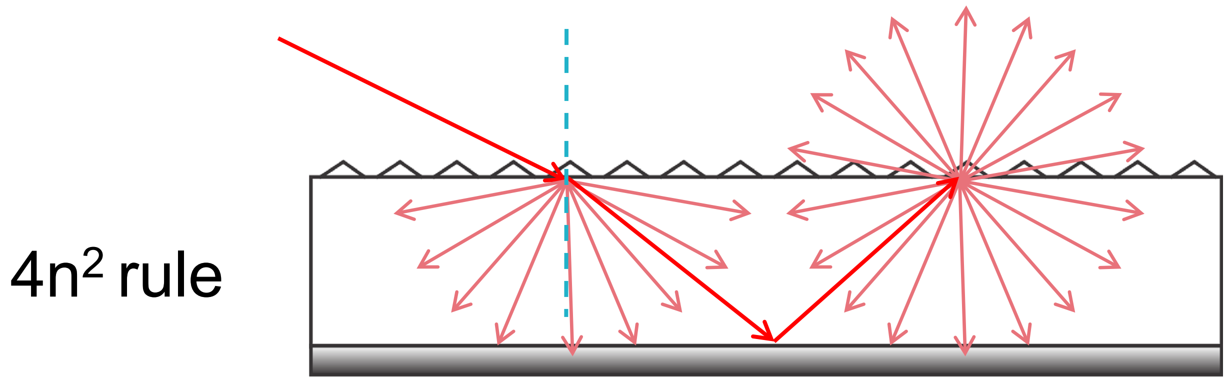
Optical analysis



Structure C

$$A_\alpha \cong 1 - e^{-2\alpha \cdot d}$$

$$\varepsilon_{upper} = 1 - n_r^2 \int_0^{\theta_c} e^{-2\alpha d/\cos\theta} \cdot 2\cos\theta \sin\theta \cdot d\theta$$



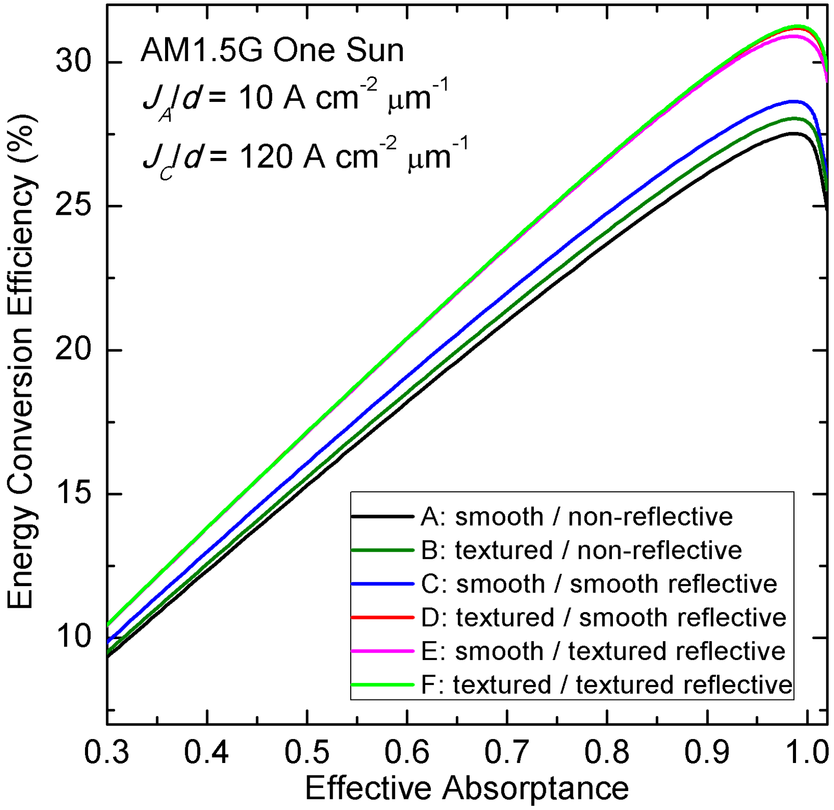
Structure D

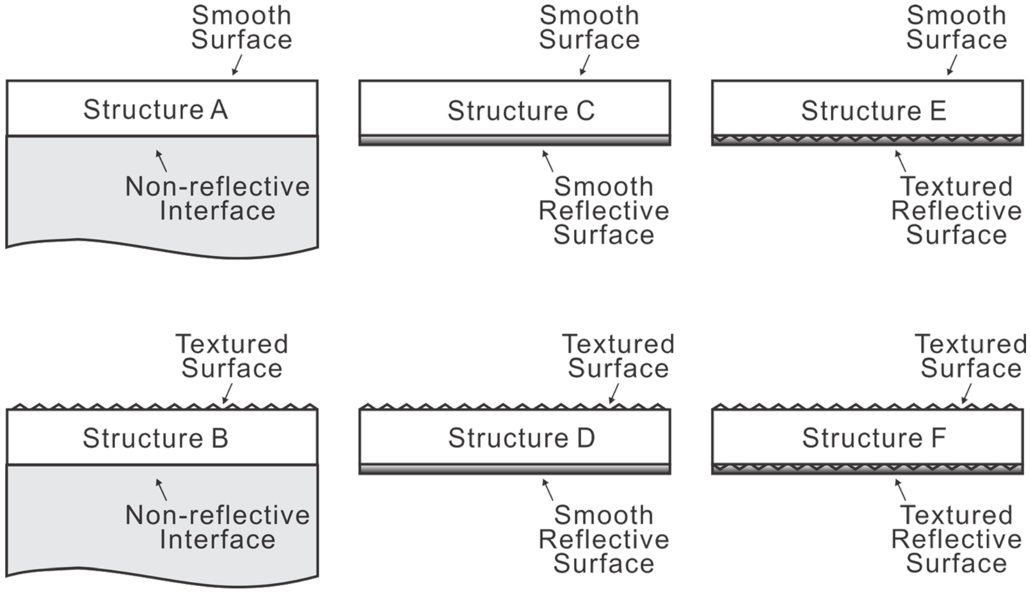
$$A_\alpha = \frac{1 - t_\alpha}{1 - \left(1 - \frac{1}{n_r^2}\right) \cdot t_\alpha} \qquad \varepsilon_{upper} = A_\alpha$$

$$t_\alpha = \int_0^{\pi/2} e^{-2\alpha d/\cos\theta} \cdot 2\cos\theta \sin\theta \cdot d\theta$$

D. Ding, S. R. Johnson, and Y.-H. Zhang, *Proceedings of 35th IEEE Photovoltaic Specialist Conference*, p. 2908, 2010.
D. Ding, S. R. Johnson, S.-Q. Yu, S.-N. Wu, and Y.-H. Zhang, *A Semi-Analytical Model for Semiconductor Solar Cells*, J. Appl. Phys. 110, 123104 (2011).

Theoretically achievable efficiency of GaAs cells

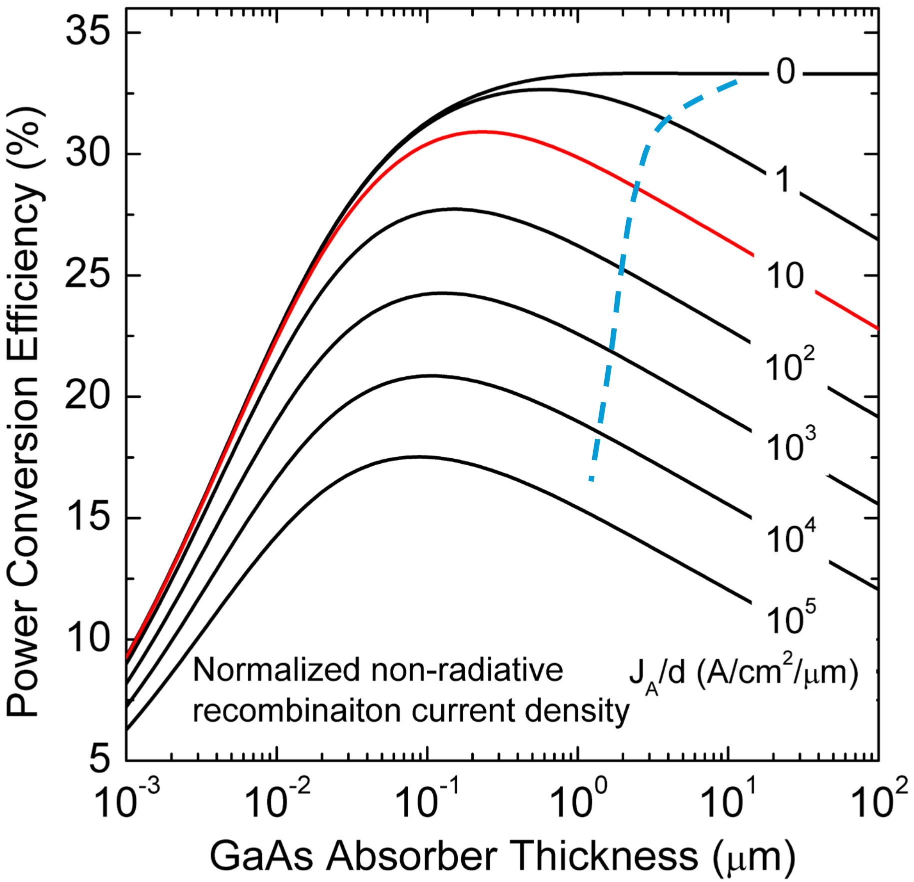




Expected achievable efficiency 31.25%.

S. Liu, D. Ding, S. R. Johnson, Y.-H. Zhang, *Optimal optical designs for GaAs single-junction solar cells,* SPIE Photonics West, Jan. 21-26, 2012.

Optimal thickness of GaAs SJ Solar Cells

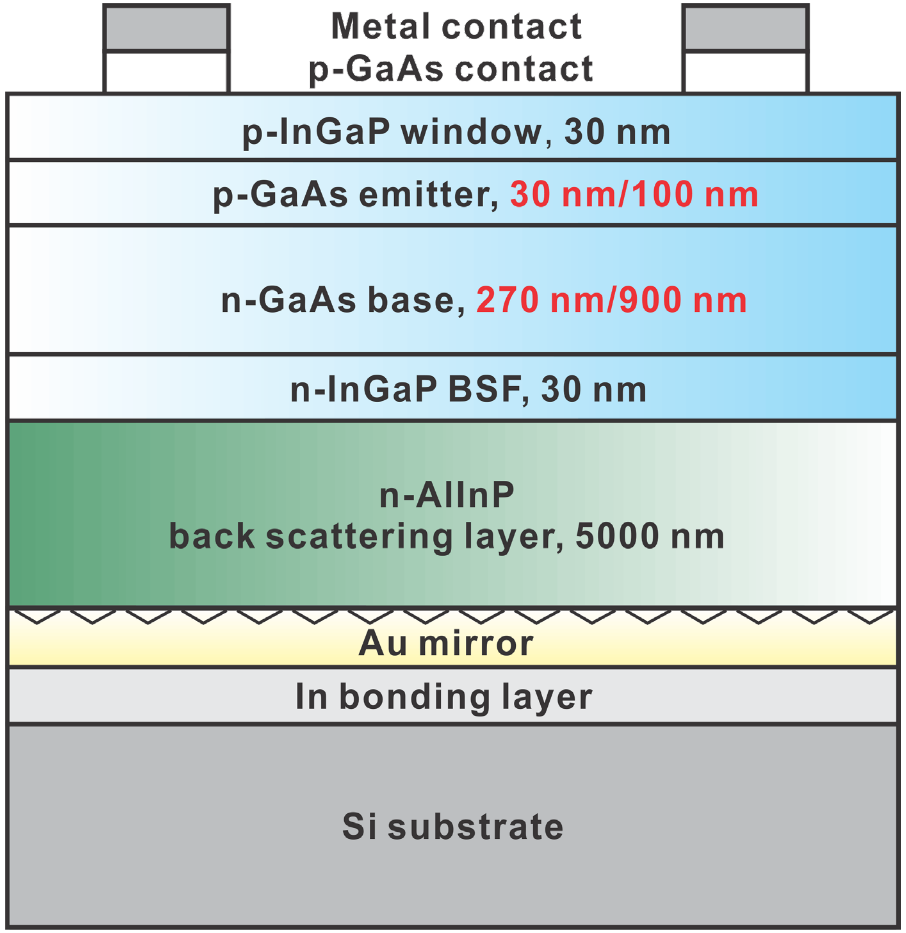


- There is an optimal thickness for SJ cell using non-ideal material.
- The higher the non-radiative recombination rate, the thinner the optimal thickness.

How to achieve optimal efficiency using material with *average* quality?

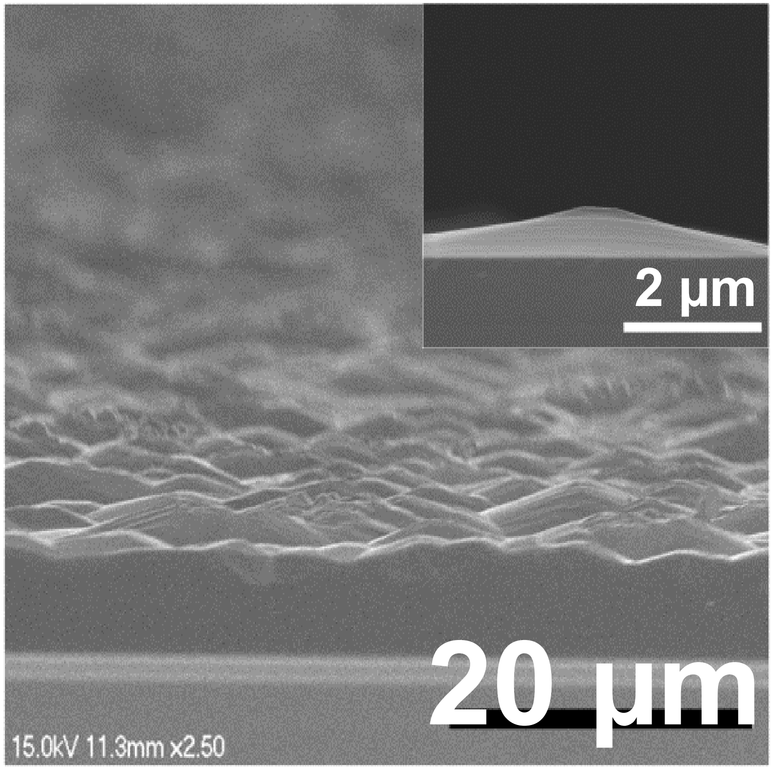
Use scattering to trap the light and thin layer to reduce the non-radiative recombination

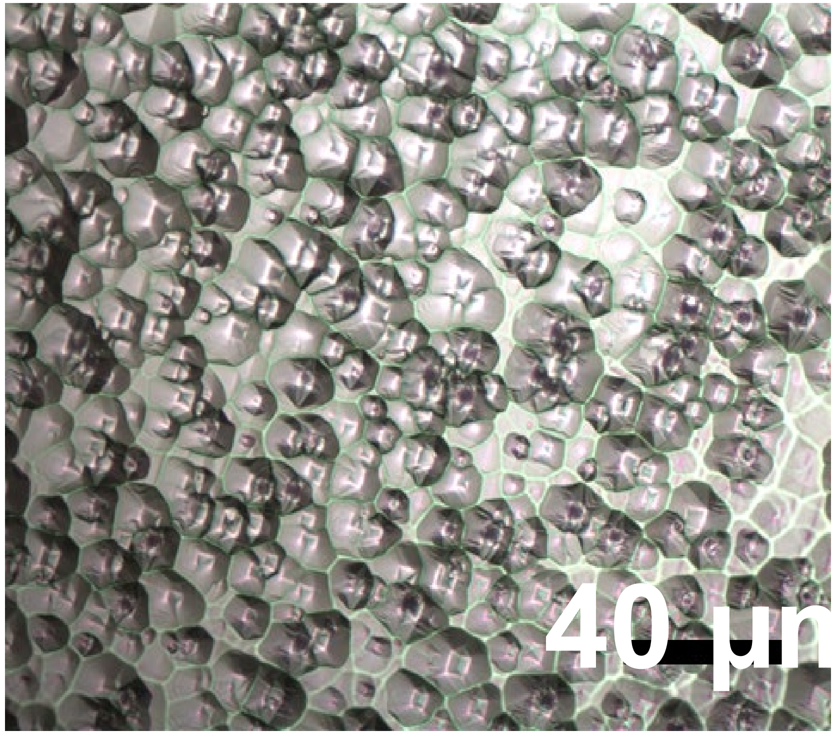
Device Structure



Two types of device structures: 300 nm/1000 nm absorber

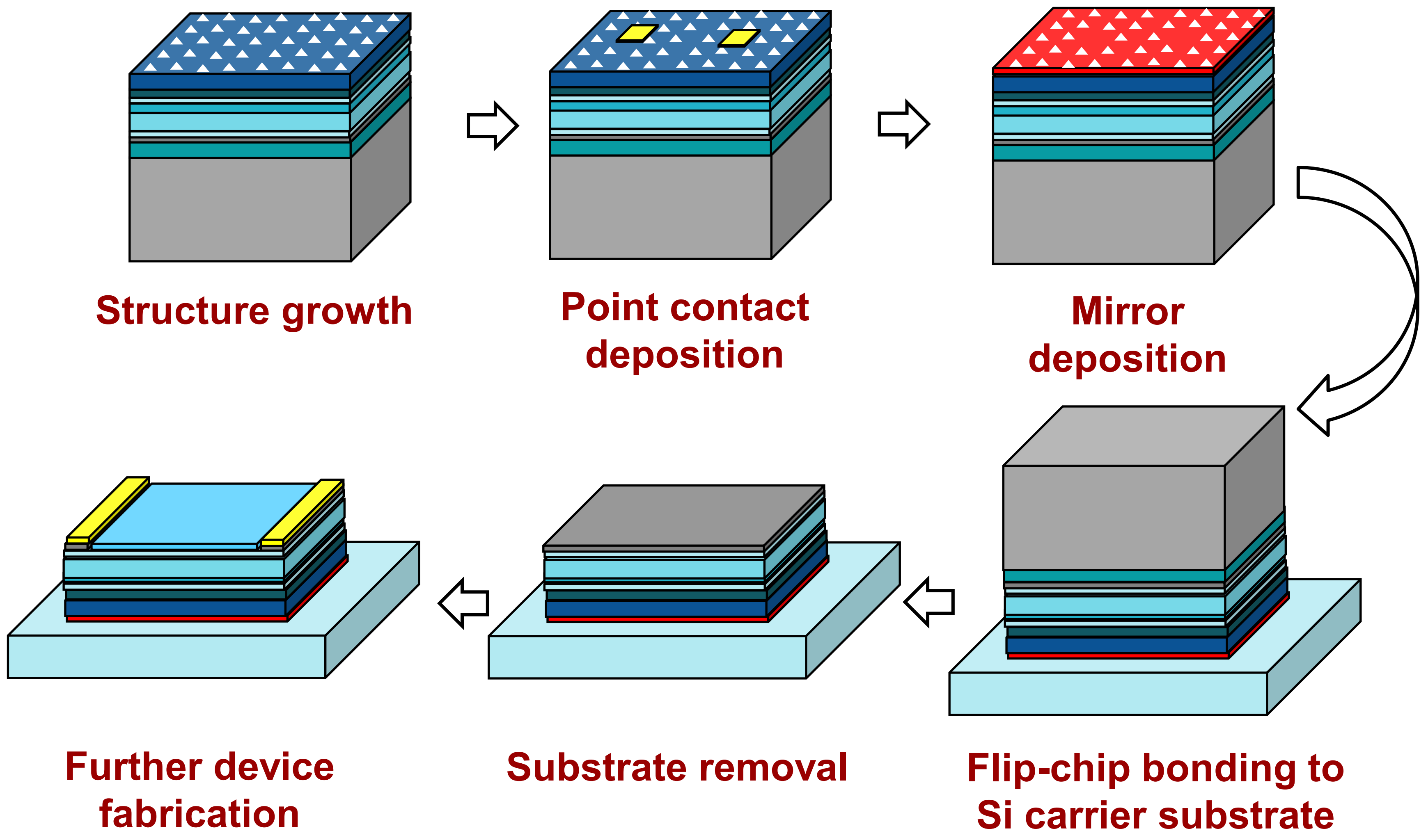
As-Grown Textures of AlInP Layer





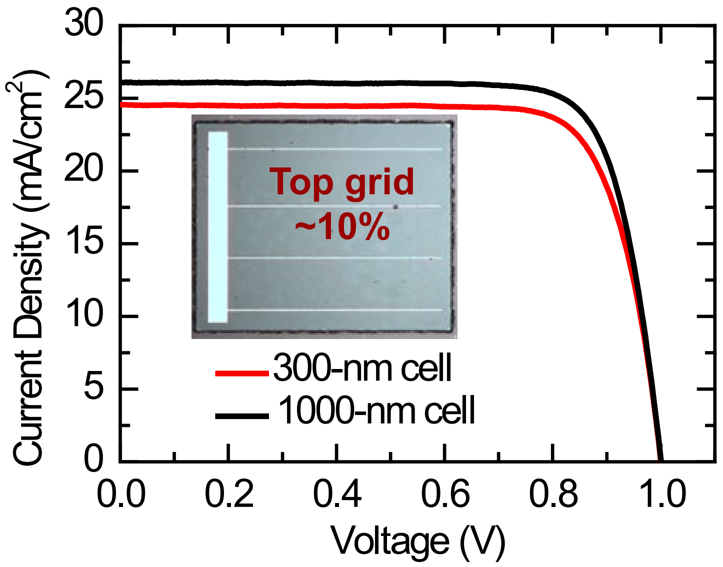
High-density cone textures were formed intentionally during MOCVD growth.

Process Flow



Performance of Fabricated Cells

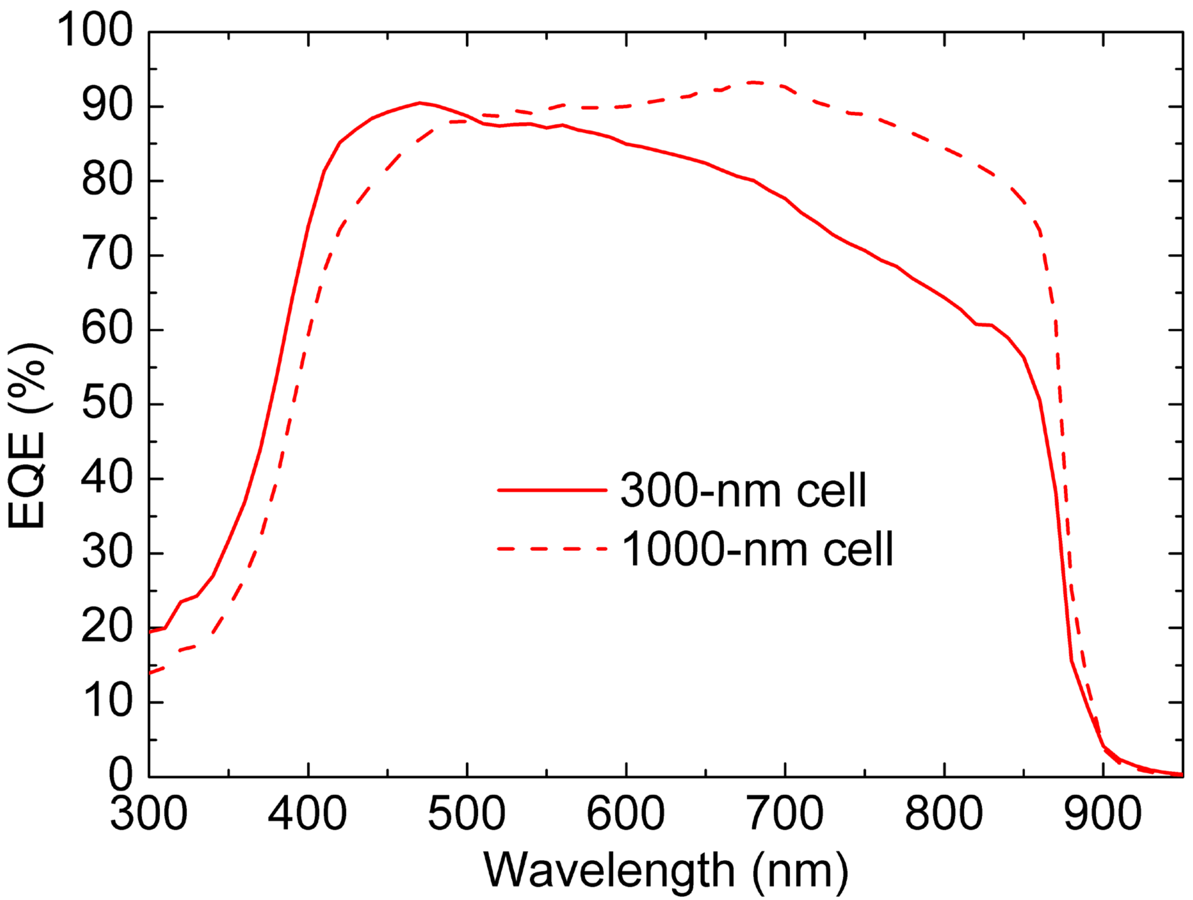
GaAs thickness	V_{oc}	J_{sc}	FF	η	Top grid coverage	Anticipated η with 2% top grid
300 nm	1.00 V	24.5 mA/cm²	77.8%	19.1%	9.7%	20.7%
1000 nm	1.00 V	26.1 mA/cm²	78.8%	20.6%	10.7%	22.6%



J_{sc} (mA/cm²)		
Measured (~10% grid & 3.8% ref.)	Corrected (~2% grid & 3.8% ref.)	Maximum (~2% grid, 2% ref. & Lambertian)/Δ
24.5	26.6	30.2, Δ=3.6
26.1	28.6	30.2, Δ=1.6

W. Yang, J. Becker, S. Liu, Y.-S. Kuo, J.-J. Li, B. Landini, K. Campman, Y.-H. Zhang, *Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer*, JAP 115, 203105 (2014).

External Quantum Efficiency



At short λ: Higher extraction efficiency of carriers in the 300 nm cells

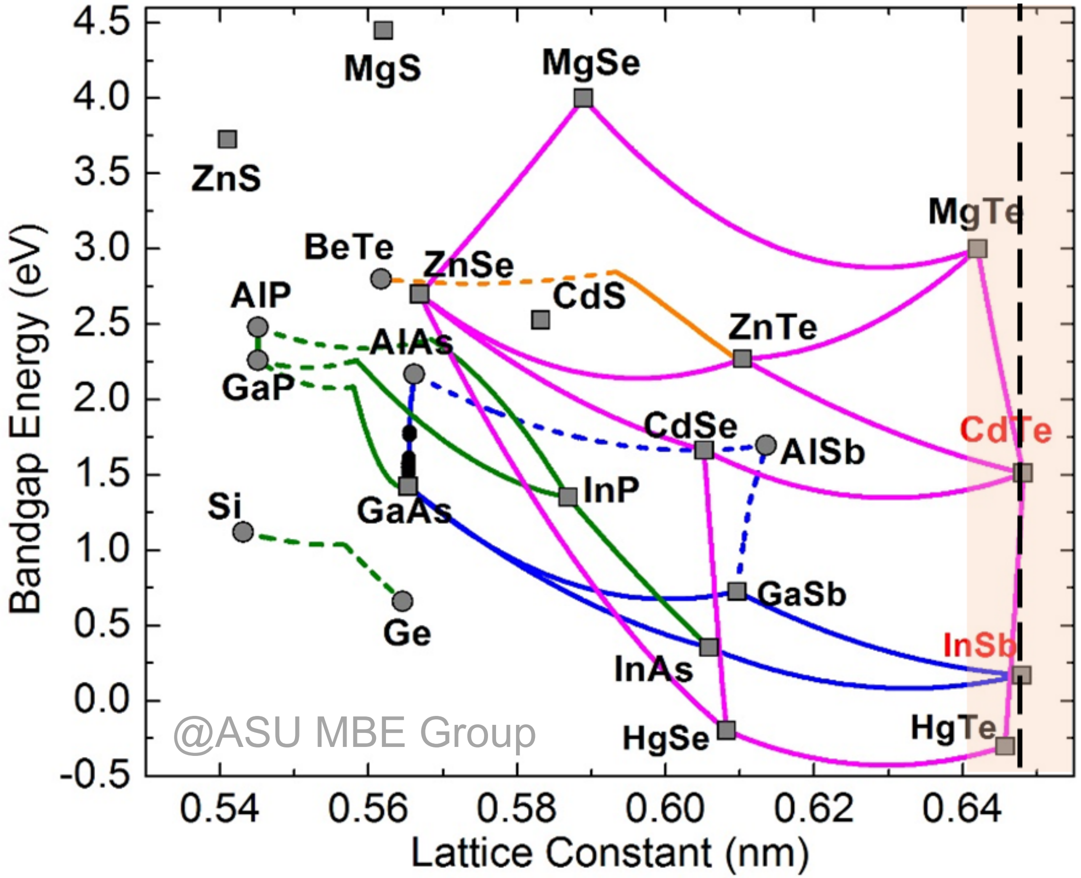
At long λ: More light absorption in the 1000 nm cells

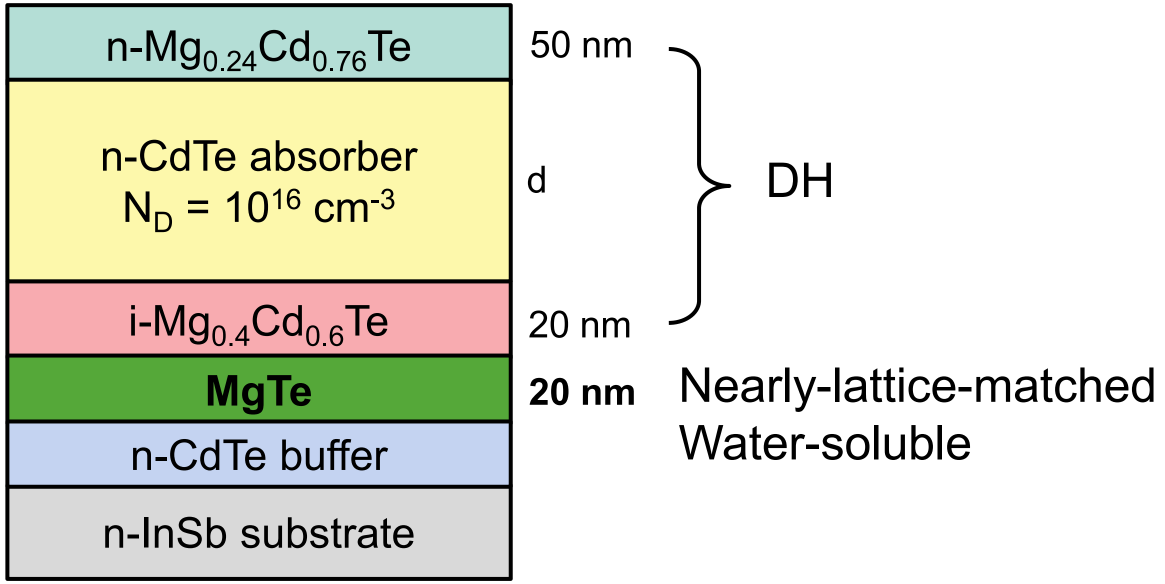
MBE Optoelectronics Group

W. Yang, J. Becker, S. Liu, Y.-S. Kuo, J.-J. Li, B. Landini, K. Campman, Y.-H. Zhang, *Ultra-thin GaAs single-junction solar cells integrated with a reflective back scattering layer*, JAP 115, 203105 (2014).

ELO Using MgTe Sacrificial Layer

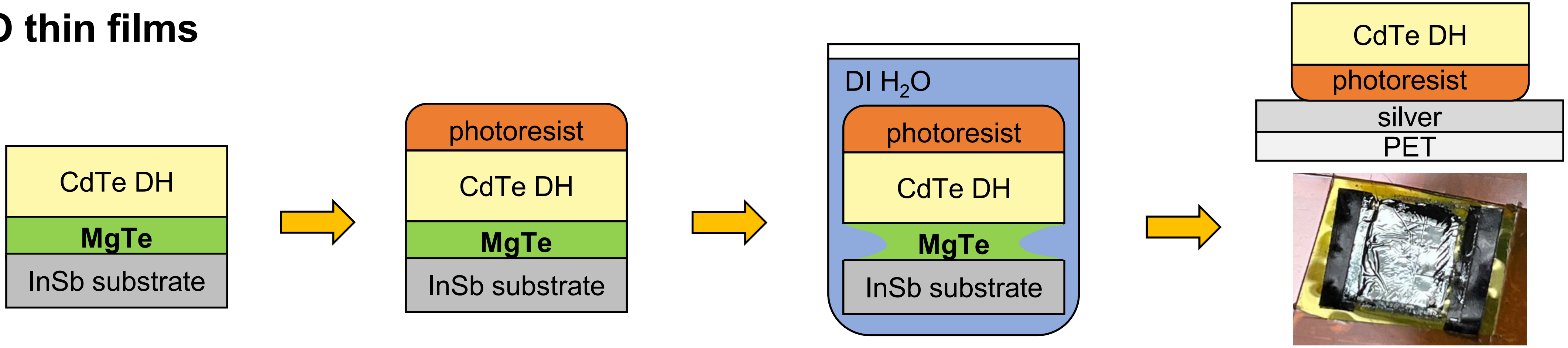
Lattice-Matched 6.5 Å-Family





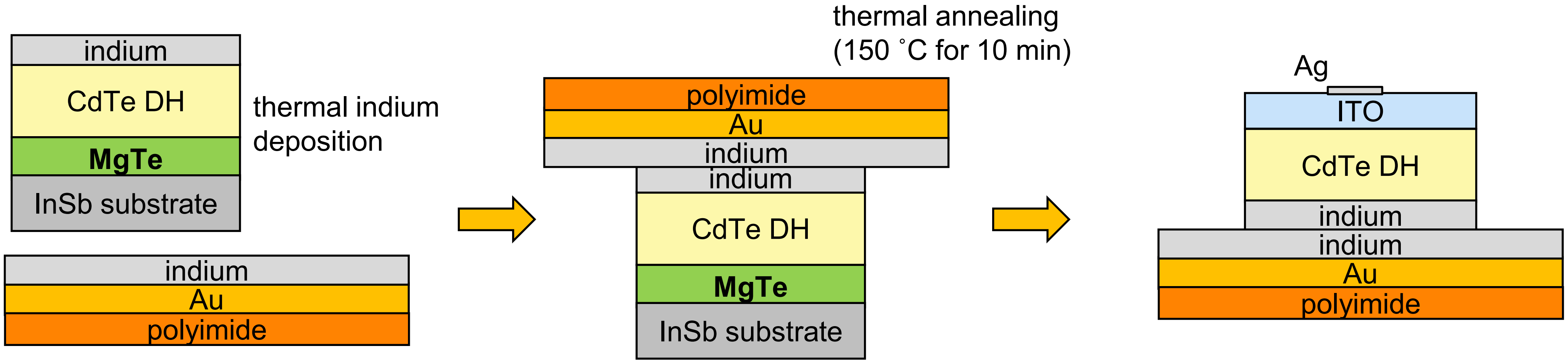
ELO process of CdTe DH thin films / Devices

- **ELO thin films**



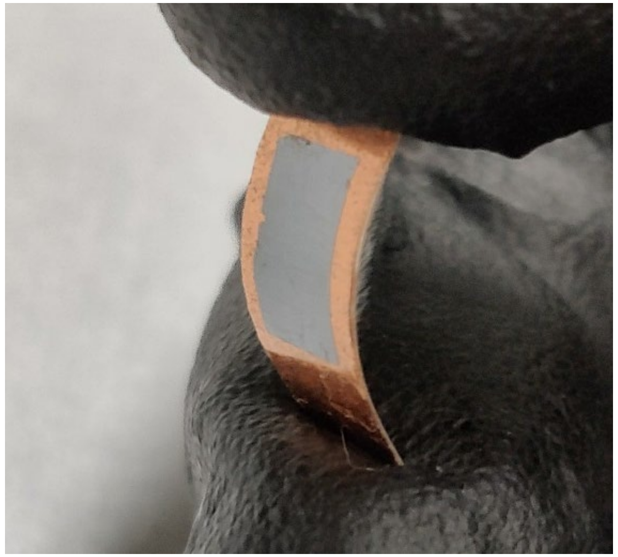
C. M. Campbell, C.-Y. Tsai, J. Ding, and Y.-H. Zhang, *Epitaxial Lift Off of II-VI Thin Films Using Water-Soluble MgTe*, JPV **9**, 1834-1838 (2019)

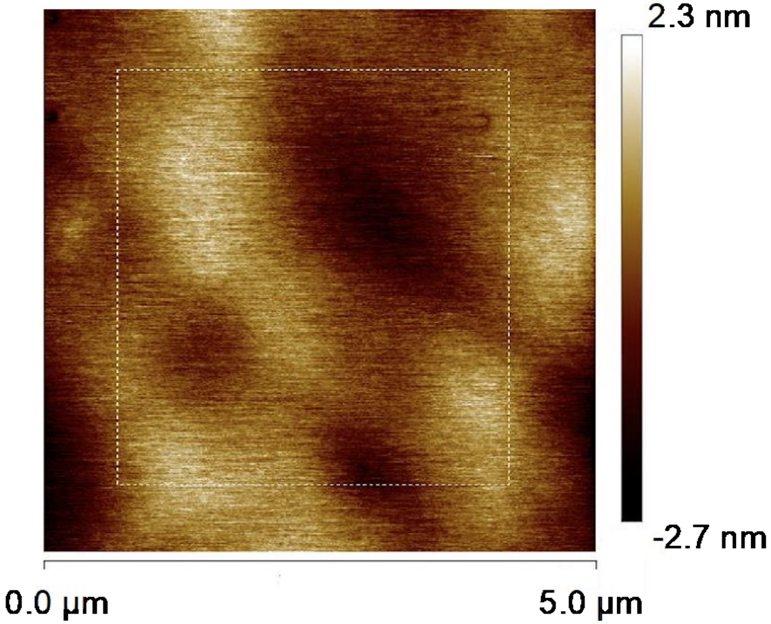
- **Monocrystalline CdTe thin-film solar cells**

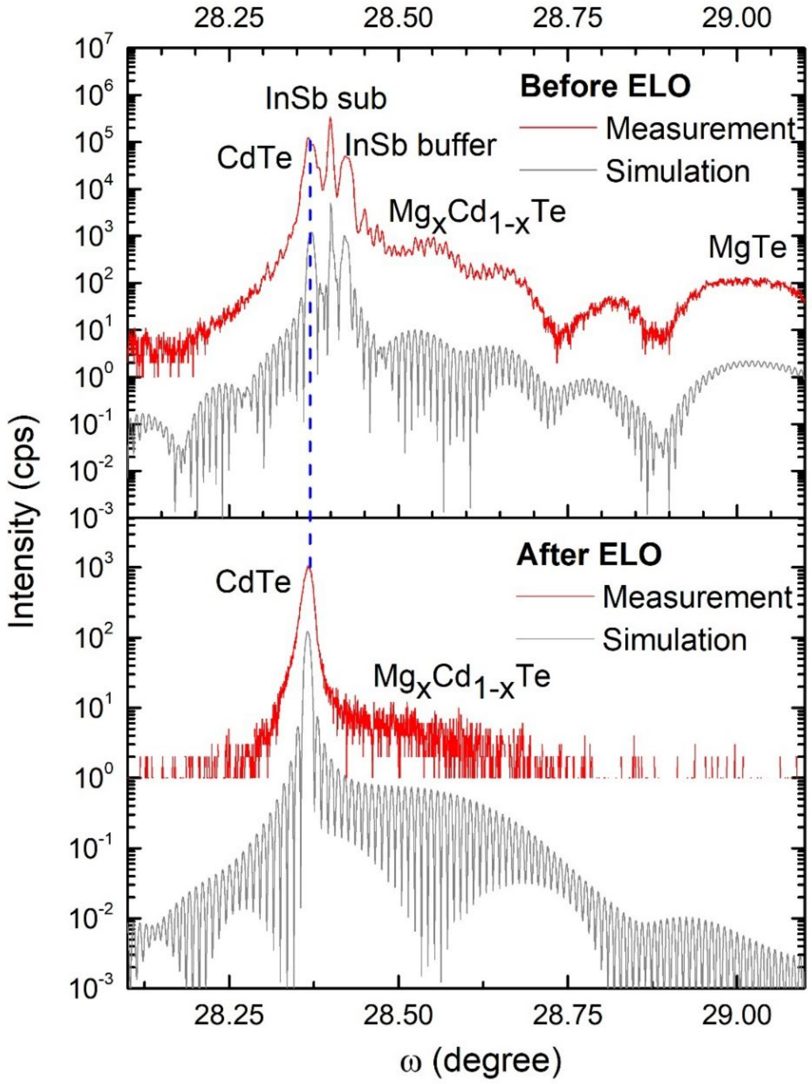


Thin Film Characterizations

AFM: RMS roughness of 0.67 nm







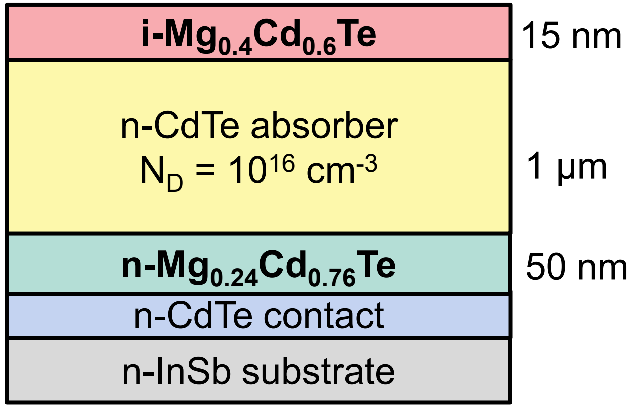
- Smooth and intact lift-off surface revealed by AFM image.
- CdTe/MgCdTe DH survives the ELO.
- Highly selective etching of MgTe vs. CdTe using DI water.

C. M. Campbell, C.-Y. Tsai, J. Ding, and Y.-H. Zhang, *Epitaxial Lift Off of II-VI Thin Films Using Water-Soluble MgTe*, JPV **9**, 1834-1838 (2019)

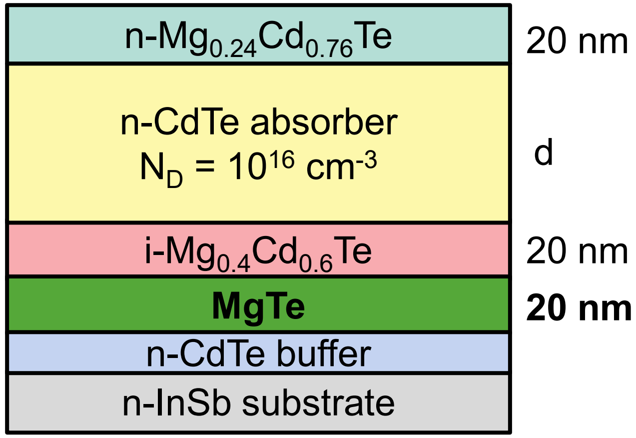
J. Ding, C.-Y. Tsai, Z. Ju, and Y.-H. Zhang, *Epitaxial lift-off CdTe/MgCdTe double heterostructures for thin-film and flexible solar cells applications*, APL **118**, 181101 (2021). (Featured article, Editor's pick as Scilight)

Photoluminescence Before/After ELO

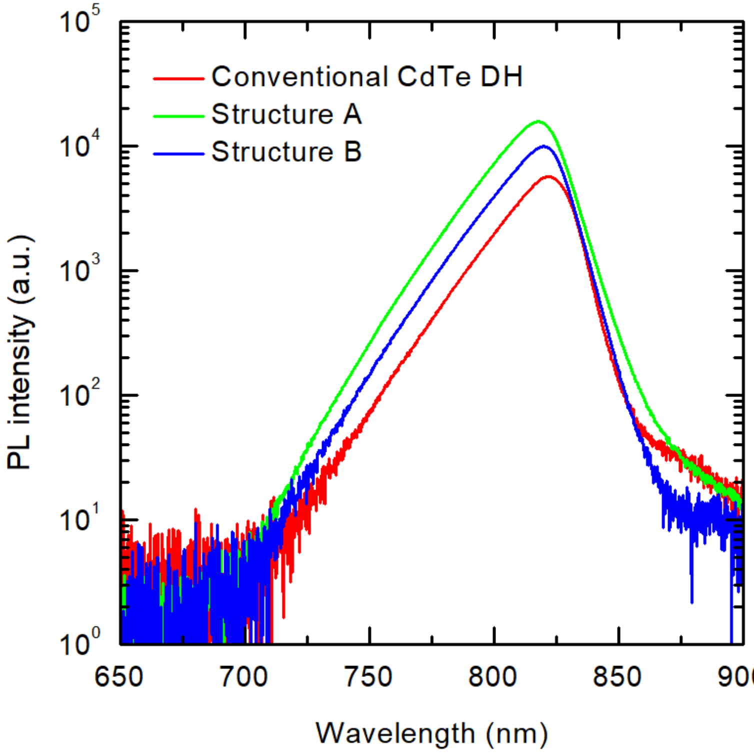
Conventional CdTe DH



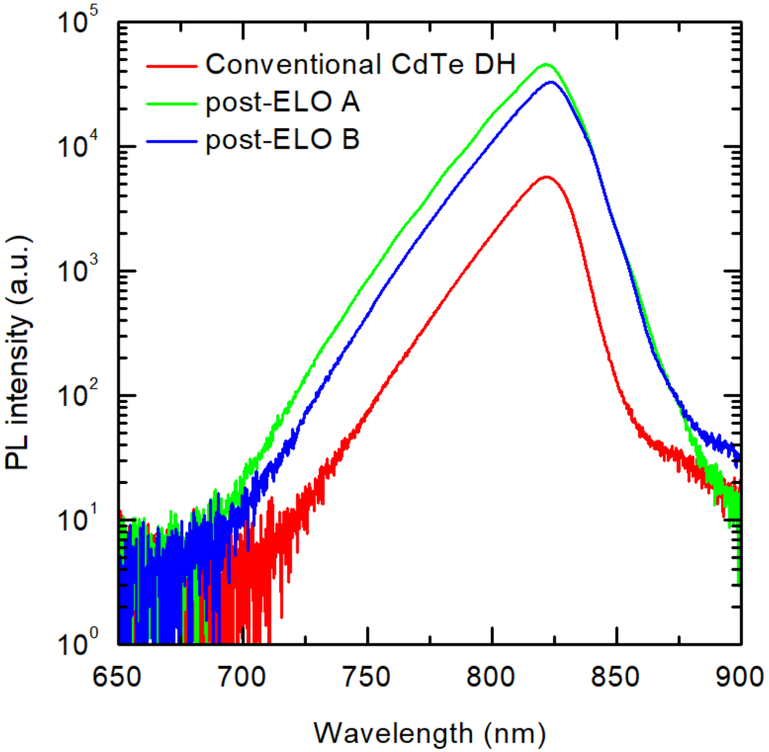
Structure A: d = 0.5 μm
Structure B: d = 1 μm



As-grown samples
before ELO

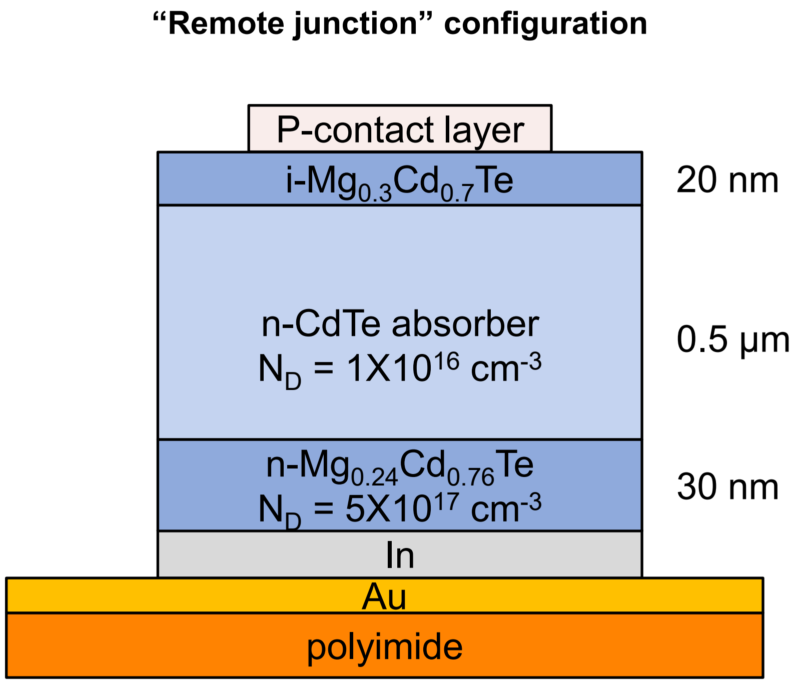


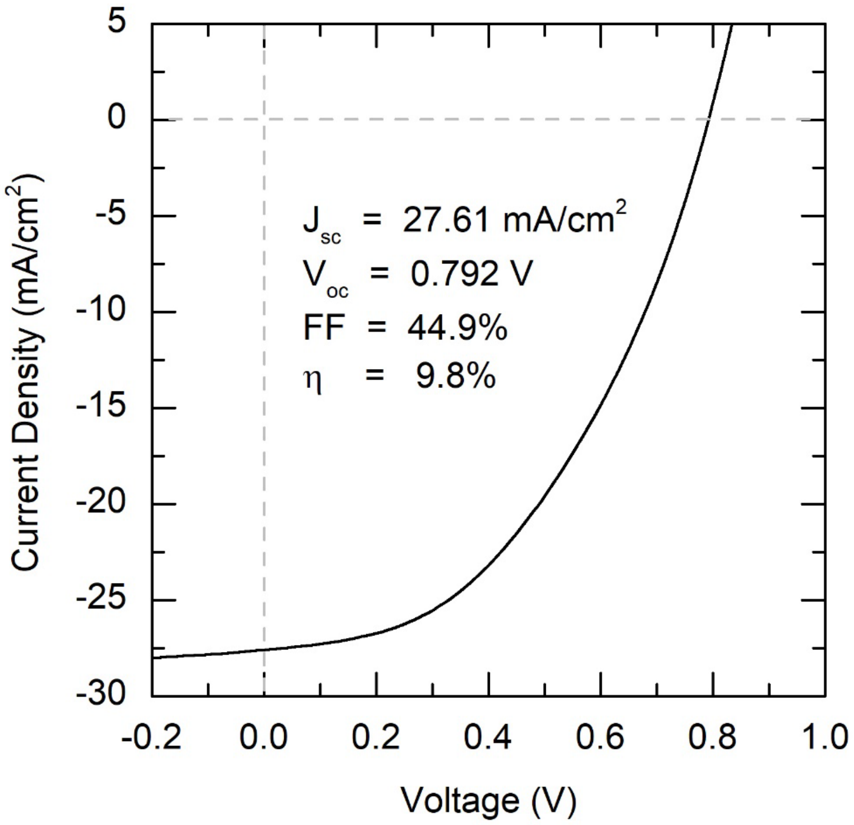
Lift-off thin films
after ELO



J. Ding, C.-Y. Tsai, Z. Ju, and Y.-H. Zhang, *Epitaxial lift-off CdTe/MgCdTe double heterostructures for thin-film and flexible solar cells applications*, APL **118**, 181101 (2021). (Featured article, Editor's pick as Scilight)

Preliminary result of CdTe thin-film devices





Summary

- Using nearly-lattice-matched, water-soluble MgTe as a sacrificial layer. High-quality CdTe DH can be grown on MgTe layer by using MBE.
- Smooth and intact lift-off surface, and enhanced optical performance of the lift-off thin films.
- CdTe lift-off thin films
  - iV_{OC} = 1.152 V
  - J_{sc} = 24.7 mA/cm^2 based on simulation
- Flexible CdTe thin-film solar cells
  - Efficiency = 9.8%, V_{OC} = 0.79 V

21.4% efficient CdSeTe/CdTe solar cells using highly resistive intrinsic ZnO buffer layers

L. Kujovic, X. Liu, M. Togay, A. M. Law, A. Abbas, L. O. Jones, K. Curson, L. C. Infante-Ortega, K. L. Barth, J. W. Bowers and J. M. Walls
Loughborough University, Loughborough, UK

O. Oklobia, D. A. Lamb and S. J. C. Irvine
Swansea University, Swansea, UK

W. Zhang, C. Lee, T. Nagle, D. Lu and G. Xiong
First Solar Inc, Santa Clara, CA, USA

j.m.walls@lboro.ac.uk

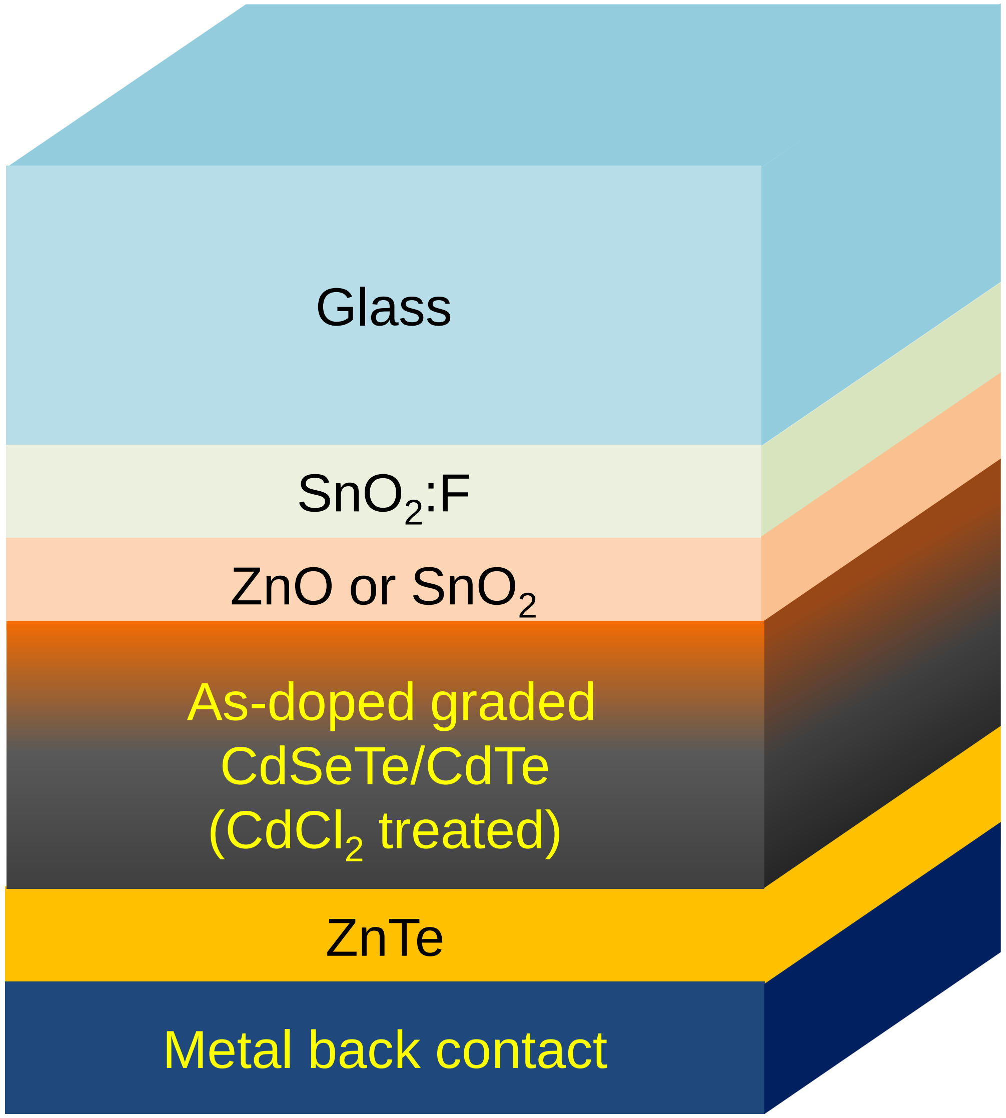
CdTe Workshop, 25th-27th October 2023

SUPERGEN SuperSolar

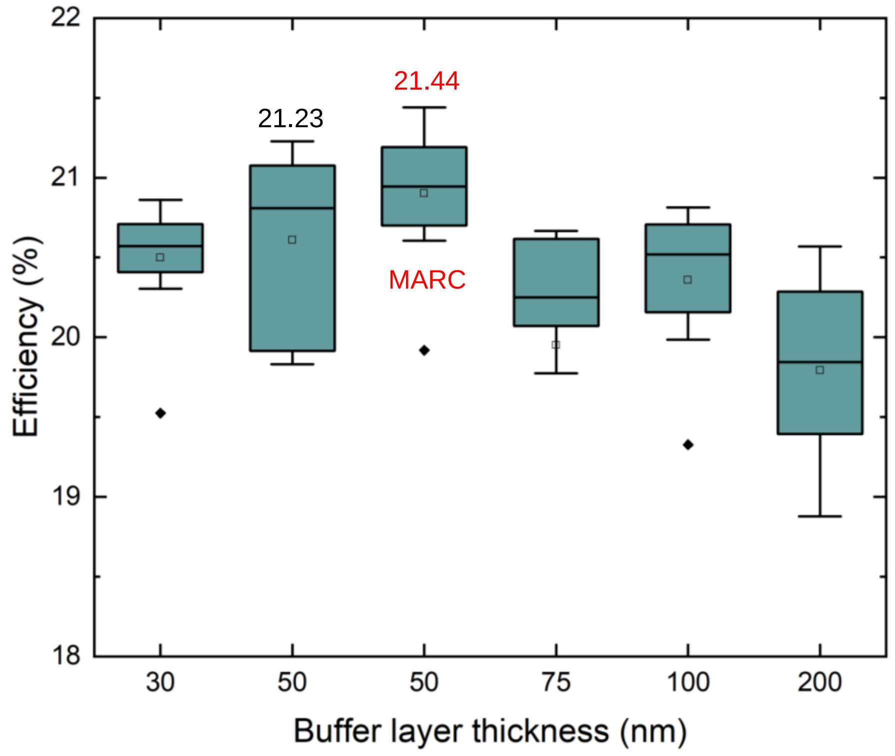
Loughborough University

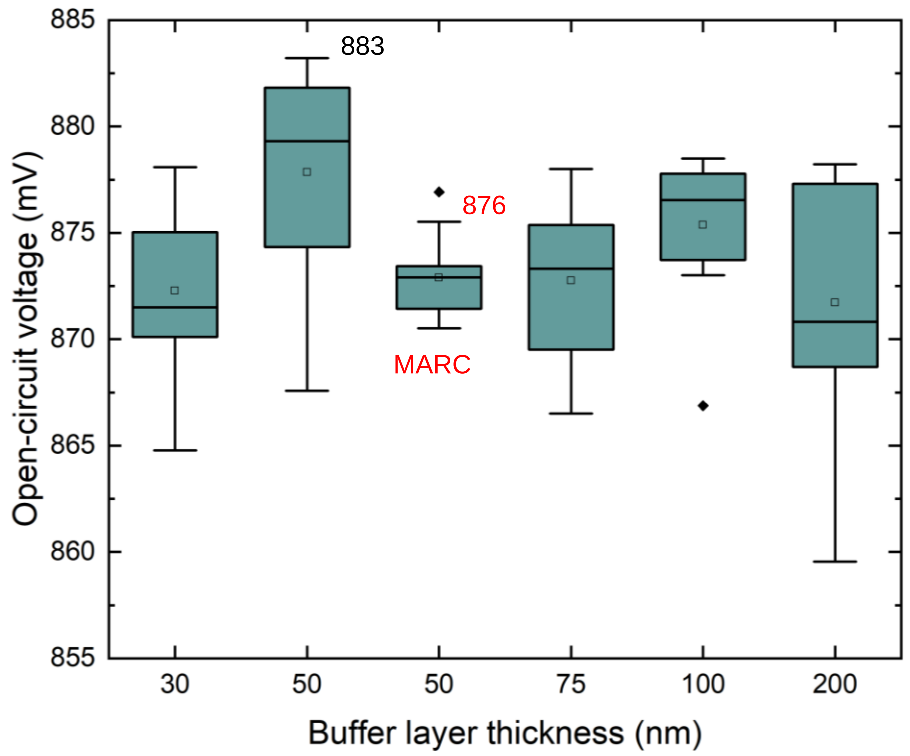
Introduction

- Intrinsic ZnO and SnO_2 buffer layers deposited on NSG TEC™ glass using RF sputtering
- The buffer layers fabricated into As-doped CdSeTe/CdTe devices at First Solar Inc



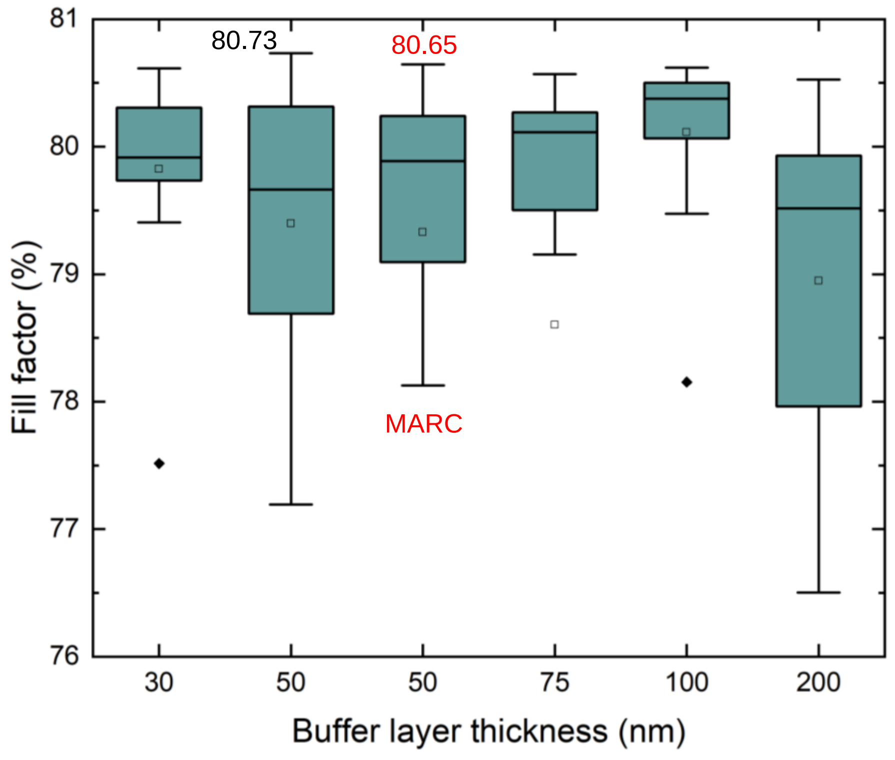
ZnO Thickness vs. Efficiency and V_{oc}

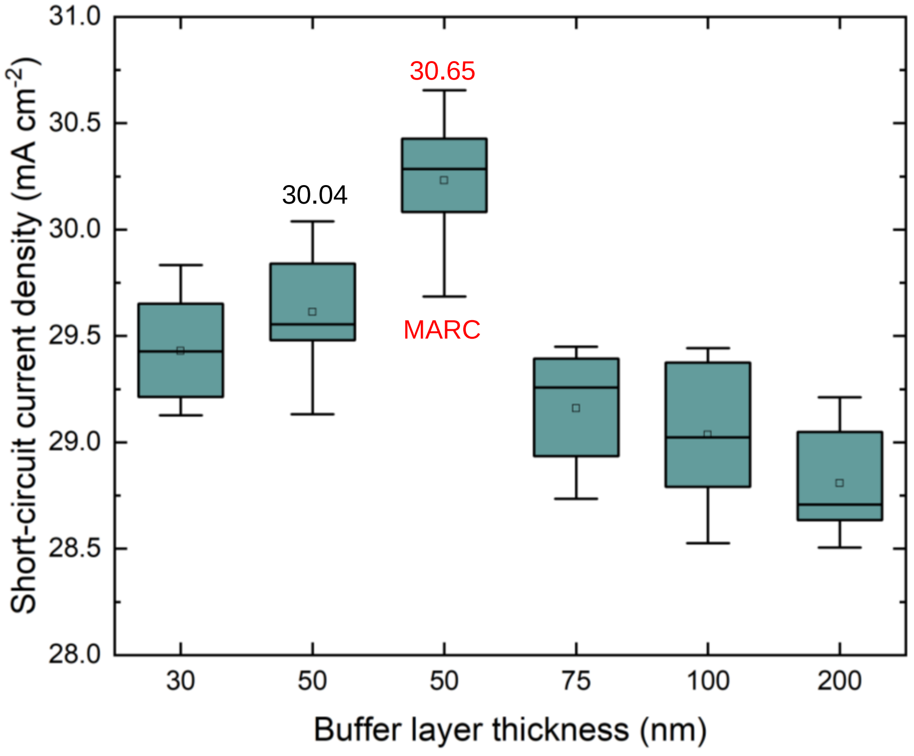




Initially, the optimal ZnO thickness was 50 nm

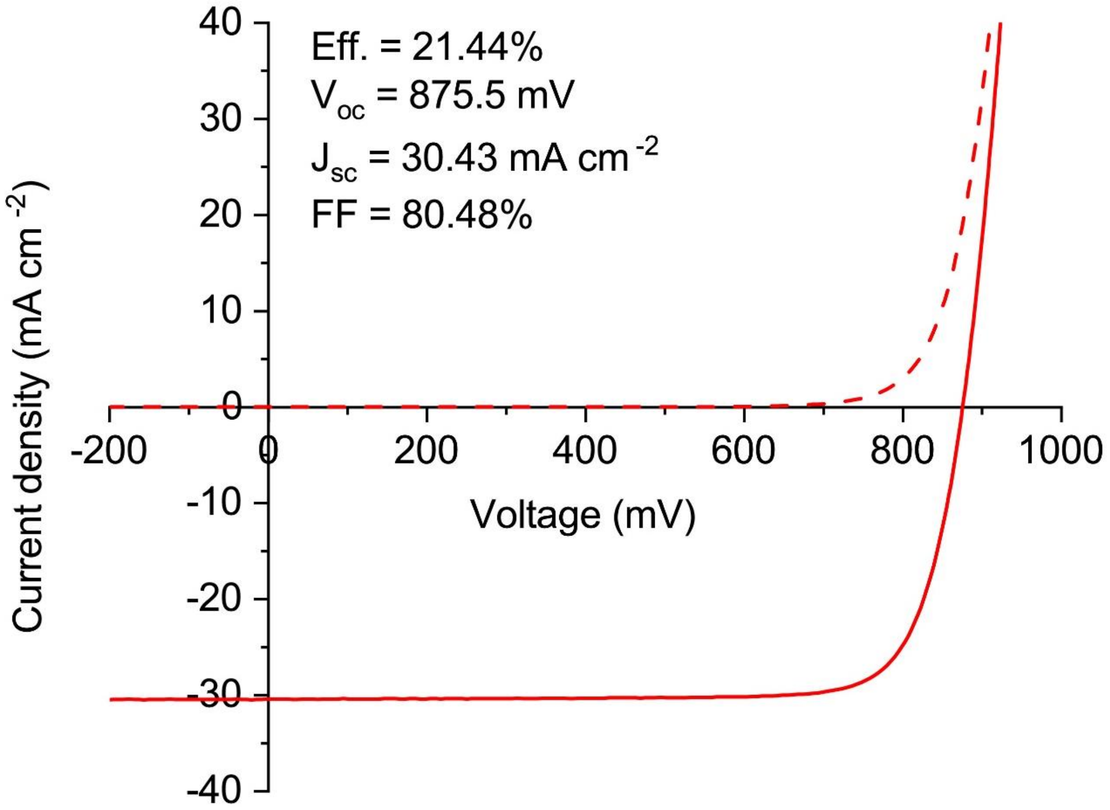
ZnO Thickness vs. FF and J_{sc}



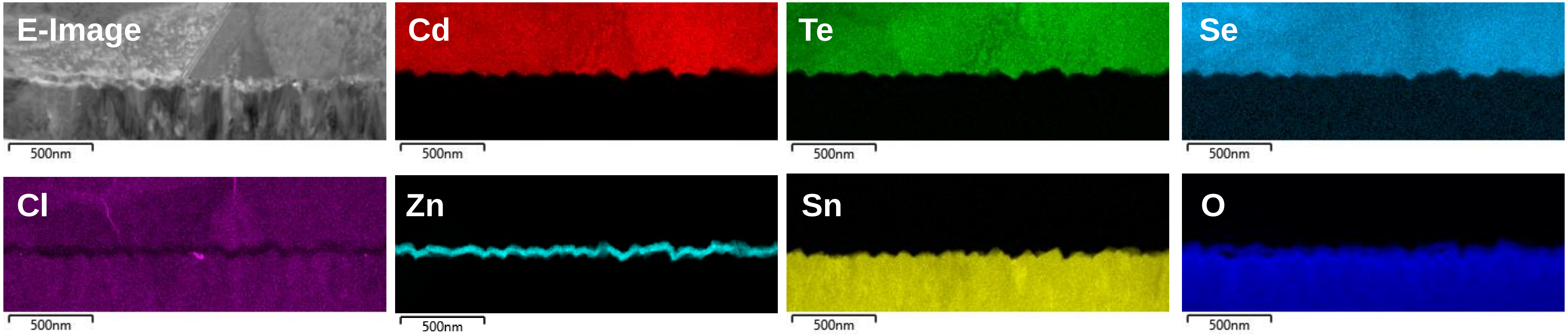


J-V

- An efficiency of 21.44% was achieved by incorporating an intrinsic ZnO buffer layer
- Pre-deposited Multilayer AR coating
- The ZnO buffer layer is 50 nm thick
- Deposited at room temperature

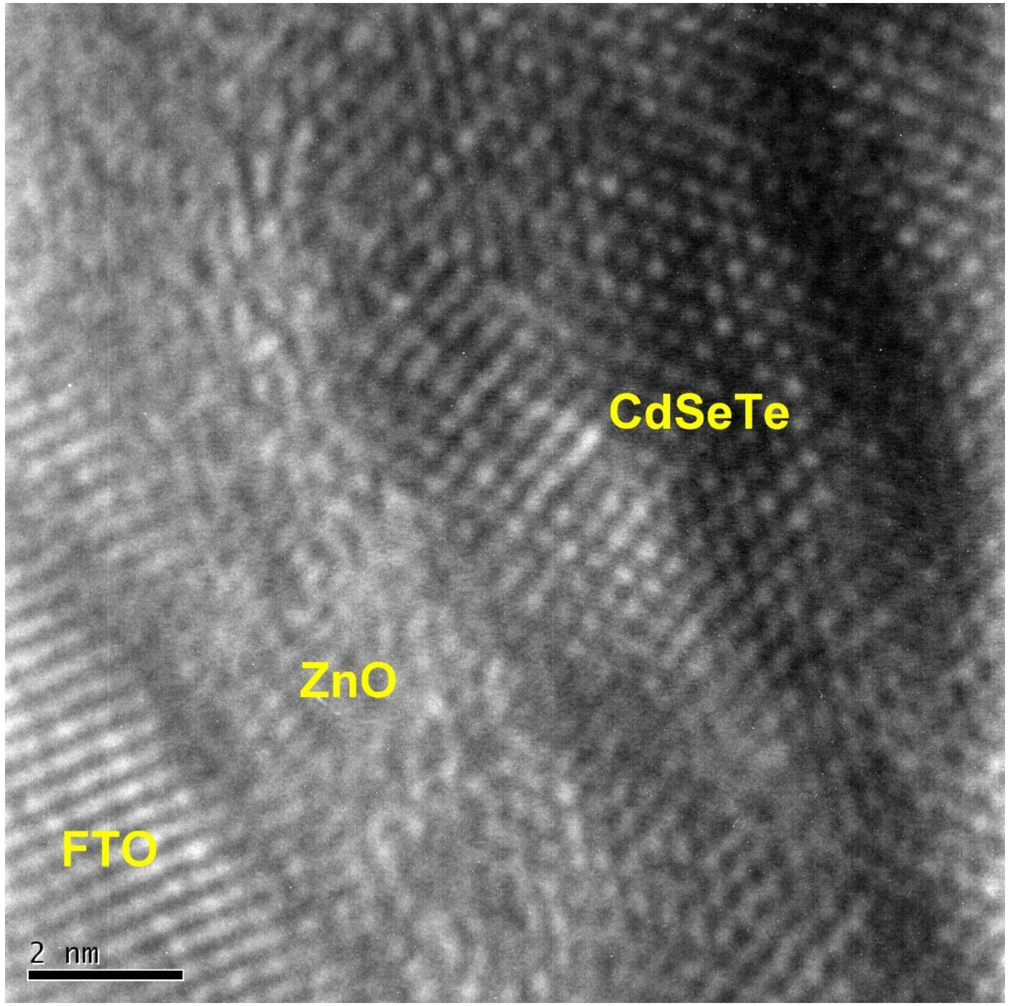


STEM-EDX



- Continuous ZnO layer, with no apparent Zn diffusion occurring during the high temperature CdSeTe/CdTe deposition or $CdCl_2$ treatment
- No CdSeTe diffusion into the ZnO is observed, showing the durability/stability of the buffer layer
- The unusual omission of Cl at the junction suggests that the microstructure of the ZnO/CdSeTe interface is of high quality

High-Resolution TEM



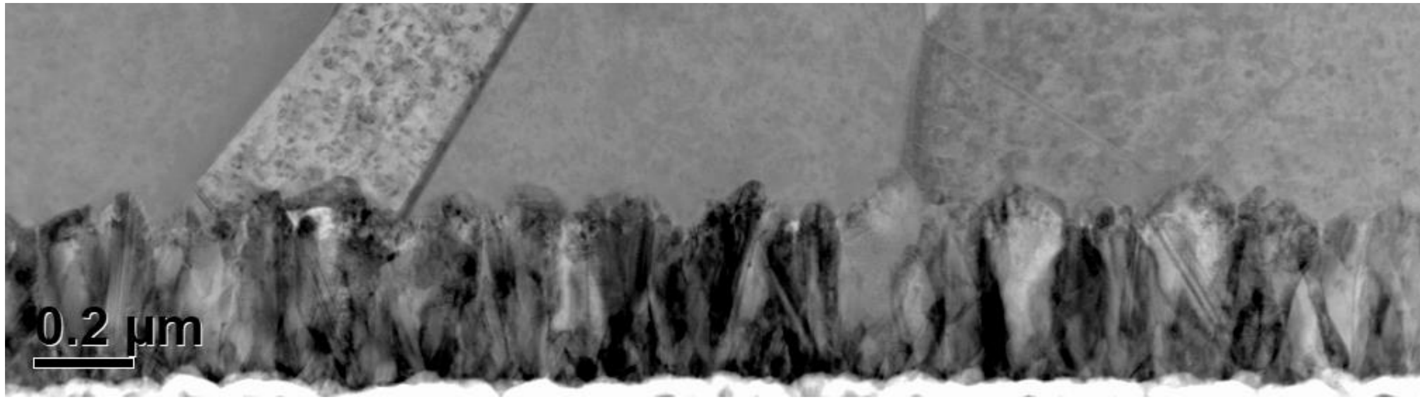
- High-quality interfaces between FTO/ZnO and ZnO/CdSeTe
- Confirms the nanocrystalline structure of the ZnO layer (ZnO deposition at room temp.)

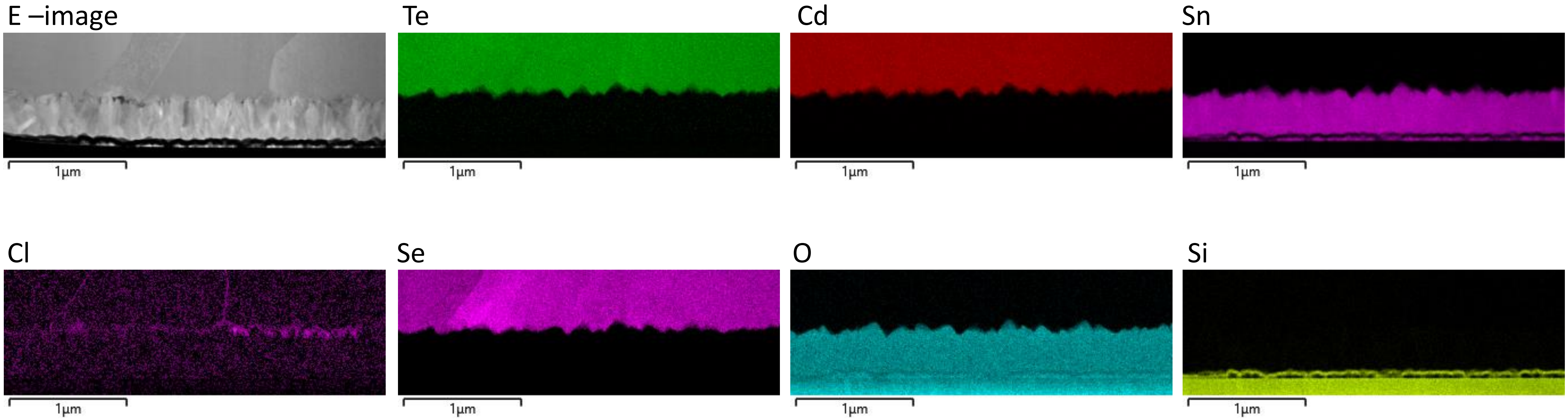
STEM-EDX: SnO2 50nm buffer layer

CdSeTe

SnO_2 50nm

FTO





Conclusions

- The optimal ZnO and SnO_2 thicknesses are 65 nm and 70 nm, respectively.

- ZnO devices have a higher efficiency, Voc and FF than SnO_2 devices. However, SnO_2 devices have a higher Jsc.

- The interface quality between ZnO and CdSeTe is exceptionally good. Chlorine is not observed in EDX.

- The carrier concentrations in the two buffer types differ by at least 6 orders of magnitude

Loughborough University

Thank you

Discussions with Eric Colegrove, Matt Reese and Craig Perkins (NREL) gratefully acknowledged.

Engineering and Physical Sciences Research Council

SUPERGEN SuperSolar

Progress and Future Directions of CdTe Devices

Dingyuan Lu, Rouin Farshchi, Chungho Lee, Xiaoping Li, Rajni Mallick, Gang Xiong

First Solar

October 26th, 2023

First Solar

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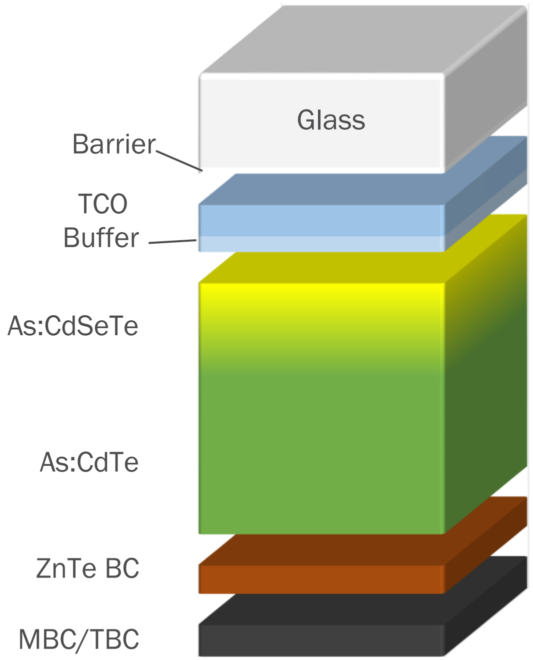
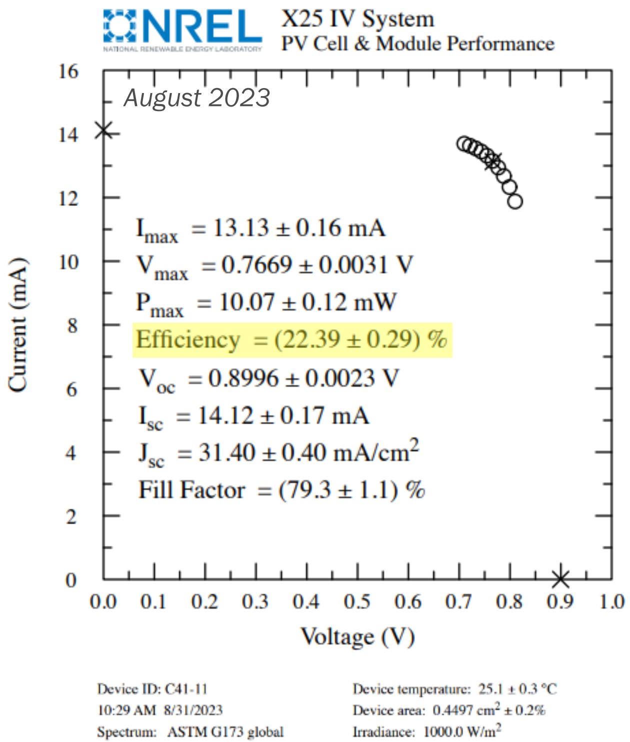
New CdTe Record Efficiency 22.4%

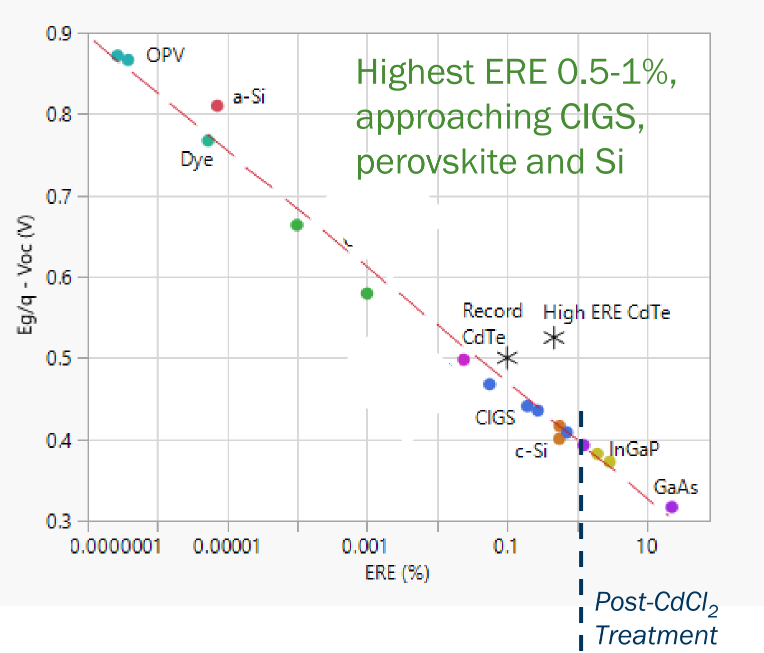




Outlook for CdSeTe:As Performance

	2023	Near-term	Mid-term
✓ Voc	900	917	1000*
✓ FF	79.3	81	82.5↑
✓ Jsc	31.4	31.7	31.7
Cell Eff.	22.4%	23.5%	>26.2%

- 23.5% from Voc and FF measured from independent cells
- 1000 mV is estimated based on 0.5%ERE



Future Directions for CdSeTe

Potential fluctuation improvement?

- How to validate? How to improve?
- Interface that is less sensitive to non-uniform absorber?
- As activation ratio: why is 3-6% and how to improve?

Back contact passivation and carrier selectivity

- For Voc, thinner absorber, and bifaciality.

High ERE (iVoc) to high Voc?

- Interpretation of contact selectivity of the material space?

Alternative dopant – phosphorus?

- Reduced sub-band defects for efficiency entitlement?
- Better activation?

Novel device structure, e.g. n-i-p?

First Solar®

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Antimony-doping Approaches for Vapor Transport CdSeTe

Bill Shafarman

Institute of Energy Conversion, University of Delaware

Bin Du, Daniel Obikoya, Ujjwal Das, Kevin Dobson, Shannon Fields, Anderson Janotti, Intuon Chatratin, Igor Evangelista

Consultant: Brian McCandless

Jason Baxter, Gregory Manoukian, Alex Ashley

Aaron Arehart, Aayush Nahar

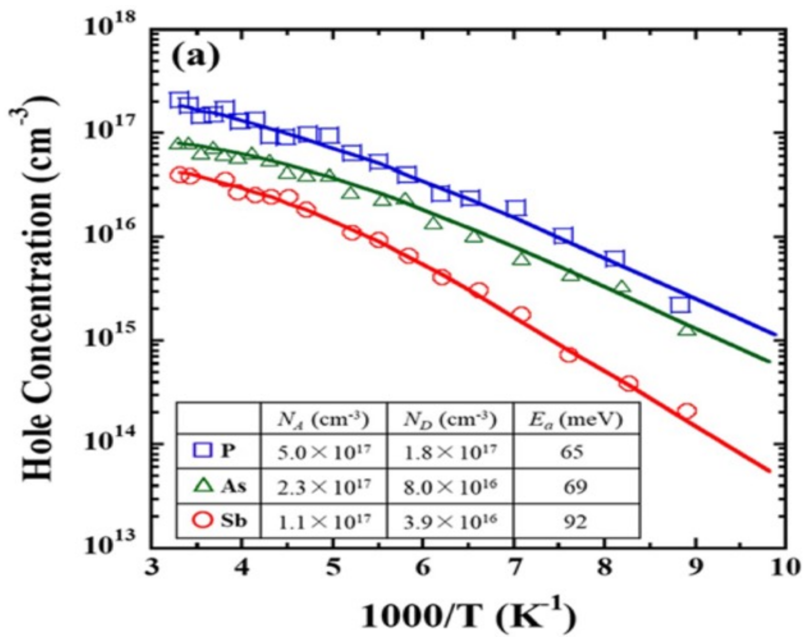
Harvey Guthrey

Award # DE-EE0009344

Group V doping of CdTe

- Temperature-dependent Hall data on doped single crystals ⇒
  P, As, Sb are all shallow acceptors with ionization energies ~ 100 meV.

A. Nagaoka *et al.*, Appl. Phys. Lett. **116**, 132102 (2020)



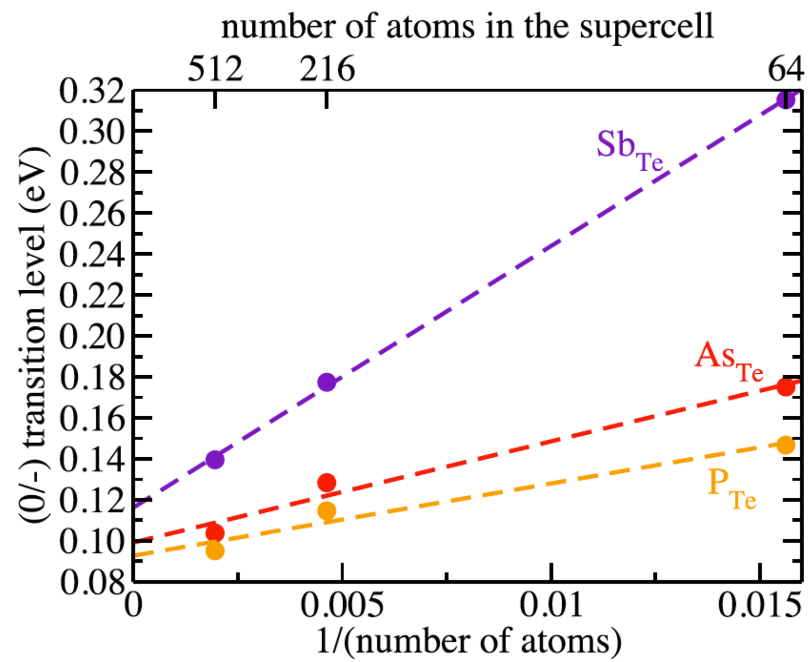
	N_A (cm^{-3})	N_D (cm^{-3})	E_a (meV)
□ P	5.0×10^{17}	1.8×10^{17}	65
△ As	2.3×10^{17}	8.0×10^{16}	69
○ Sb	1.1×10^{17}	3.9×10^{16}	92

Group V doping of CdTe

- First-principles DFT calculations for P_{Te}, As_{Te}, and Sb_{Te}

  Chatratin, et al., *J. Phys. Chem. Lett.* (2023).

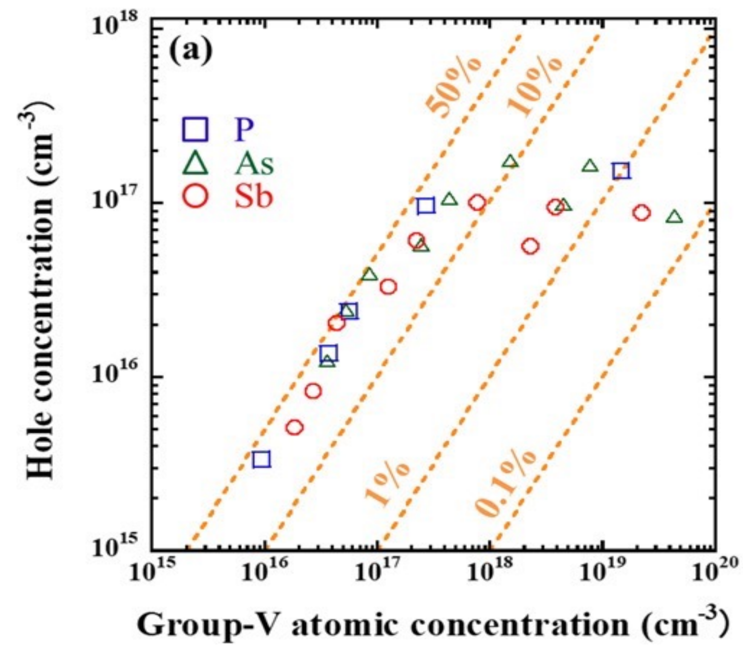
  - Use large supercell sizes and add effects of spin-orbit coupling
  - Calculate ionization energies:
    93 meV for P
    99 meV for As
    116 meV for Sb
  - Differs from earlier calculations



Group V doping efficiency

Doping efficiency (activation):
hole concentration / atomic concentration

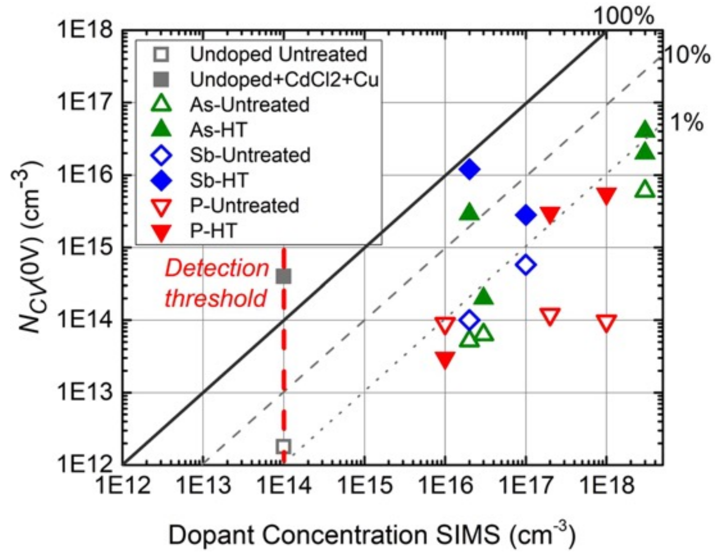
- Doped single crystals:
  doping efficiency ≤ 50% (Nagaoka)
  - compensating defects
- Thin films: typically have p/[As] ≈ 1%
  for films grown by various methods
  (VTD, evaporation, MOCVD, …)
- Potential explanations of low doping efficiency:
  - dopant clusters or inclusions
  - accumulation along grain boundaries
  - formation of compensating defect, e.g. AX centers, increased bandtails



Antimony doping of CdTe

Choice of Sb for group V dopant:

- Atomic radius: compare
  R_{Te} = 136 pm
  R_{Sb} = 140 pm
  R_{As} = 120 pm
  R_{P} = 106 pm
- VTD with in-situ Sb, As, or P ⇒ highest doping efficiency with Sb
  McCandless, et. al., *Sci. Rpts.* 8, 14519 (2018)



- Time decay of hole concentration for 2 years: "Sb-doping is more stable than As and P doping which may come from slow diffusion" (Nagaoka)

Doping considerations

Processing issues:

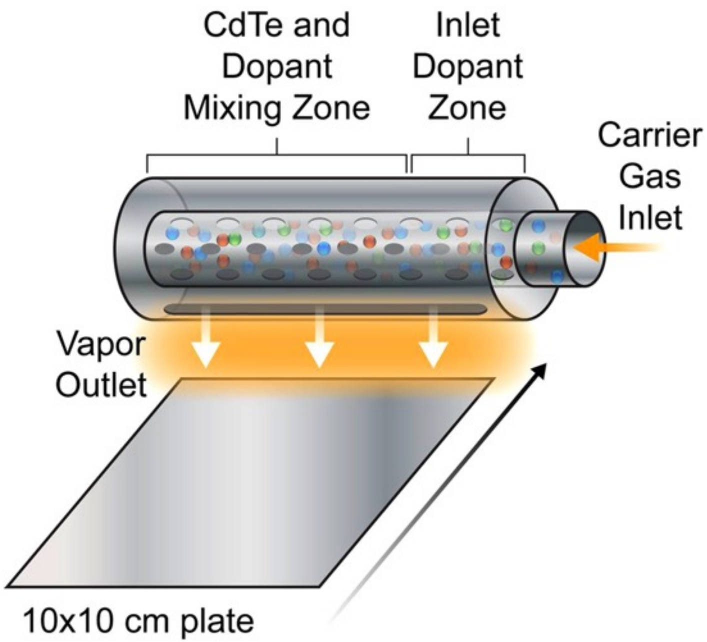
- ❑ In-situ vs. ex-situ doping – diffusion characteristics
  (Colgrove, J. Phys. D 51 075102 (2018))
- ❑ Defect formation vs. Cd overpressure during deposition and cooling rate
- ❑ Cluster formation in vapor phase processing: propose pyrolysis enhanced vapor
- ❑ Non-equilibrium growth due to doping, Se grading

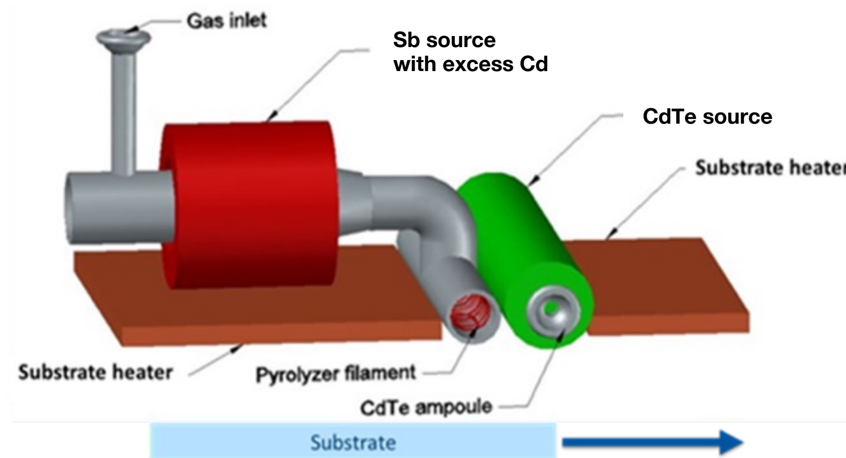
Device and electronic issues:

- ❑ Higher doping ⇒ shallow depletion width ≈ 0.3 μm
  - ➢ SRH recombination near surface, Se grading
  - ➢ Increased interface recombination (Metzger, *Nat Energy* 4, 837 (2019))
- ❑ Impact of excess dopant on recombination, lifetime

Approach: overlapping CdTe + Sb vapors

Two-stage Sb + Cd VT source with pyrolysis stage to crack Sb vapor





Sb-doped CdTe process and device fab

- Evaporated CdSeTe/CdTe layer + HTA to eliminate WZ phase
- VT CdTe:Sb with different deposition conditions
  - dopant temperature T_D, pyrolyzer temperature T_P, Cd excess
  - thickness ≈ 4 μm, translation speed = 0.5 or 1.5 in/ min
  - T_{SS} ≈ 470 C
- Device process / back contact
  - $CuCl_2$ dip anneal / graphite paste

CdTe:Sb (4 μm) [VTD]

CdTe (0.25 μm) [Thermal evap]

CdSeTe (0.50 μm) [Thermal evap]

Substrate: Tec_12D

Substrate
- Tec-12D

→ Front layer
- CdSeTe/CdTe
- HTA at 575C

→ VTD
CdTe:Sb
T_P, T_D, …

→ Back Contact
$CuCl_2$ dip
Anneal: 260C, 30 min

→ Graphite paste

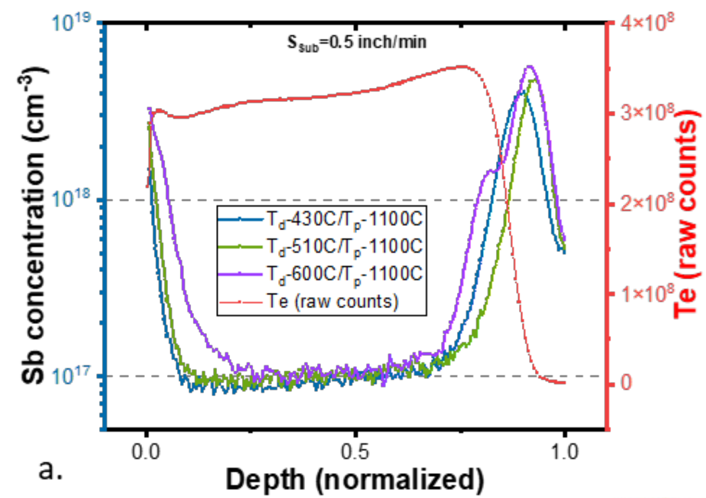
Sb flux, pyrolysis ⇒ doping efficiency

Translation = 0.5 in/min, effective growth rate = 2 µm/min

Sb source		Pyrolyzer		Doping		
T_D (°C)	Sb flux* (mole/s)	T_P (°C)	Monotonic Sb*	$[Sb]^{SIMS}$ (cm^{-3})	$p = [N_A\text{-}N_D]$ (cm^{-3})	Doping efficiency
430	0.2×10^{-9}	1100	100%	1×10^{17}	1×10^{15}	1 ± 0.2%
510	1×10^{-9}	1100	100%	1×10^{17}	4×10^{15}	4 ± 0.6%
600	5×10^{-9}	1100	100%	1×10^{17}	2×10^{16}	20 ± 3%

* calculated

- Sb flux increase by 25X with no change in film concentration
  - limitation of doping source
- Increased carrier concentration
  - doping efficiency ≤ 20% with $p = [N_A\text{-}N_D] = 2 \times 10^{16}$ cm^{-3}
  - uncontrolled change in Cd flux
  - also affects V_{OC} in devices



a.

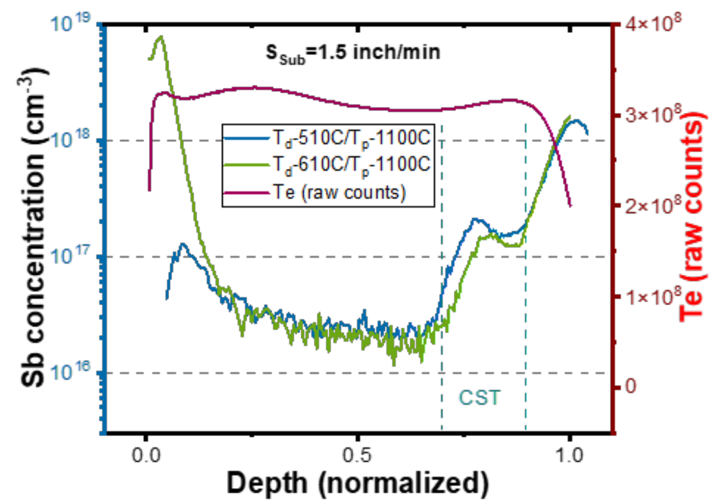
Sb flux, pyrolysis ⇒ doping efficiency

Translation = 1.5 in/min, effective growth rate = 6 μm/min

Sb source		Pyrolyzer		Doping		
T_D (°C)	Sb flux* (mole/s)	T_P (°C)	Monotonic Sb*	$[Sb]^{SIMS}$ (cm^{-3})	$p = [N_A-N_D]$ (cm^{-3})	Doping efficiency
510	1×10^{-9}	805	10%	2×10^{16}	4×10^{14}	2 ± 1%
510	1×10^{-9}	1100	100%	2×10^{16}	1.5×10^{15}	9 ± 4%
610	6×10^{-9}	1100	100%	2×10^{16}	3.3×10^{15}	20 ± 9%

* calculated

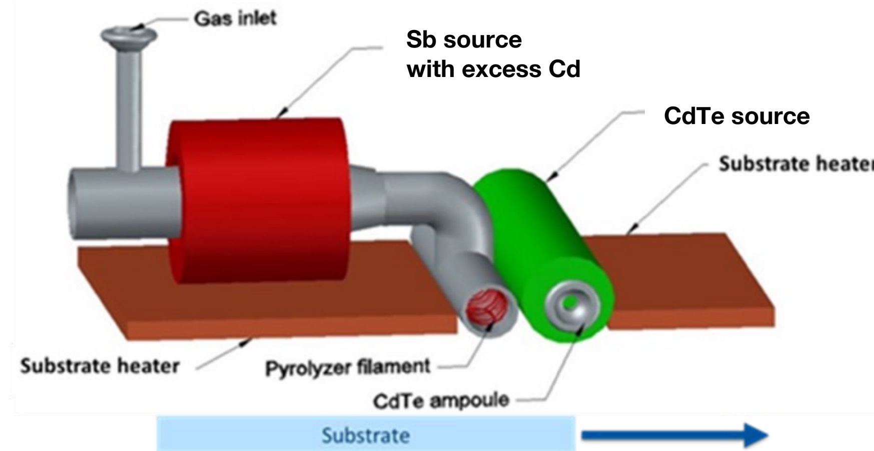
- Sb flux increase by 6X with no change in film concentration
- Increased carrier concentration by 4X with pyrolysis of Sb flux
  - doping efficiency ≤ 20%
- Diffusion of Sb into evaporated graded CdSeTe front stack



Doping source upgrade

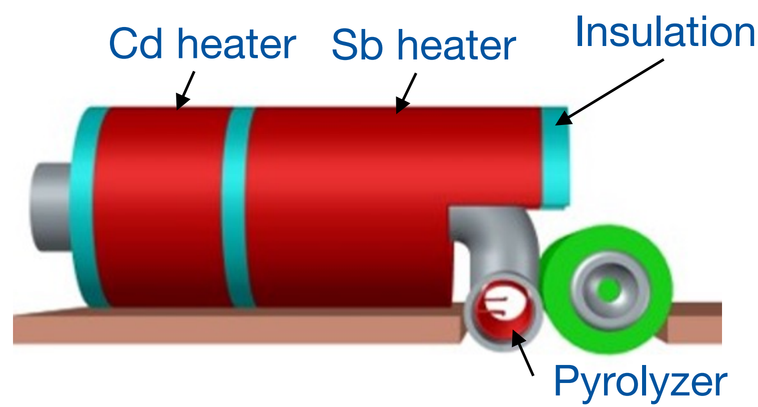
Gen.1 source

- Condensation at elbow limits Sb flux
- Cd and Sb sources at same temperature



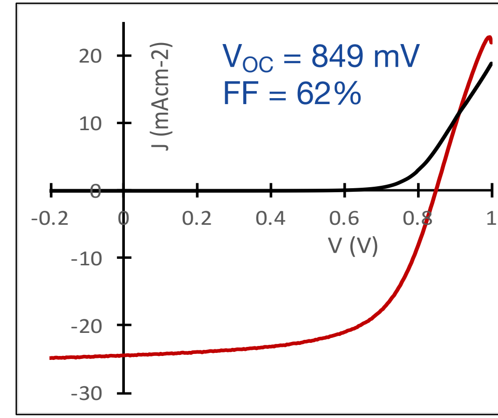
Gen.2 source

- 2-zone heater for independent control of Sb and Cd fluxes
- Extended heater to eliminate condensation at cold zones



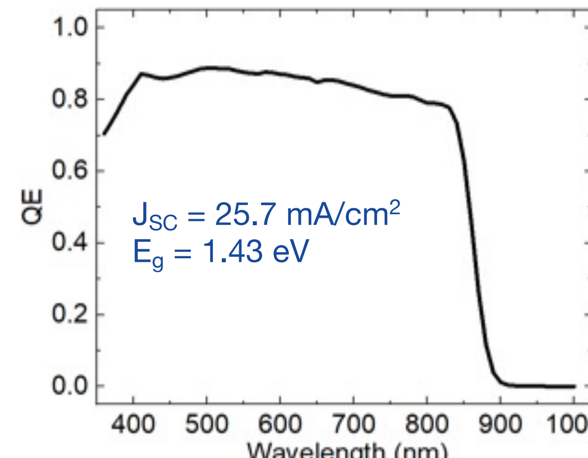
Carrier Dynamics

- Lifetime determined by global fitting of TRTS and TRPL with transport equations
  Manoukian et al.
- CdTe:Sb and CdSeTe:Sb deposited on Al_2O_3 passivation layer
- Lifetime > 10 ns for CdTe:Sb
  > 30 ns for CdSeTe:Sb
- Sb has minimal impact on lifetime: $p \leq 5x10^{15}$ cm^{-3}



Device Results

- Baseline process ⇒ V_{OC} = 830-850 mV
  W_{OC} = 600 mV
  - but aggressive $CdCl_2$ treatment lowers carrier concentration to mid-10^{14} cm^{-3}
  - efficiency limited by non-optimized back contact ⇒ low FF

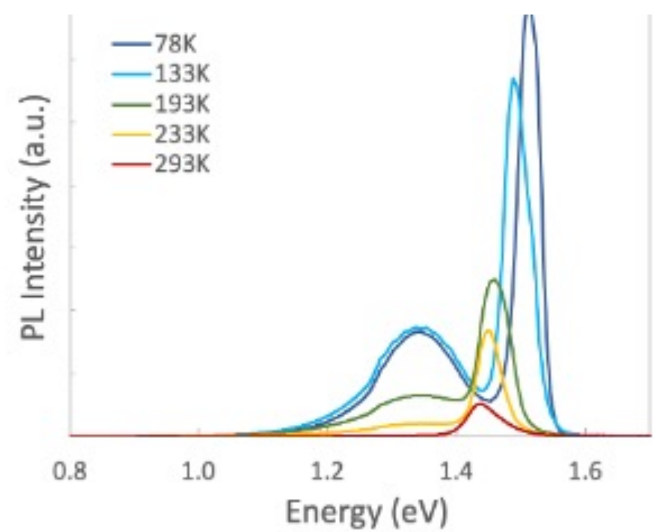


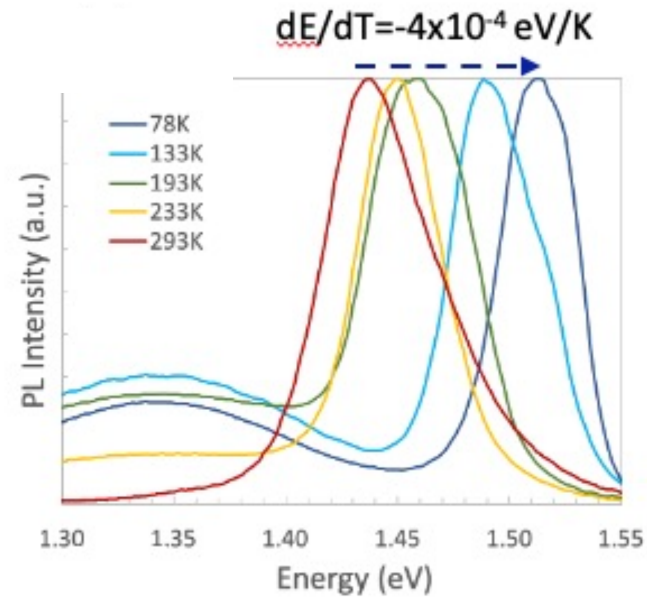
Temperature-dependent PL of CdSeTe:Sb

- Bandgap emission dominates PL with relatively small sub-bandgap emission
- Blue-shift with decreasing temperature
- Differs from sub-bandgap dominated PL with red-shift reported for CdSeTe:As

  Kuciauskus et al. *Adv. Energy. Mat.* 13, 2301784, 2023

$p = 5x10^{15}\ cm^{-3}$





PL measurements by Calvin Fai and Chuck Hages, U. Florida

Conclusions

- Vapor transport CdTe with in-situ Sb-doping
  - 20% doping efficiency in CdSeTe:Sb sample at p = $[N_A-N_D] > 10^{16}$ cm^{-3}
  - Sb -pyrolysis enhanced doping efficiency by 4X
  - Identified need to control Cd-overpressure and Sb flux ⇒ Gen.2 doping source
- CdSeTe:Sb device with V_{OC} = 850 mV
- Lifetime > 30 ns for CdSeTe:Sb,
- Low-T PL dominated by blue-shifted bandgap emission
  – potential for reduced loss from bandtails, fluctuations
- More details on CdSeTe:Sb at 7th CdTE Workshop:
  - Greg Manoukian: Quantifying carrier dynamics and PL characterization of antimony-doped CdTe and CdSeTe
  - Bin Du: Pyrolyzer assisted Sb-doped CdTe deposition
  - Aaron Arehart: Defects and Doping in Sb-doped CdTe
  - Anderson Janotti: Theory of Formability and Diffusivity of Point Defects and Impurities in Cd(Se,Te)

Detailed physical modeling for prompt actionable feedback to process development

Dmitry Krasikov
Igor Sankin
Kevin McReynolds

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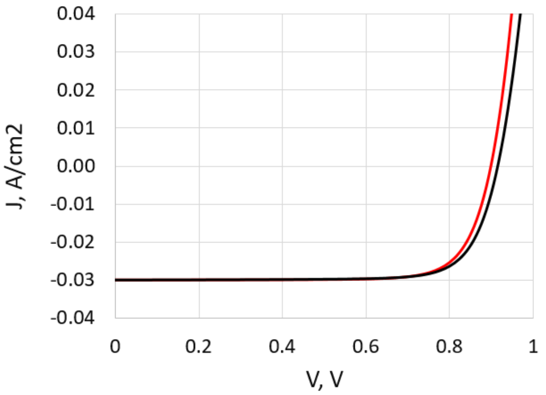
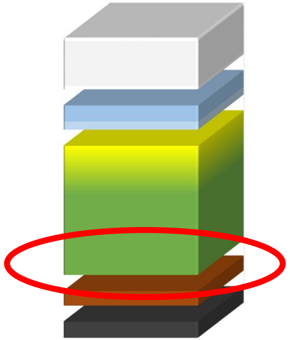
Goal

To diagnose physical reasons behind small performance changes



Compare signals with reference device



- Analyze losses
- Find out what actually changed in the device

Provide intel for process improvement

Physical modeling of CdSeTe PV device

- Mature technology, complex device structure
  - Small process/design changes – small Eff improvements
  - Multi-layer thin-film heterojunction diode with graded absorber
  - Downstream changes impact “upstream” layers and vise versa
- Purpose of device modeling
  - Diagnose physics behind small changes in performance
  - Analyze losses and suggest improvement pathways
- Challenges
  - Comprehensive model (tens of params) to capture small changes
  - Most of parameters cannot be measured directly – must be fitted
  - Fast feedback required to guide process development

Components of solution

Physical model	Model parametrization	Analysis
Comprehensive physical description	Global optimization in 20+D parameter space	Identity/Quantify loss components
Efficient/robust numerical solver	Experimental constraints (measurement)	Compare w/reference, Suggest improvement

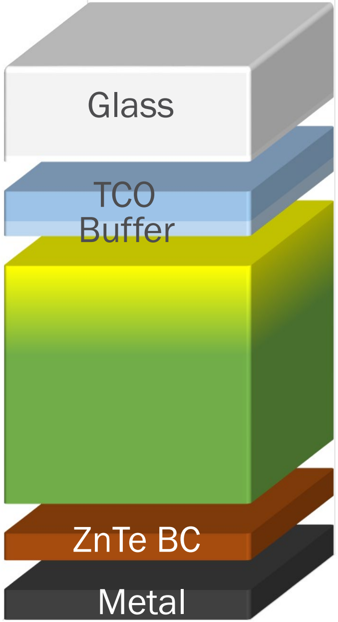
- Robust and efficient technique to enable accurate and unique parametrization – key challenge. Welcome any help from community!
- Details and current status in the following slides

Detailed physical description

Comprehensive description required to capture/quantify small performance changes caused by small process changes

- 65+ parameters total
- ~20 measurable parameters
- ~25 parameter values from 1st principle studies or assumed based on previous modeling

➢ *20+ key params must be fitted*



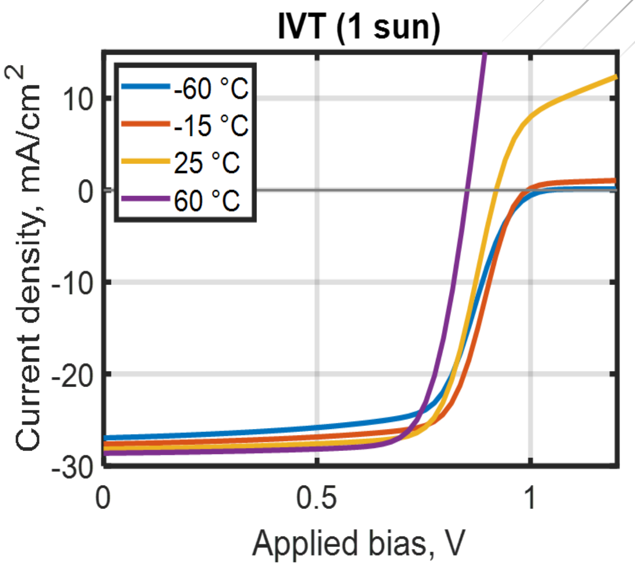
Front IF:
CBO, deep, shallow acceptors (density, $\sigma_{e/h}$)

Absorber:
Compensated doping, non-shallow acceptors, graded Se%, stoichiometry-dependent properties(E_g,χ,σ,τ,μ)

Back IF:
VBO, deep, shallow donors (density, $\sigma_{e/h}$)

Efficient and robust numerical solver

- **Fast:** ≥40 times faster than SCAPS (parallel simulation on workstation)
- **Robust:** compensated doping, charge trapping, IF barriers, high IF defect density, low temperatures
- **Flexible:** any number of layers and defects, grading functions, stoichiometry-dependent properties
- **Can do:** Sunny- and film-side light/dark IV(T), QE(T), ERE



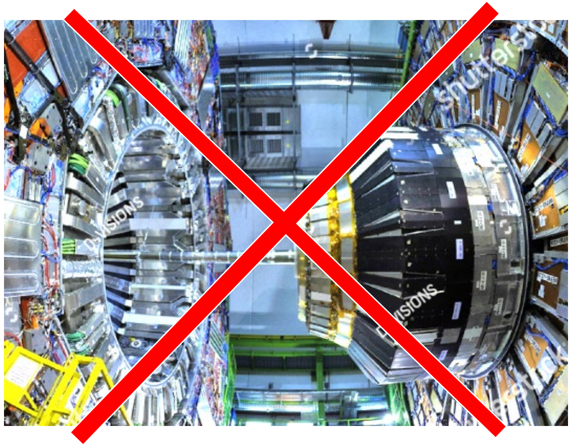
Example: challenging IV(T) set simulated in less than 1sec on single core

Choice of experimental constraints

To fit model parameters, we need experimental signals that are:

1. Easy to interpret
2. Fast to measure
3. Fast to simulate
4. Provide sufficient constraints to ensure model uniqueness

➢ **Light/Dark IV(T) is the first choice**



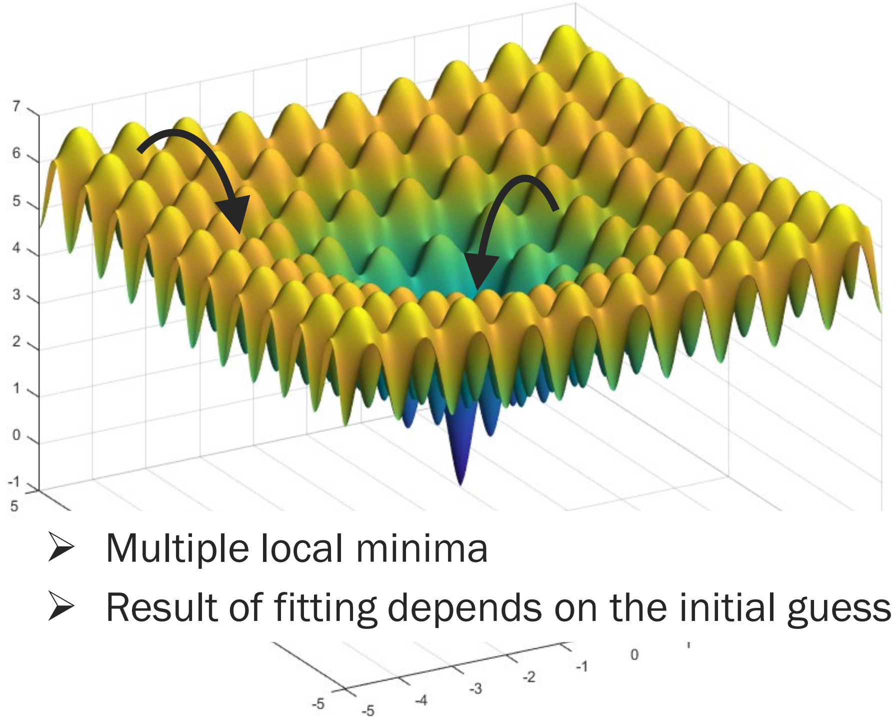
Model parametrization

Parallel fitting starting from hundreds of initial guesses to:

✓ Find global minimum in multi-dimensional parameter space

✓ Analyze model non-uniqueness

$$\text{Error}(\mathbf{P}) = f(IVT_{exp} - IVT_{model}(\mathbf{P}))$$



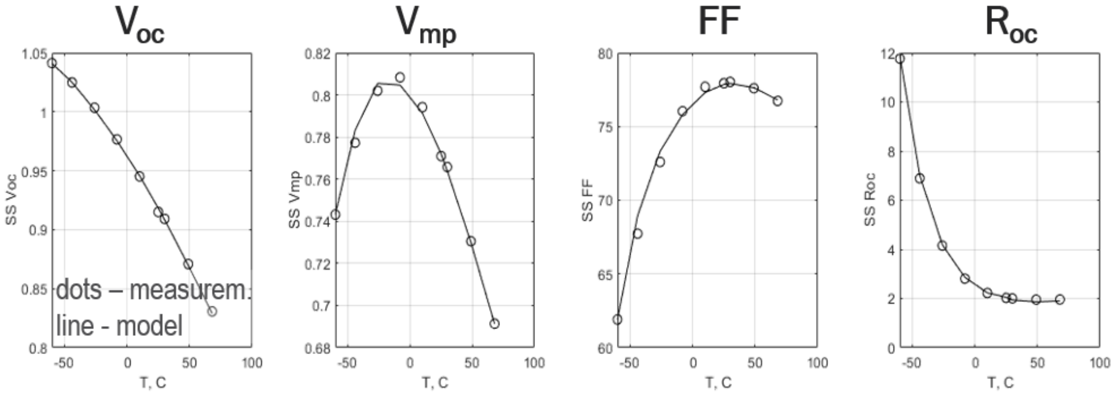
- ➢ Multiple local minima
- ➢ Result of fitting depends on the initial guess

Current status: non-unique fit with 4-pack

Model #1:

Front IF recomb = 0.1%

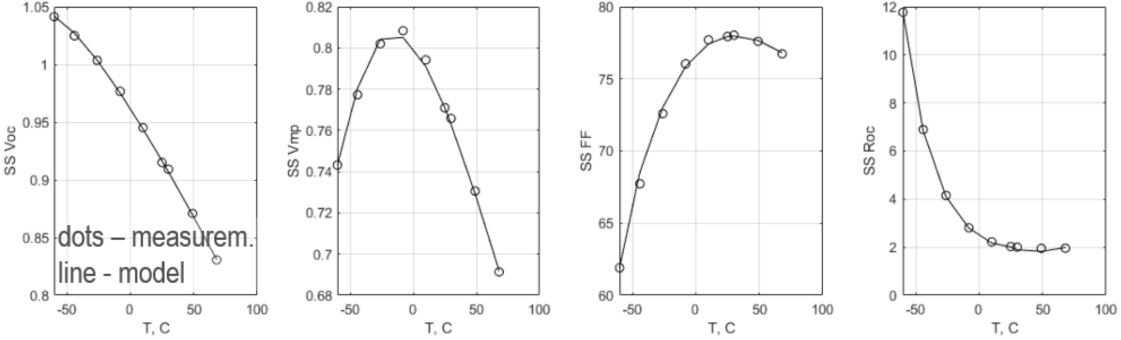
CBO=-0.50 eV, less IF defects



Model #2:

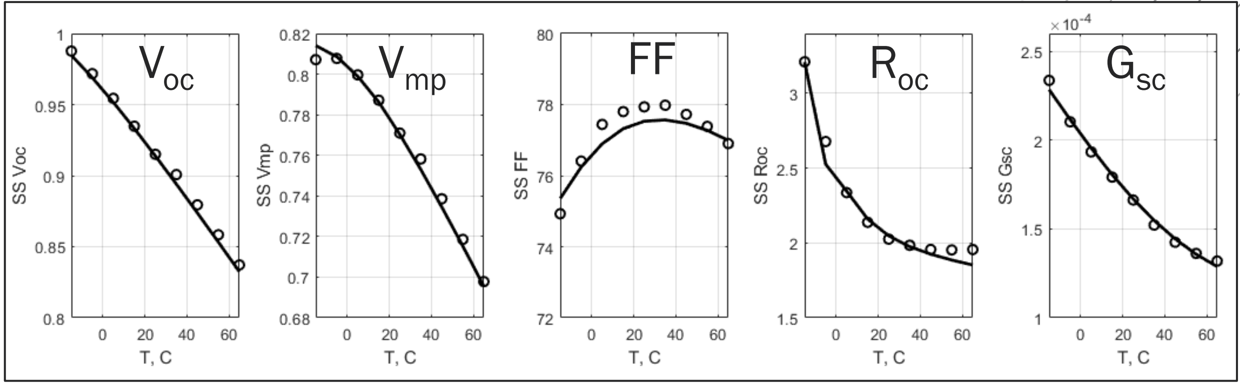
Front IF recomb = 43%

CBO=-0.37eV, more IF defects



Current status: adding additional constraints (5-pack)

- More difficult to fit with G_{sc}
- More unique model



Some low-level model parameters

CdSeTe: $\tau_p >> \tau_n$

CdSeTe: recomb. on main acceptor ($\sigma_n >> \sigma_p$)

CBO = –0.4eV

Breakdown of recombination losses

	Recombin, %	
Region	**At MPP**	**At OC**
Front contact	9.7	19
Absorber	90	80
Back contact	0.3	1

Quality(eff entitlement) of absorber and contacts

Entitlement of	Eff, %
Front contact	23.3%
Absorber	22.1%
Back contact	27.5%

Key messages

- Simplistic model cannot capture/quantify small performance changes and ensure correct conclusions – comprehensive description is required
- "Advanced" characterization is not practical for rapid device diagnostics based on physical device model; IV(T) is enough to constrain model
- Efficient parametrization in multi-D space remains key challenge - Math and data science support are welcome!

LEADING THE WORLD'S
SUSTAINABLE ENERGY FUTURE

Voc Loss Analysis: Combining Simulation with Characterization

Marco Nardone, Sakshi Gupta, Eva Mulloy

Bowling Green State University
Dept. of Physics and Astronomy

CdTe PV Workshop
NREL, Golden, Colorado
Oct. 26, 2023

Bowling Green State University

Outline

- Quantify Voc losses – front interface, back interface, bulk.

- Integrate Data and Modeling:
  - JVTi, QE, TRPL, PL analysis and simulations for comparison to data.

- JVTi simulations over a broad parameter space:
  - front interface conduction band offset, ΔE_c or CBO
  - front interface recombination velocity, S_f
  - bulk non-radiative lifetime, τ
  - temperature and light intensity, *T* and *I*
  - back interface recombination velocity set to $S_b = 10^5$ cm/s, consider impact after other parameters

<u>NREL Device V617</u>:

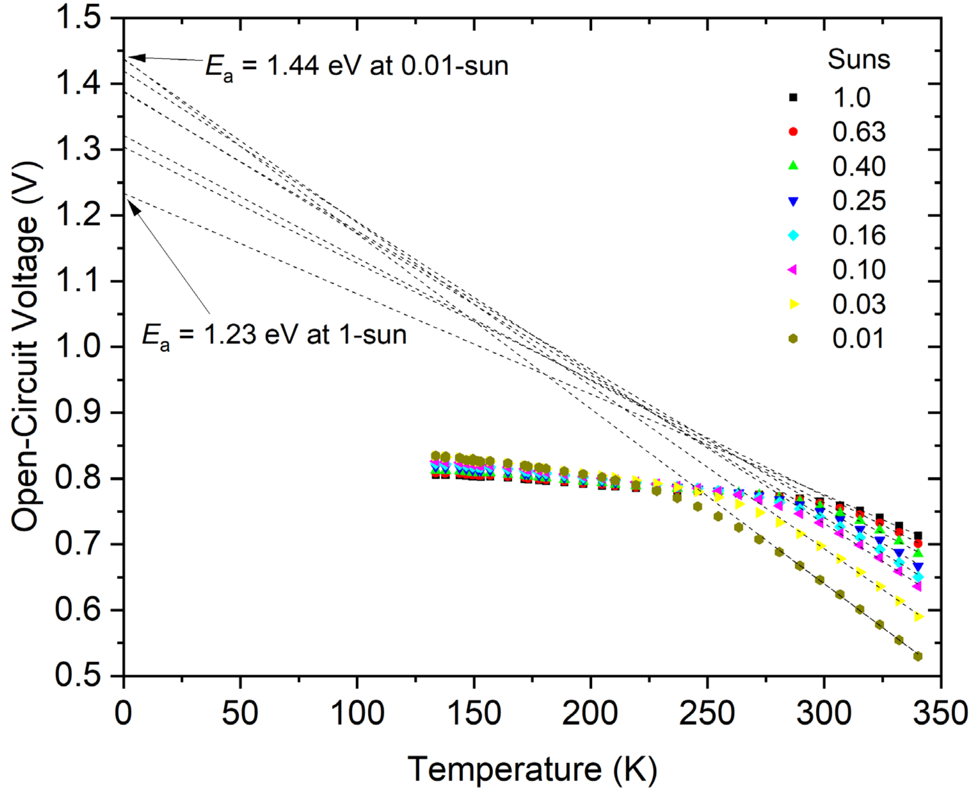
- TEC12D/CdSe0.3Te0.7(500nm)/CdTe(250nm)/CdTe:As(~2.5um)
- Post-VTD densification anneal – 575C-10m
- CdCl2 = 450C-60m
- Doping from CV: $N_A \sim 2\text{x}10^{16}$ cm^{-3}
- Data available: JVTi, QE, TRPL, absolute PL

	V617
V_{oc}	0.742
J_{sc}	29.4
FF	72.9
η	15.9

JVTi Data

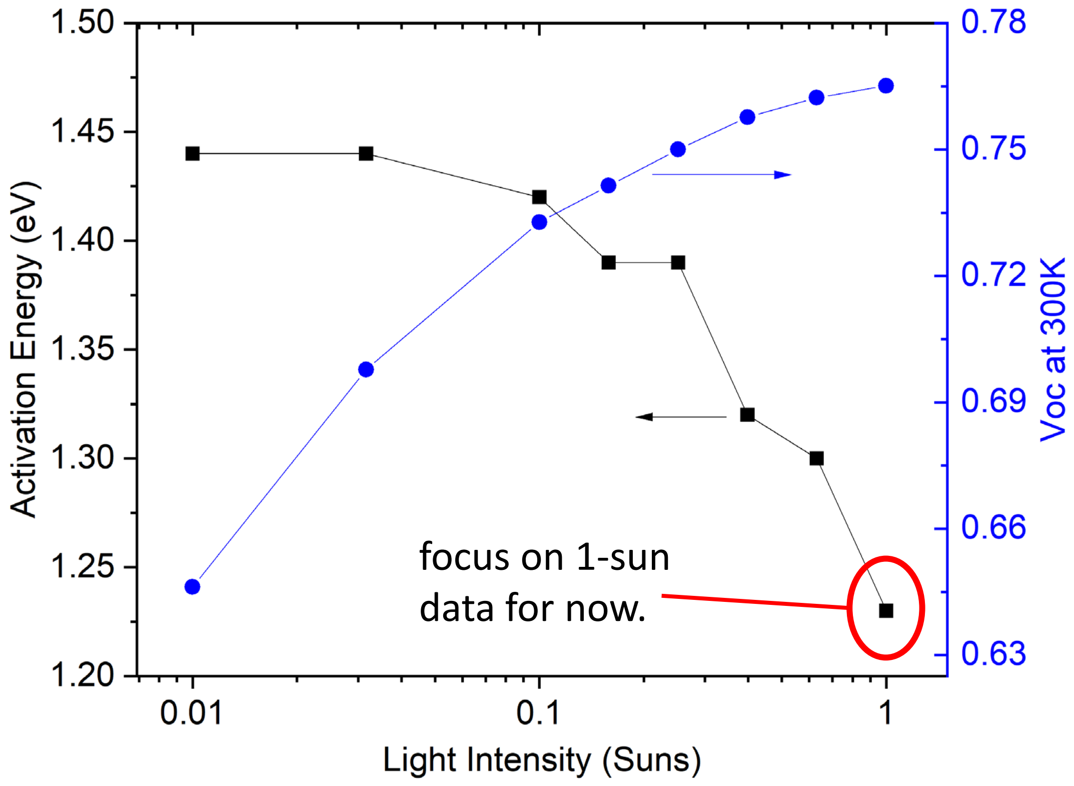
<u>Voc vs T at various light intensities</u>

$$V_{oc} = \frac{AkT}{q}\ln\left(\frac{J_{sc}}{J_0}\right) = \frac{E_A}{q} - \frac{AkT}{q}\ln\left(\frac{J_{00}}{J_{sc}}\right)$$



JVTi data courtesy of Steve Johnston (NREL)

<u>E_a and V_{oc} dependence on light intensities</u>



JVTi Study

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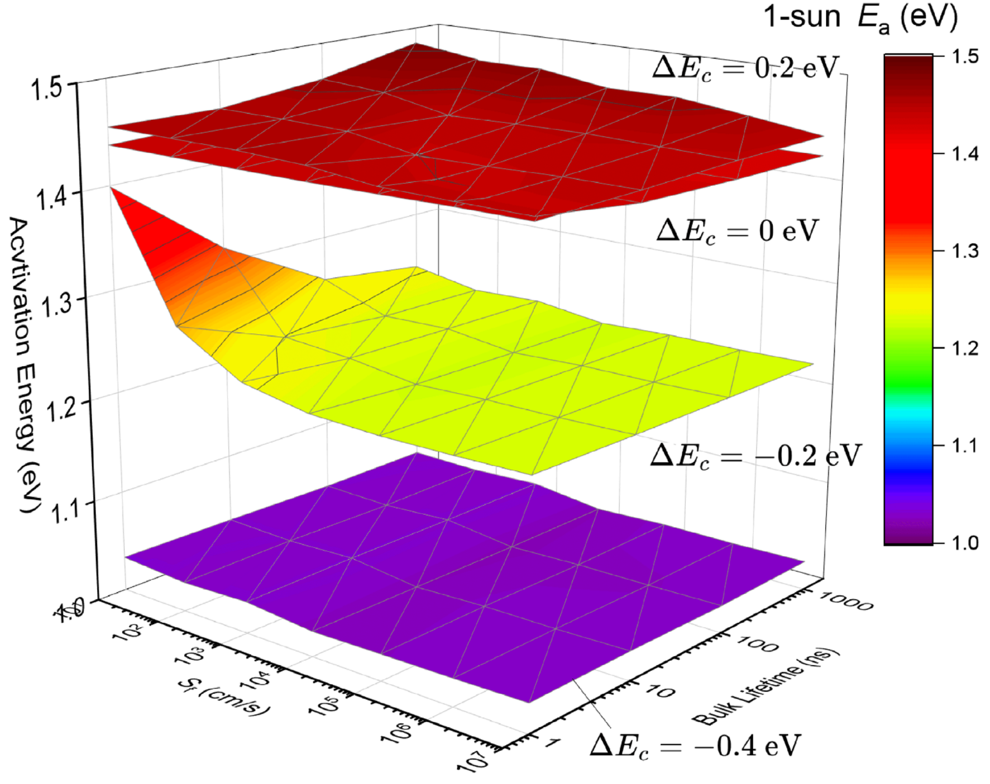
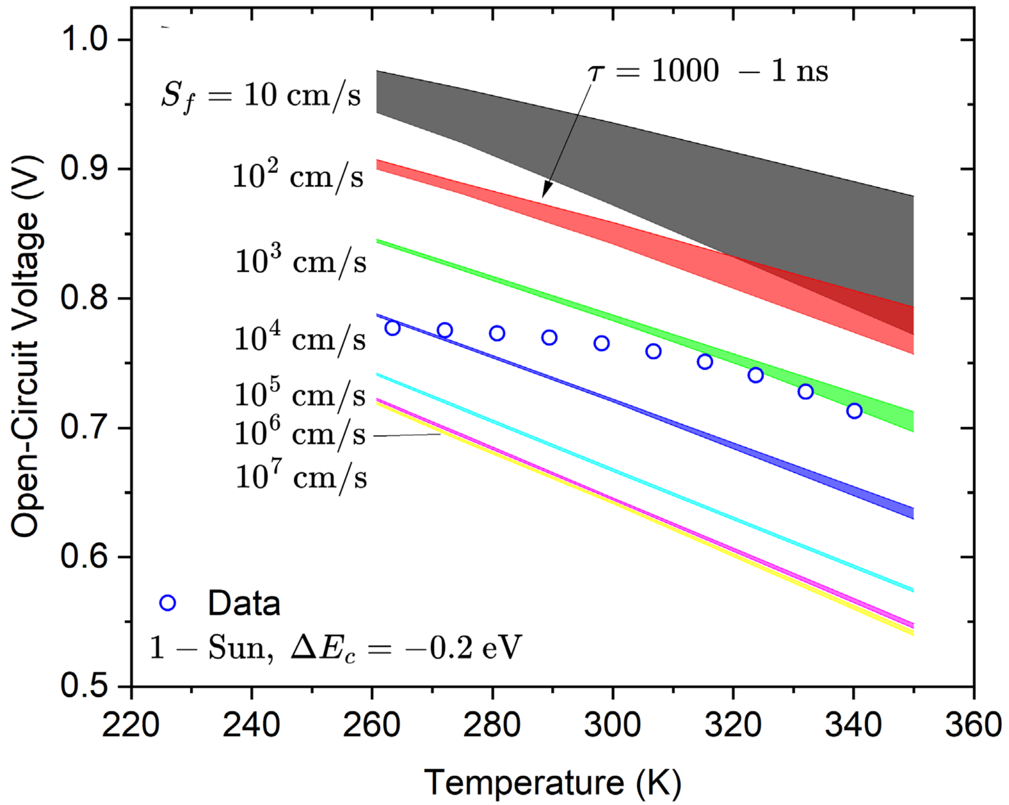
Activation energies from simulated JVT at 1-Sun



- Modeling indicates that measured E_a ~ 1.23 eV requires CBO ~ -0.2 eV (cliff) over a wide range of S_f and τ.

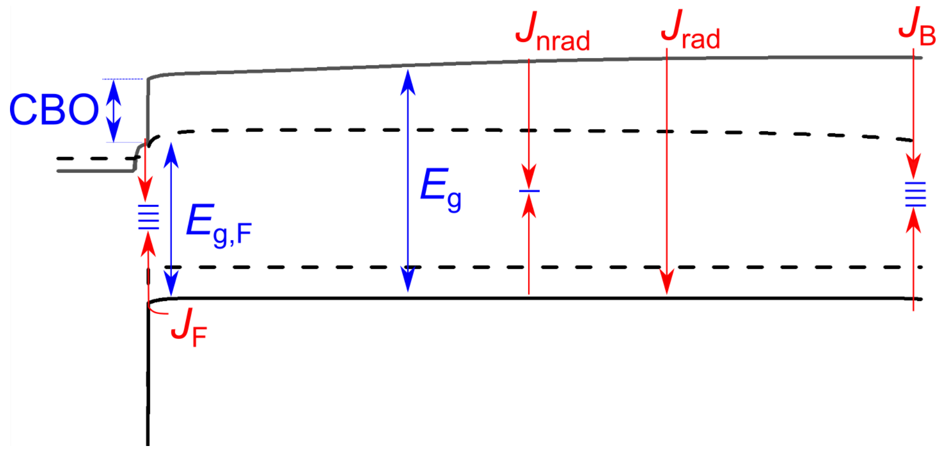
1-sun, CBO = -0.2 eV



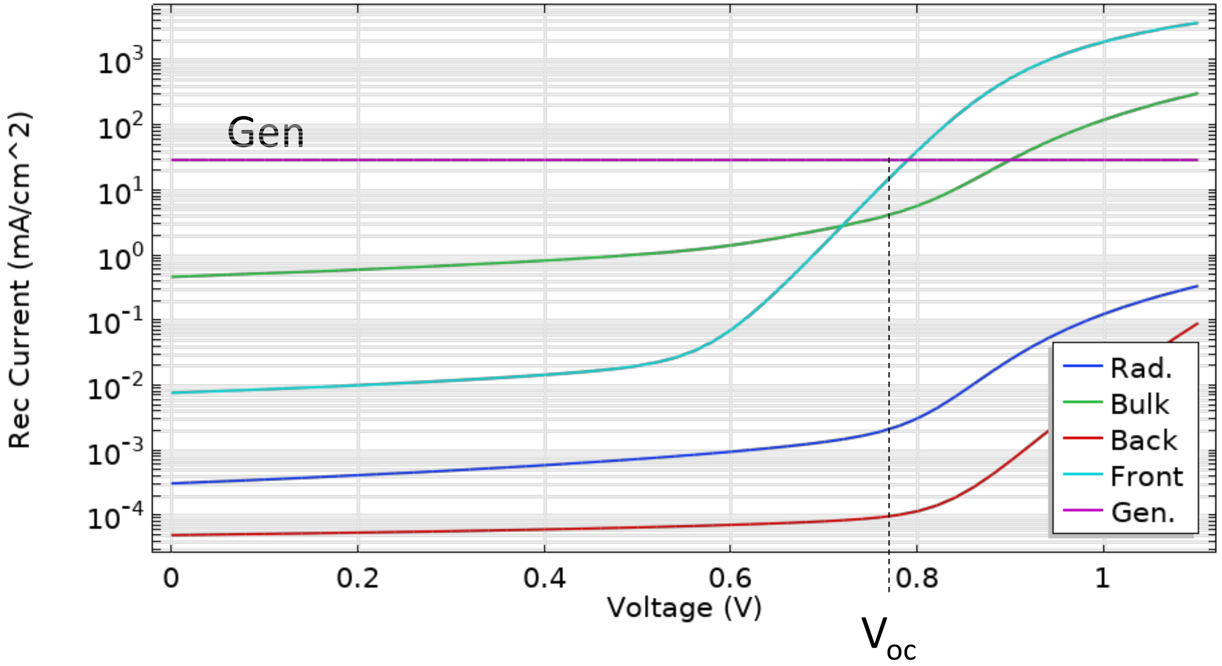
- Comparing data to simulated V_{oc} vs. T suggests S_f ~ 1000 cm/s, but wide range for τ.
- QE and TRPL suggest τ ~ 1 – 5 ns.

Comparison of Recombination Current Densities

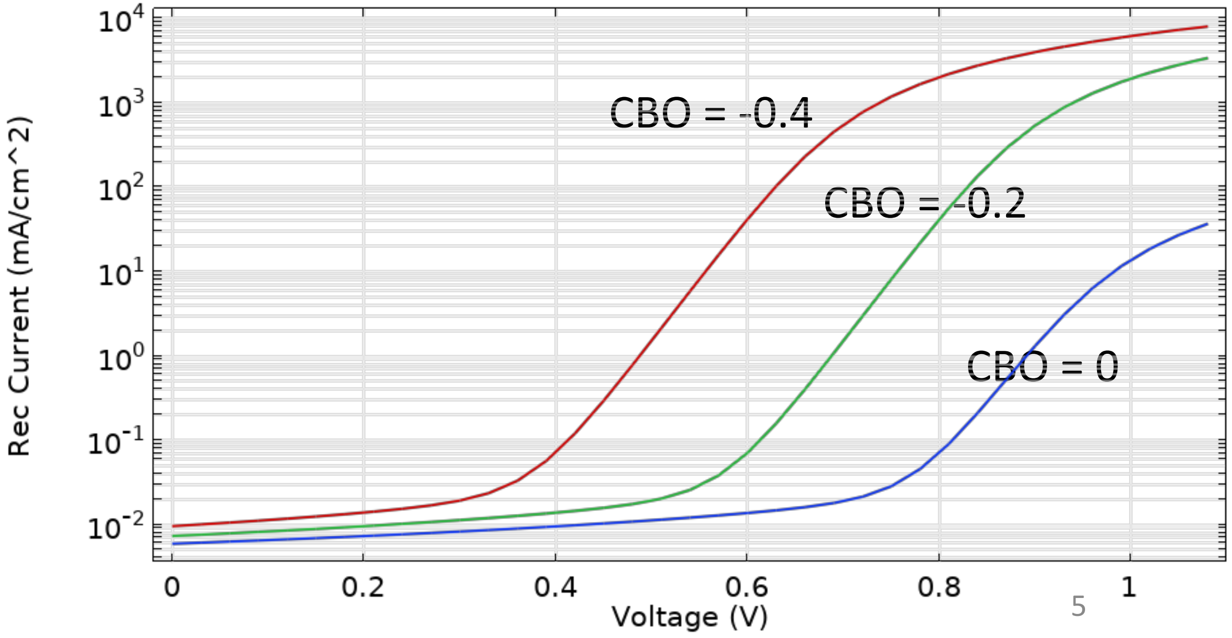
- Front interface recombination dominates at V_{oc}.
- Bulk also contributes at V_{oc} and dominates at $V < V_{oc}$.
- Decreasing CBO (increasing cliff) increases front interface recombination exponentially for fixed S_f.



All recombination contributions for:
S_f = 1000 cm/s, τ = 1 ns, CBO = -0.2 V



Front interface recombination current density:
S_f = 1000 cm/s, τ = 1 ns, various CBO



PL for Band Tail Analysis

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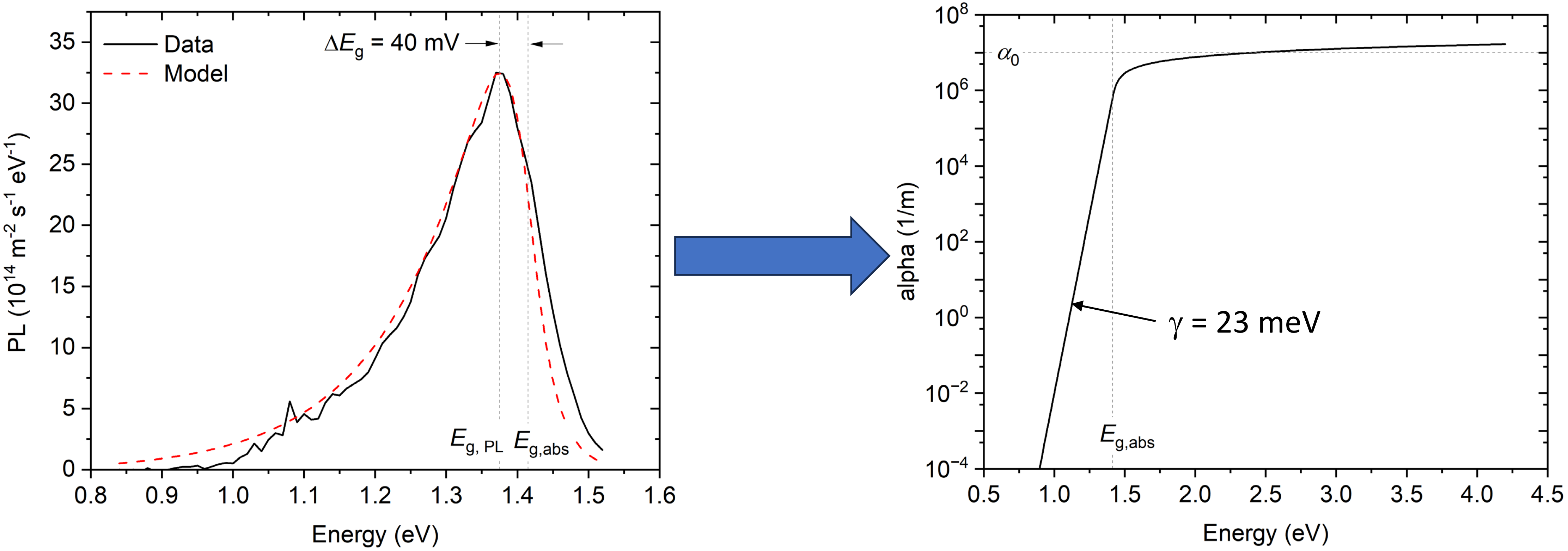
- PL fitting parameters [1]: $E_{g,abs}$ = 1.415 eV, T = 310 K, $\Delta\mu$ = 0.684 eV, **γ = 0.023 eV, θ = 1**
- PLQY within 2% for model and data.
- Extracted absorption coefficient, α, and band bap shift, ΔE_g, used in device models [2].



PL data courtesy of Darius Kuciauskas (NREL)

[1] J. K. Katahara and H. W. Hillhouse, "Quasi-Fermi level splitting and sub-bandgap absorptivity from semiconductor photoluminescence," *Journal of Applied Physics*, vol. 116, no. 17, p. 173504, 2014.
[2] J. Wong, S. T. Omelchenko, and H. A. Atwater, "Impact of Semiconductor Band Tails and Band Filling on Photovoltaic Efficiency Limits," *ACS Energy Lett.*, vol. 6, no. 1, pp. 52–57, Jan. 2021, doi: 10.1021/acsenergylett.0c02362.

Band Tail Effects

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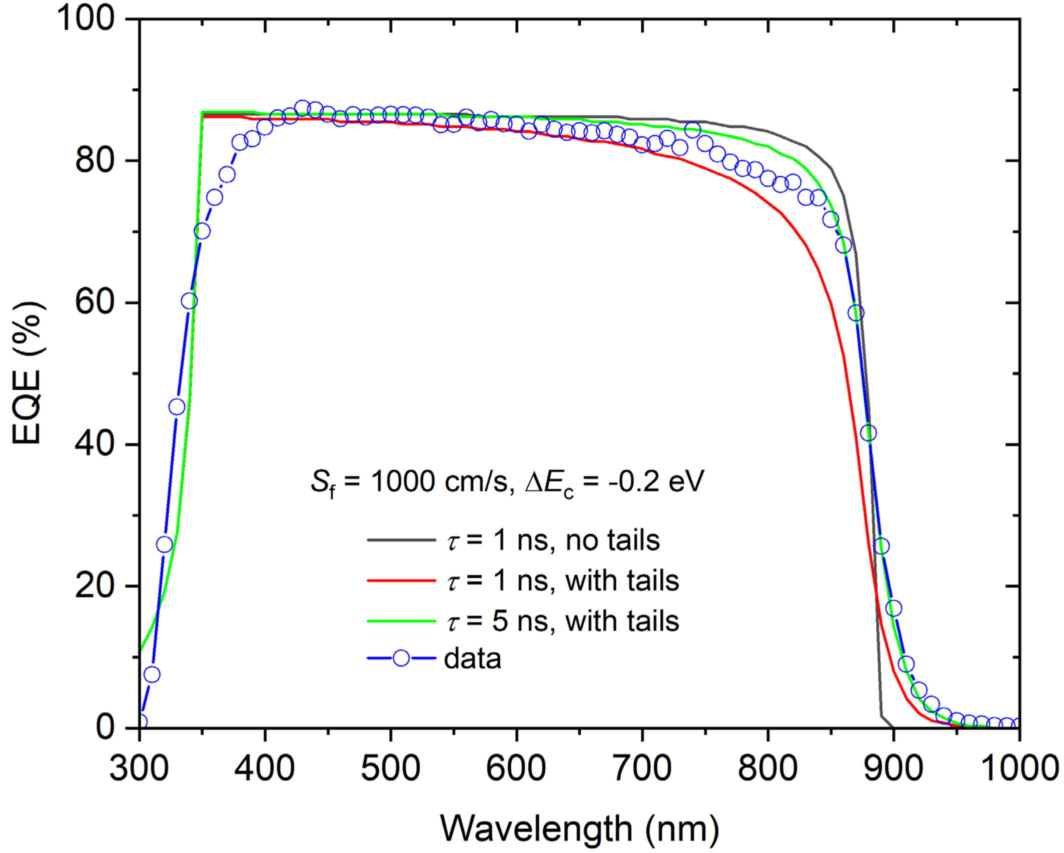
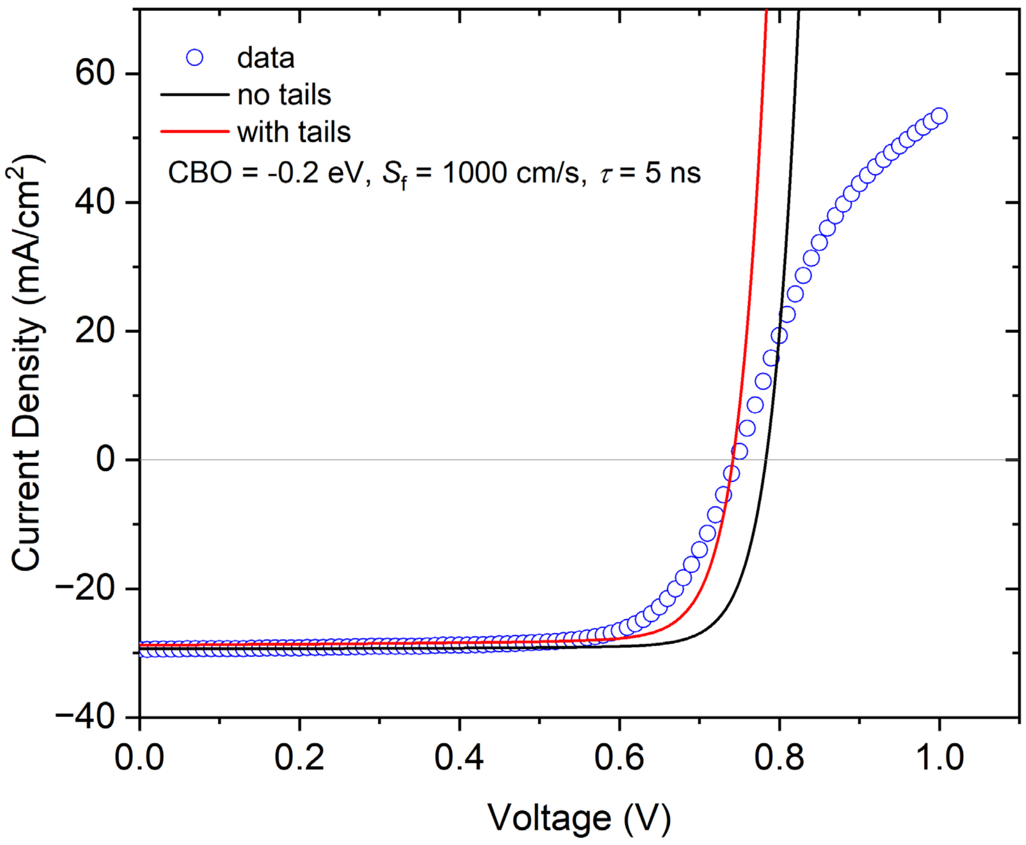
<u>QE with and without band tails</u>



<u>JV with and without band tails</u>

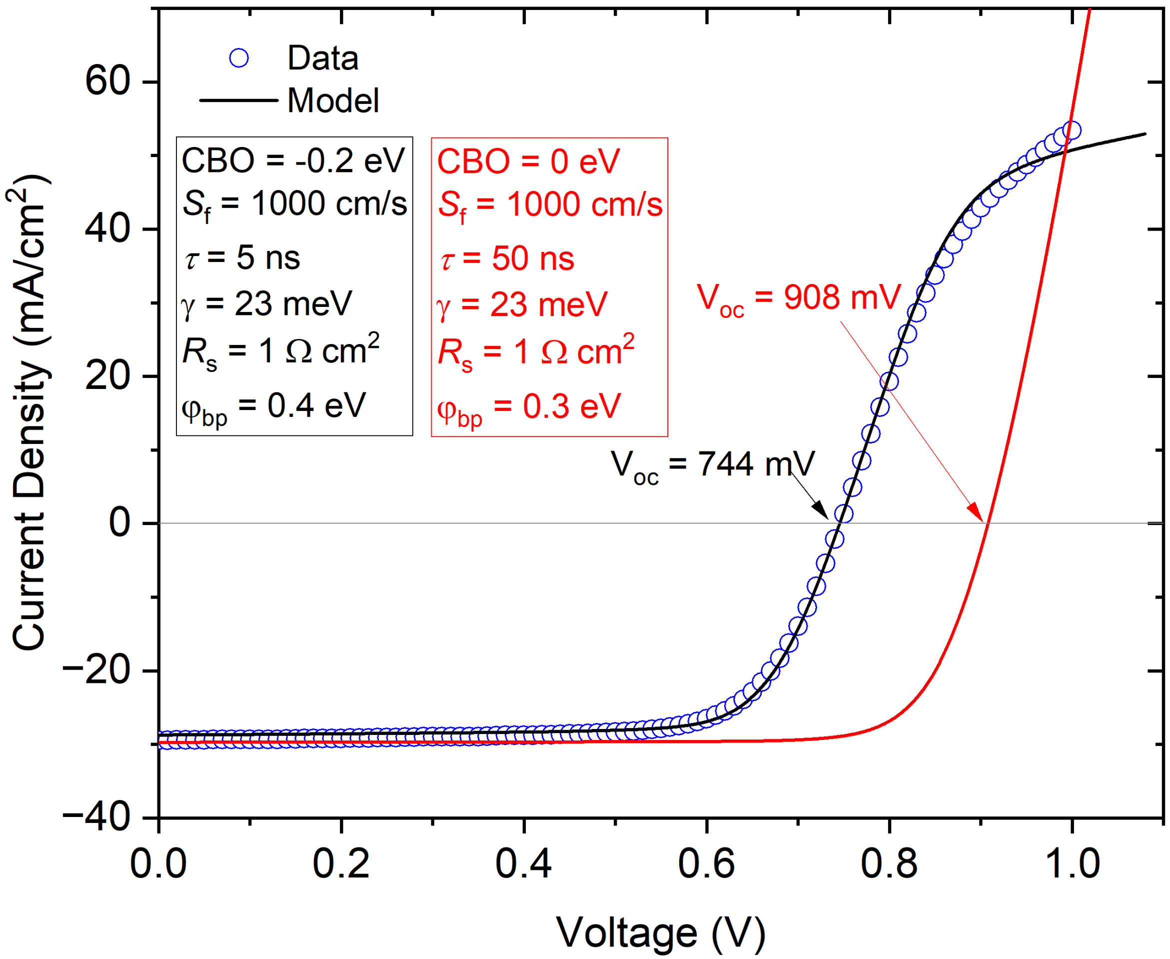


- QE at long wavelengths fits with band tails included.
- Bulk lifetime can be increased to 5 ns with tails.

- 40 mV loss due to band tails.
- JV compared to data still requires back barrier and series resistance, but reasonably good fit.

Summary

- Integrated data and modeling: parameters shown in black below.
- In this case: front interface CBO cliff dominates voltage loss.
- V_{oc} > 900 mV can be achieved if bulk lifetime is also improved (red below).
- For V_{oc} ~ 0.9 - 1 V, radiative and back interface losses are important ($S_b = 10^5$ cm/s here).



Acknowledgements

DOE-SETO/NREL: “Development and Application of Voltage Loss Analysis for Advanced Thin-Film PV”

PI: Darius Kuciauskas.

DOE-SETO/NREL: “CdTe Core Group”

PI: Matthew Reese.

Students: Sakshi Gupta, Eva Mulloy, Andrew Prostor

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Extra Slides

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QE Study

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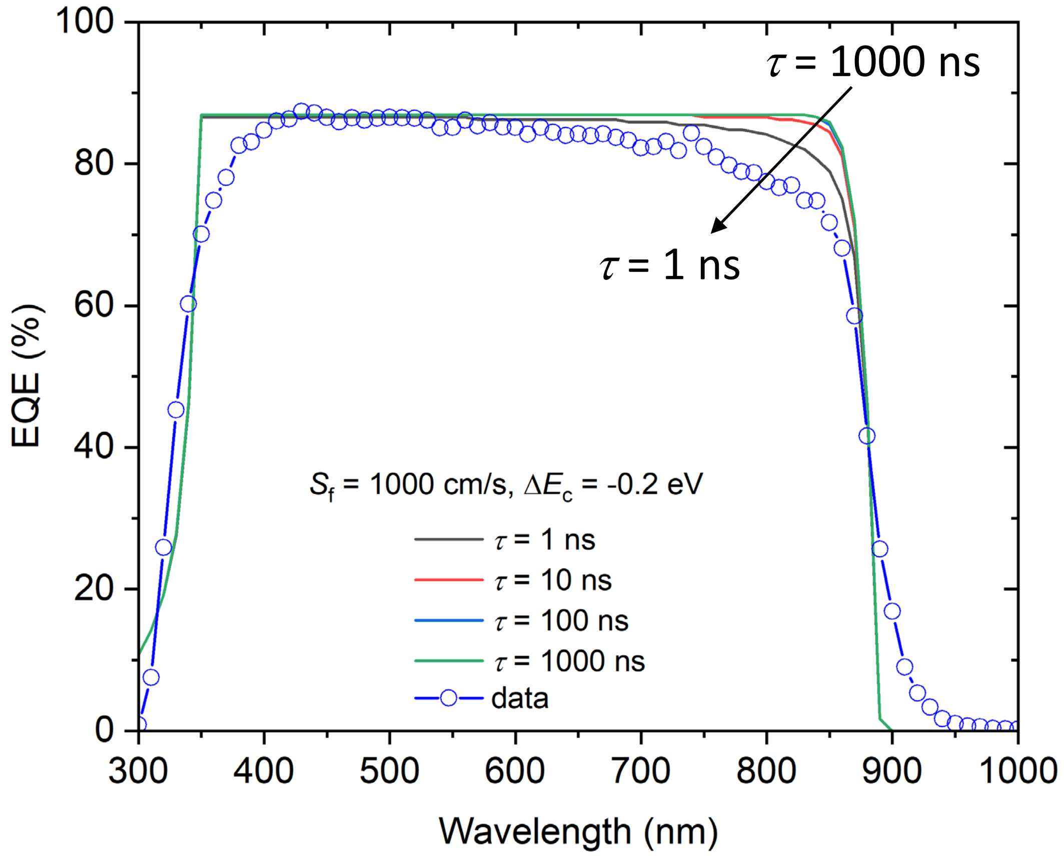
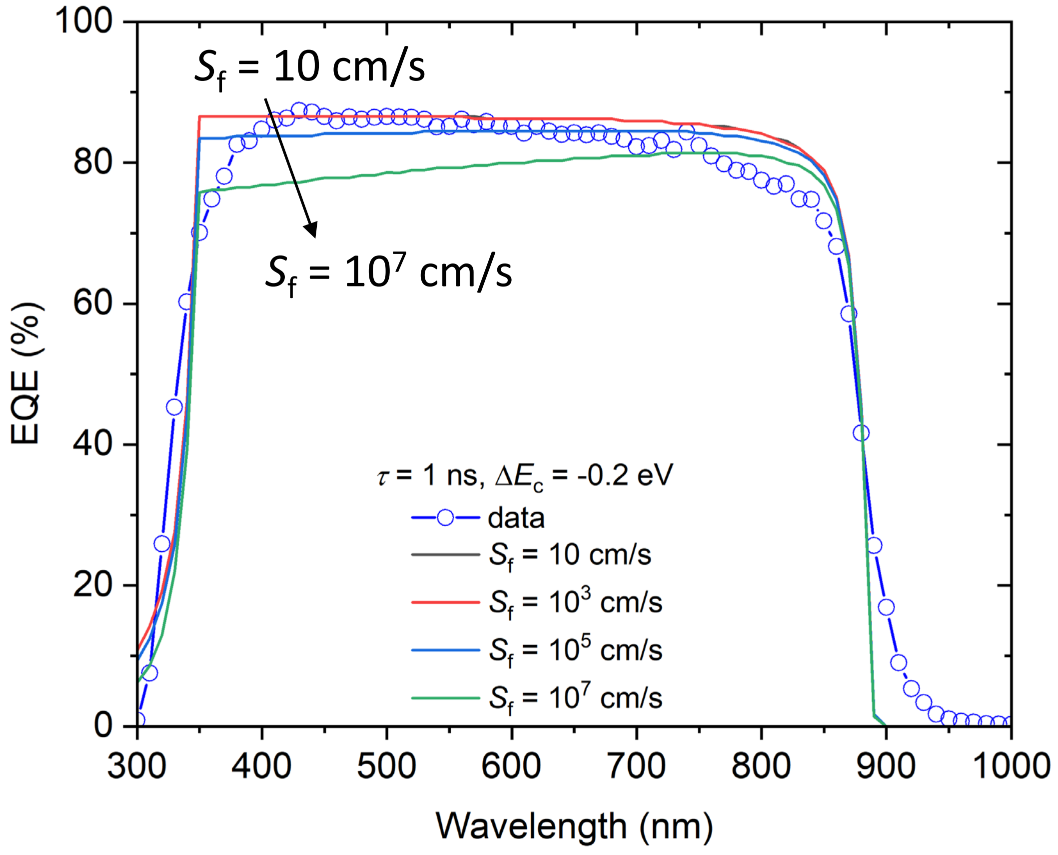
QE with variable bulk lifetime



QE with variable front SRV



- QE suggests that τ is low, possibly around 1 ns.
- Inflection point of QE gives $E_{g,abs}$ = 1.415 eV.

- Corroborates S_f ~ 1000 cm/s.
- QE does not include band tails yet – see IR region.

TRPL Study

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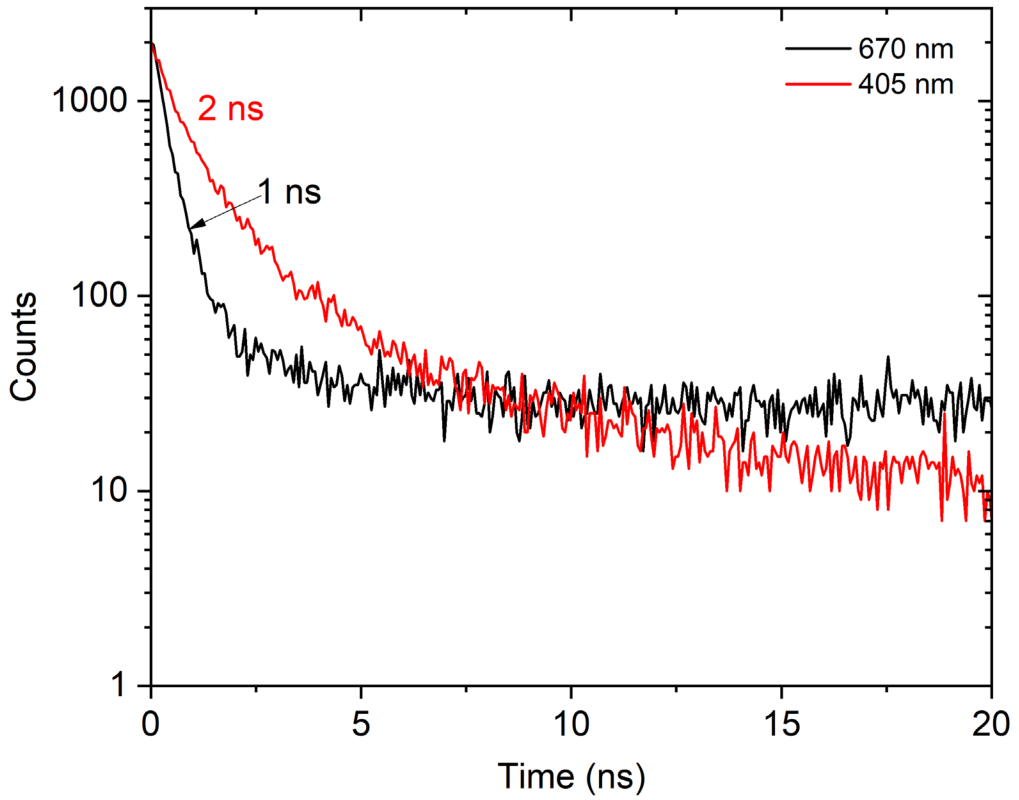
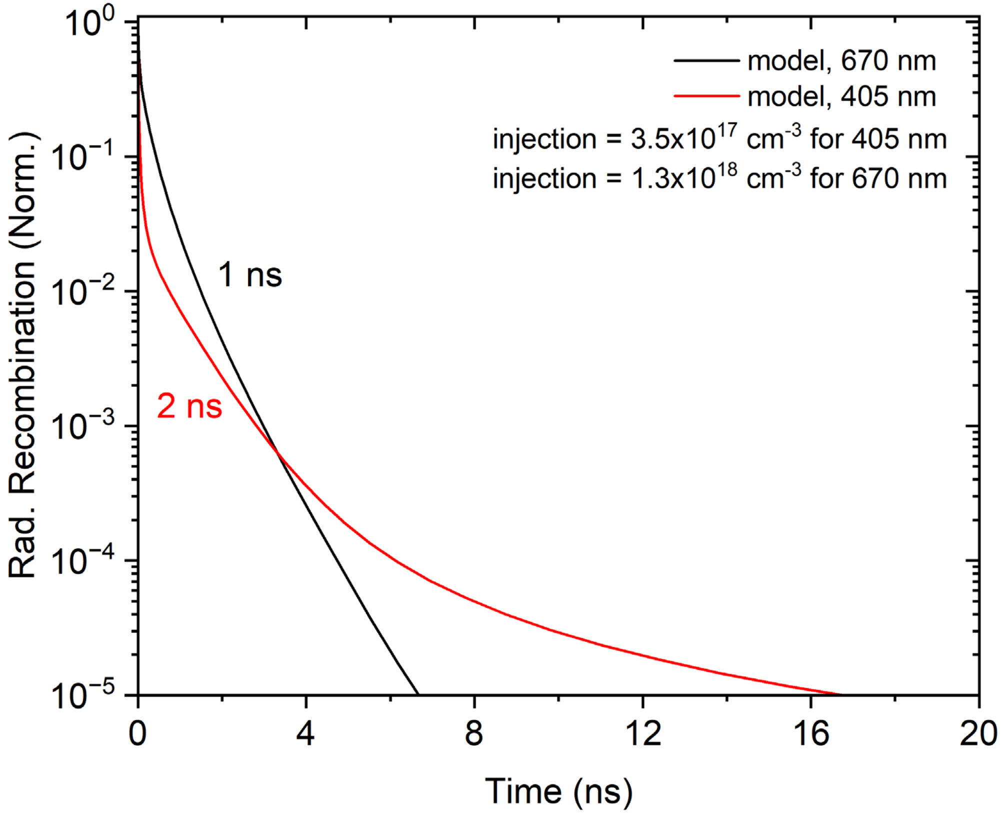
TRPL Data



TPRL Sim: S_f =1000 cm/s, τ = 1 ns, CBO = -0.2 eV



- TRPL simulation and data support ~ 1 ns lifetime.
- Data and simulation have similar wavelength dependence if first 0.3 ns is neglected.
- Wavelength dependence may suggest low bulk lifetime.
- Uncertainties – sample pre-conditioning, differences in intensity with wavelength, E_a injection dependence…

V_{oc} Loss Analysis at 1-sun Light Intensity

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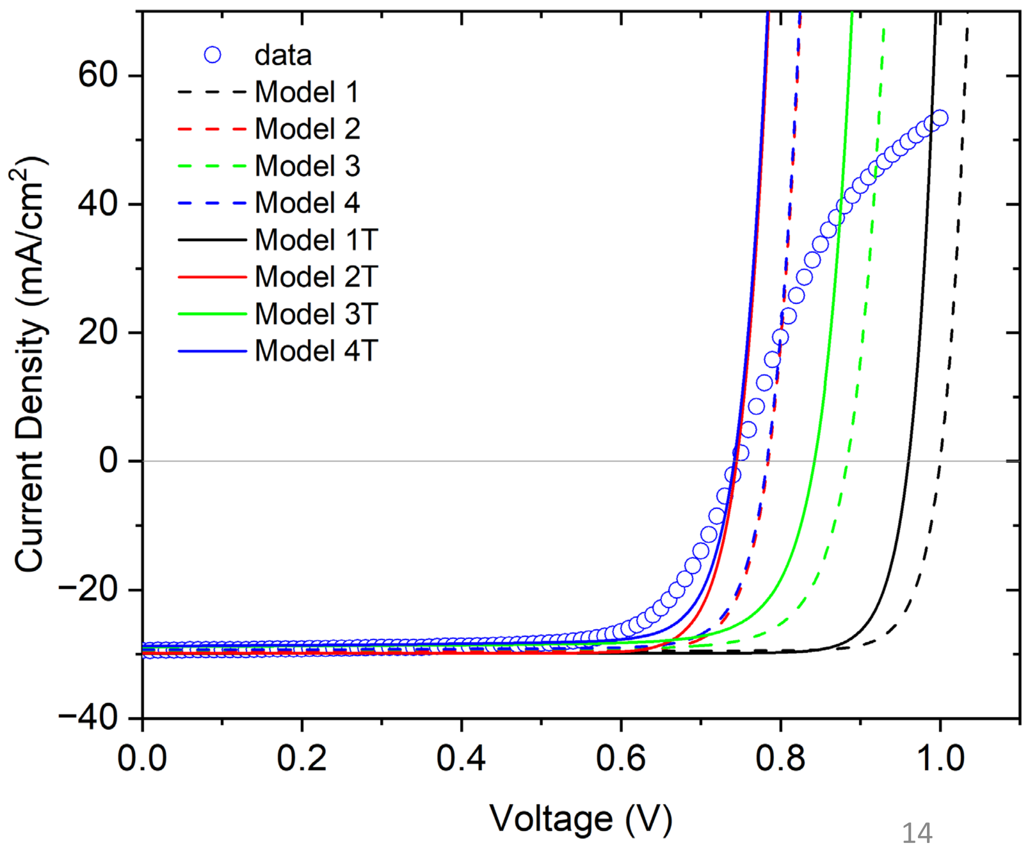
- Compare 8 scenarios (4 with tails, 4 without) - Table.
- Front interface is most significant – CBO.
- V_{oc} = 0.84 V if front is mitigated with tails, 0.88 V if no tails with the same bulk lifetime of 5 ns.
- Max V_{oc} ~ 1 V, then radiative and back losses are important ($S_b = 10^5$ cm/s here).

Model	1	1T	2	2T	3	3T	4	4T
	Ideal		Front losses		Bulk losses		Actual	
CBO (eV)	0	0	-0.2	-0.2	0	0	-0.2	-0.2
S_f (cm/s)	100	100	1000	1000	100	100	1000	1000
τ (ns)	1000	1000	1000	1000	5	5	5	5
tails*	N	Y	N	Y	N	Y	N	Y
V_{oc} (V)	1.00	0.96	0.79	0.75	0.88	0.84	0.79	0.74
ΔV_{oc} from ideal	0	0.04	0.21	0.25	0.12	0.16	0.21	0.26

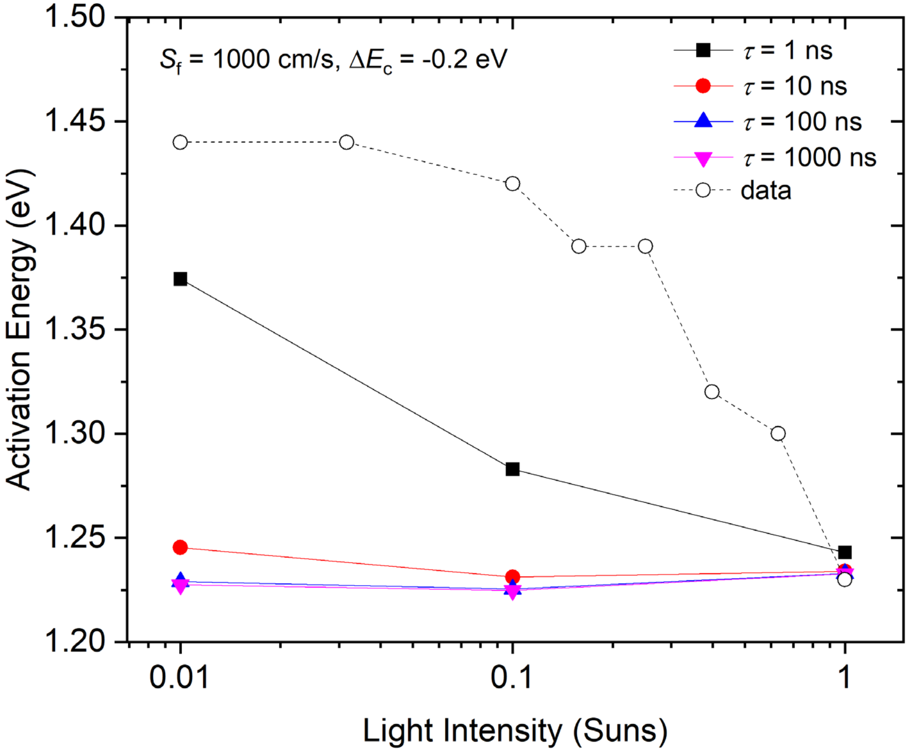
* band tail parameters: $\gamma = 0.023$ eV, $\theta = 1$



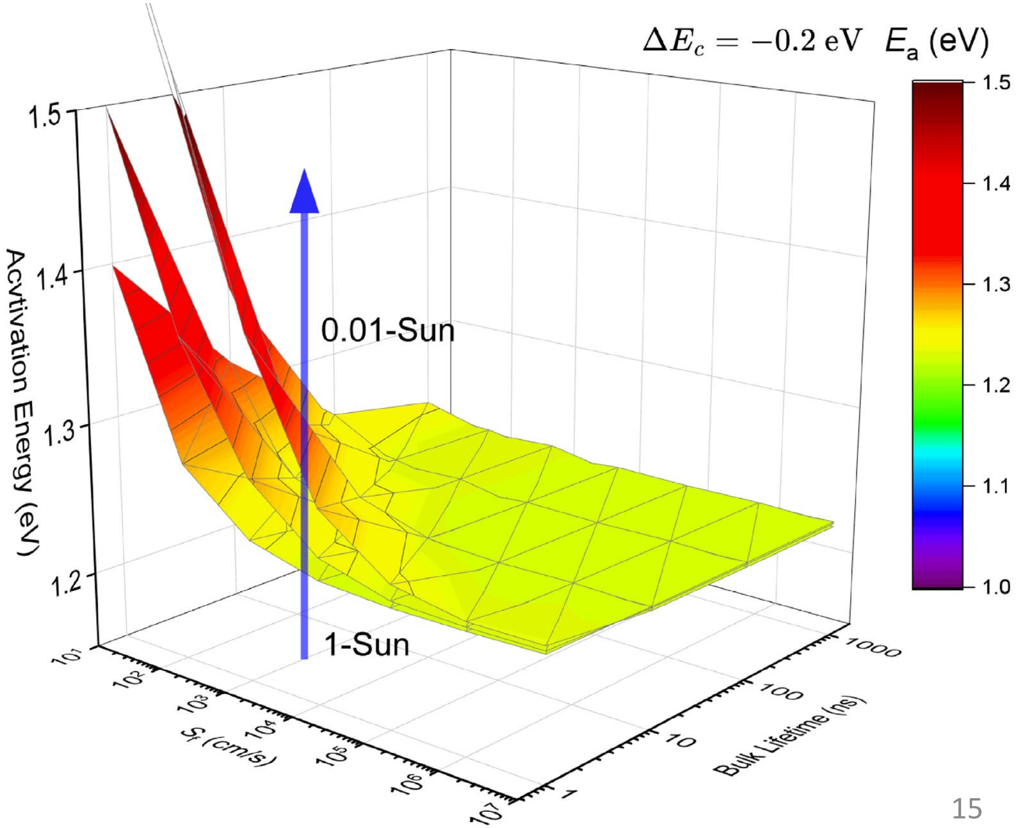
Effects of Light Intensity on Activation Energy

- Theories such as photoactive interface defects/dipole layers can be considered.
- The models without any such mechanism show a region with a similar trend as the data:
  - E_a has light dependence when S_f and τ are both low - transition from interface to bulk recombination as intensity decreases.

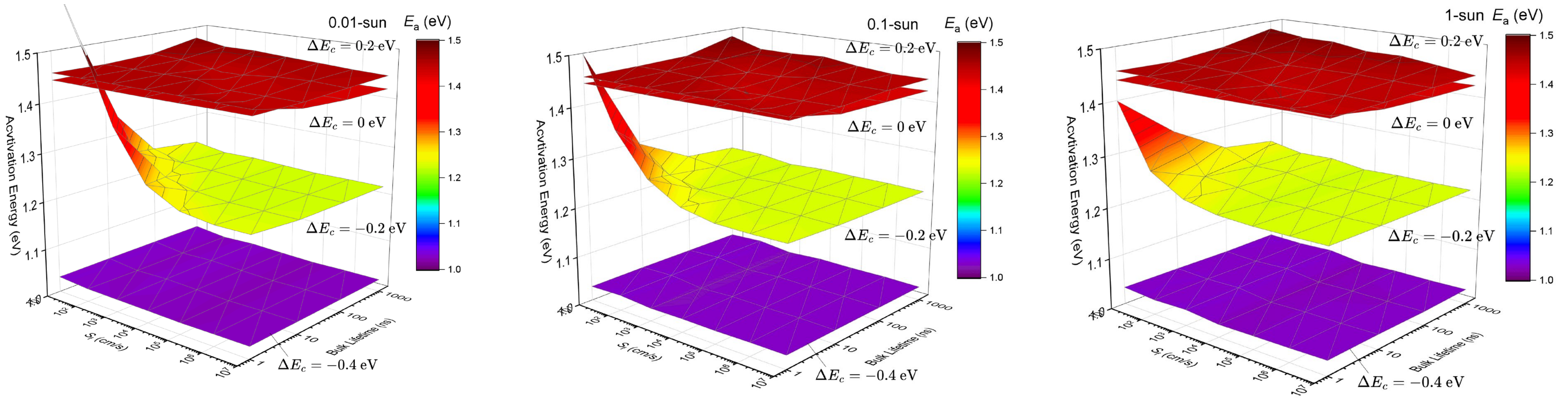
E_a vs light intensity for various τ at S_f = 1000 cm/s and CBO = -0.2 eV



E_a vs S_f and τ at three intensities with CBO = -0.2 eV



Increasing light intensity



Baseline Device Model – Bulk Properties

Bulk Parameter	Symbol	Unit	SnO_2:F	SnO_2	MgZnO	Cd(Se,Te)	CdTe
Thickness	d	µm	0.4	0.1	0.06	0.5	3.0
Band Gap	E_g	eV	3.6	3.6	varied	Graded	1.5
Electron Affinity	χ	eV	4.5	4.5	Varied w bandgap	Graded	4.5
Relative permittivity (Dielectric)	ε_s		9	9	9	9.4	9.4
Effective DOS, conduction band	N_c	cm^{-3}	2.2×10^{18}	2.2×10^{18}	2.2×10^{18}	8.0×10^{17}	8.0×10^{17}
Effective DOS, valence band	N_v	cm^{-3}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}	1.8×10^{19}
Electron & Hole Thermal velocity		$cm\ s^{-1}$	1.0×10^{07}	1.0×10^{07}	1.0×10^{07}	1.0×10^{07}	1.0×10^{07}
Mobility, electron	μ_n	$cm^2\ V^{-1}\ s^{-1}$	100	100	100	40	320
Mobility, hole	μ_p	$cm^2\ V^{-1}\ s^{-1}$	25	25	25	5	40
Shallow Acceptor Density(Paper)		cm^{-3}			--	2.0×10^{16}	2.0×10^{16}
Shallow Donor density (Paper)		cm^{-3}	1.0×10^{20}	1.0×10^{18}	1.0×10^{14}		
Neutral mid-gap state density						1.0×10^{12}	1.0×10^{13}

Contact Parameter	Symbol	Unit	SnO_2/f.c.	b.c/CdTe
Metal work function	Φ_m	eV	4.5	5.8
Recombination velocity, electrons	S_n	cm/s	var.	10^5
Recombination velocity, holes	S_p	cm/s	var	10^5

Interface	Unit	CdSeTe/MZO
Charge Type		Neutral
Concentration	cm^{-3}	varied
Energy above VBM	eV	6.0×10^{-1}
Capture Cross Section	cm^2	10^{-12}

Simple optical model to follow band gap grading:

$$\alpha = A\sqrt{h\nu - E_g}, \quad A \approx 10^5\ eV^{-1/2}\ cm^{-1}$$

Mid-gap Defect Parameter	Symbol	Unit	SnO_2:F	n-SnO_2	MgZnO	Cd(Se,Te)	CdTe
Defect concentration	N_t	cm^{-3}		10^{15}	9×10^{14}	5.0×10^{12}	5.0×10^{13}
Defect energy level	E_t	eV		0	0	0	0
Defect charge type				(+/0)	(-/0)	(+/0)	(+/0)
Capture cross-section, electron	σ_n	cm^2		10^{-12}	10^{-12}	10^{-12}	10^{-12}
Capture cross-section, hole	σ_p	cm^2		10^{-15}	10^{-12}	10^{-12}	10^{-12}
Lifetime, electron average	τ_n	ns		0.1	0.1[2]	20[2]	2[2]
Lifetime, hole average	τ_p	ns		100	0.1[2]	20[2]	2[2]

Notes:

References:

[1] B. Good, E. Colegrove, and M. O. Reese, "Effects of absorber near-interface compensation on Cd(Se,Te) solar cell performance," *Solar Energy Materials and Solar Cells*, vol. 246, p. 111928, Oct. 2022, doi: 10.1016/j.solmat.2022.111928.

Grain boundaries, polycrystallinity, Chlorine and their role in Voc deficit

Amit Munshi

10-26-23

Assistant Research Professor

Department of Mechanical Engineering

Colorado State University

The puzzle -

- ERE > 2%
- iV_{OC} > 1V
- iEfficiency >26%
- S < 100 cm/s
- TRPL $\tau > 2$ µs

If all is good, why no 1V/26%+ device yet?

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Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

WALTER SCOTT, JR. COLLEGE OF ENGINEERING
COLORADO STATE UNIVERSITY

SOLAR ENERGY TECHNOLOGIES OFFICE
U.S. Department Of Energy

SPF2050

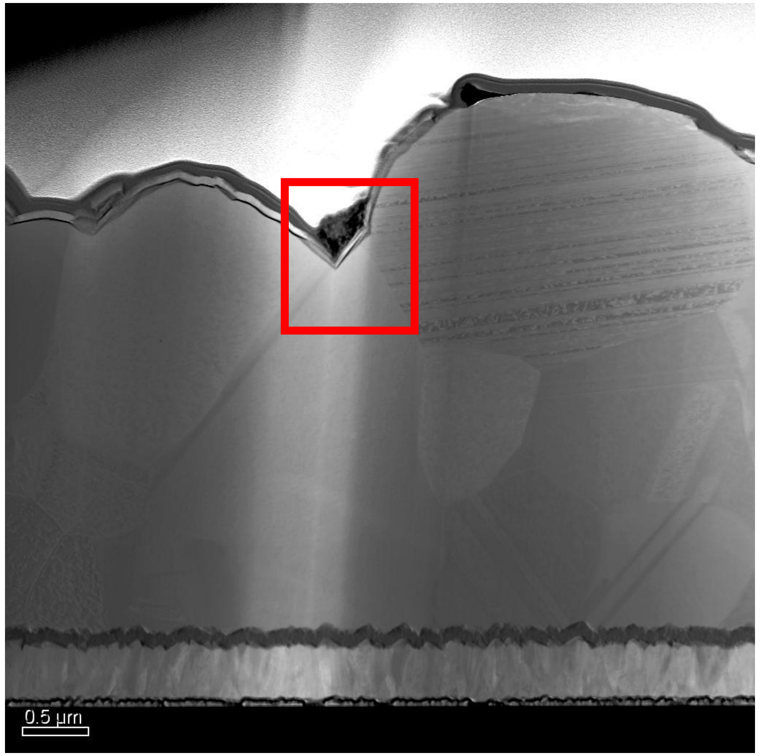
First considerations -

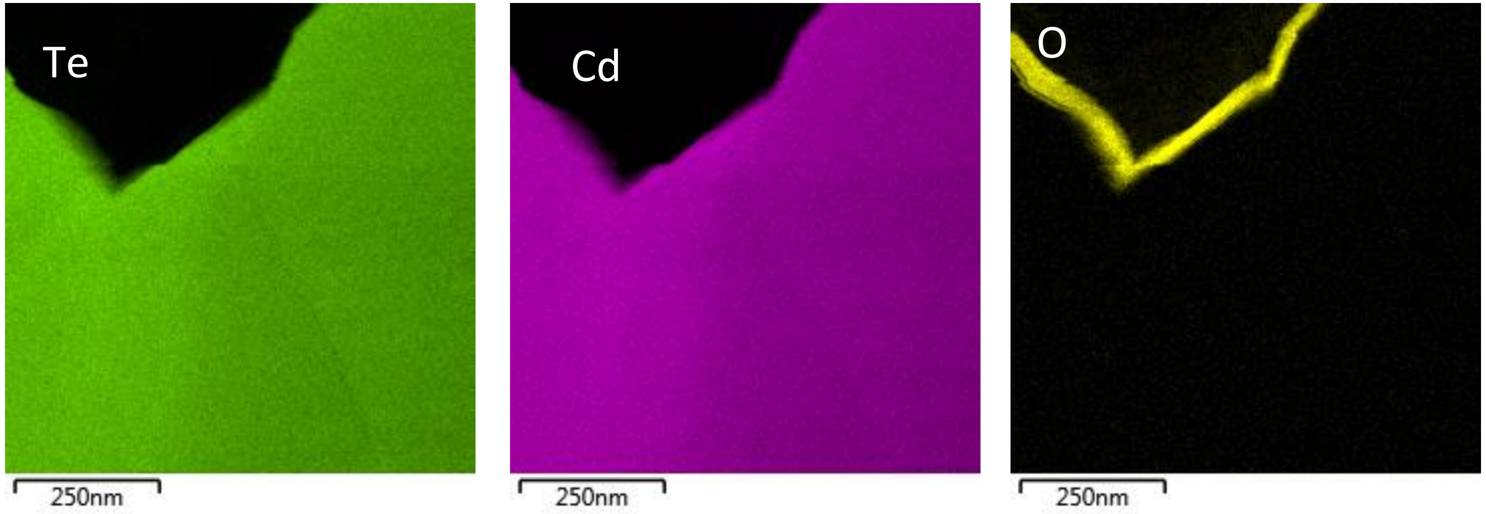
- **GaAs –**
  - Mono-crystalline : η - 29%, Voc – 1.12V, Jsc – 29.78 mA/cm^2, FF – 86.7%
  - Multi-crystalline : η - 18.4%, Voc – 0.994 V, Jsc – 23.2 mA/cm^2, FF – 79.7%

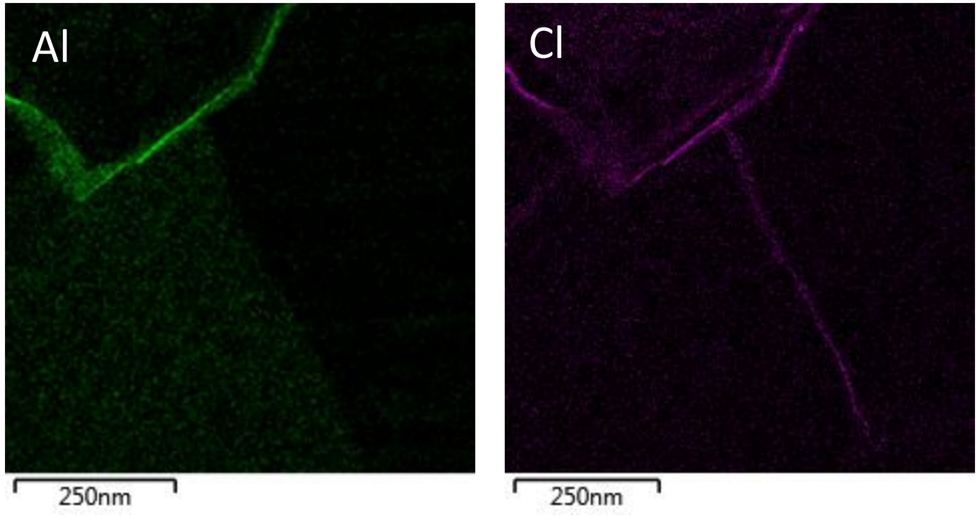
- **Silicon –**
  - Mono-crystalline : η - 26.7%, Voc – 0.738V, Jsc – 42.65 mA/cm^2, FF – 84.9%
  - Multi-crystalline : η - 21.9%, Voc – 0.672V, Jsc – 40.76 mA/cm^2, FF – 79.7%
  - Micro-crystalline : η - 11.9%, Voc – 0.550V, Jsc – 28.72 mA/cm^2, FF – 75.0%

- **CdTe –**
  - Poly-crystalline : η - 21.4%, Voc – 0.876V, Jsc – 30.25 mA/cm^2, FF – 79.4% [Presumably, CdSe/CdTe]
  - MBE CdTe (ASU) : η - 17.0%, Voc – 1.04V, Jsc – 22.3 mA/cm^2, FF – 73.6%
  - Single crystal CdTe (NREL) : η - 13.6%, Voc – 1.017V, Jsc – 25.2 mA/cm^2, FF – 61.7%

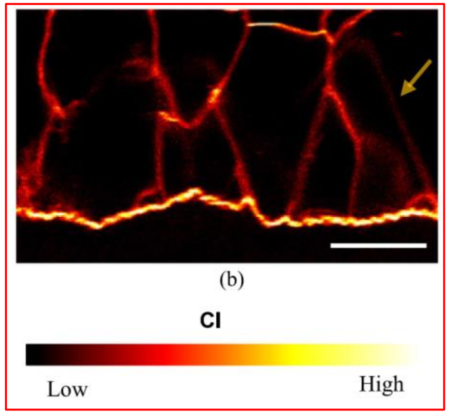
Interface (Surface) and Chlorine -



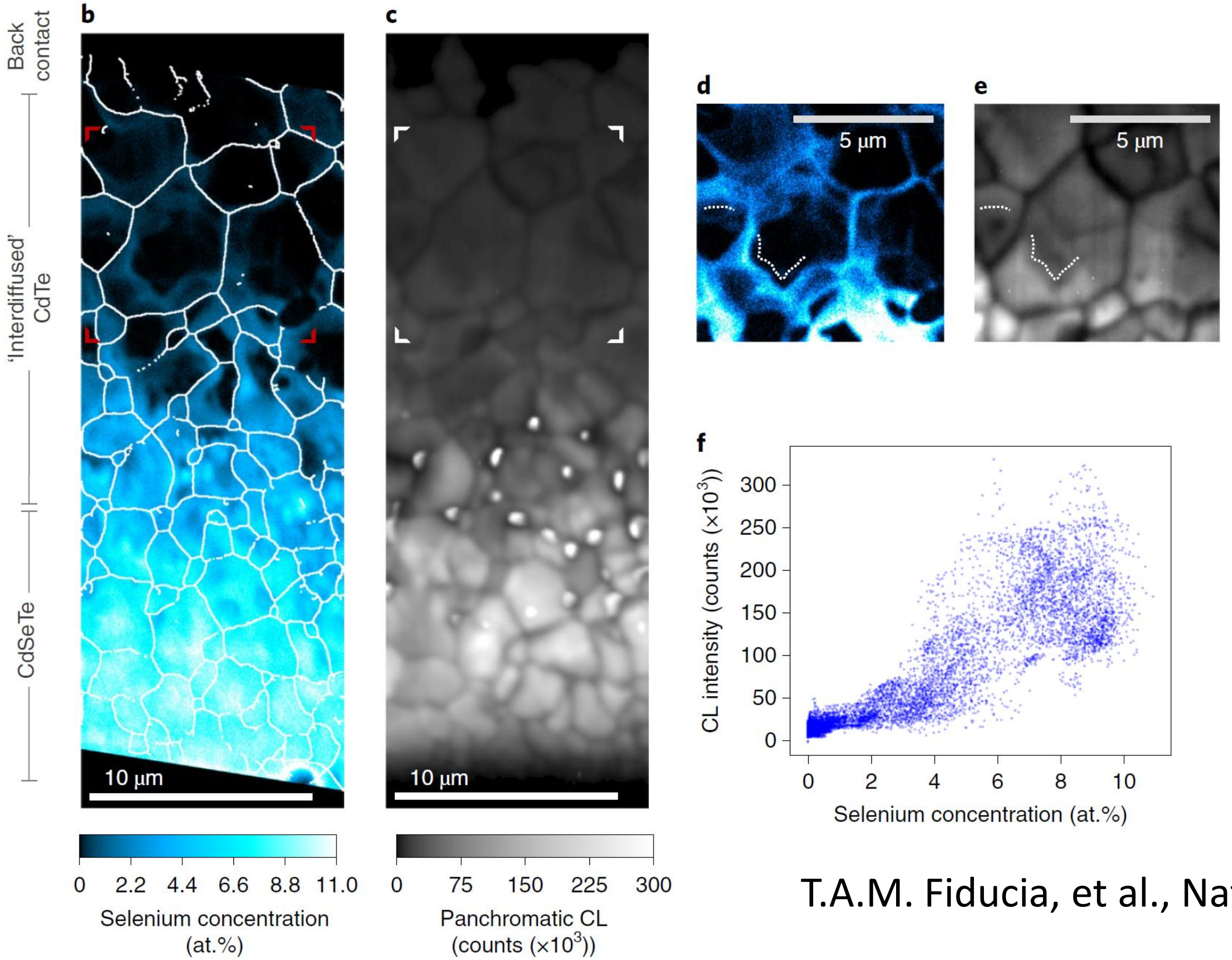




Also, Cl at the front interface

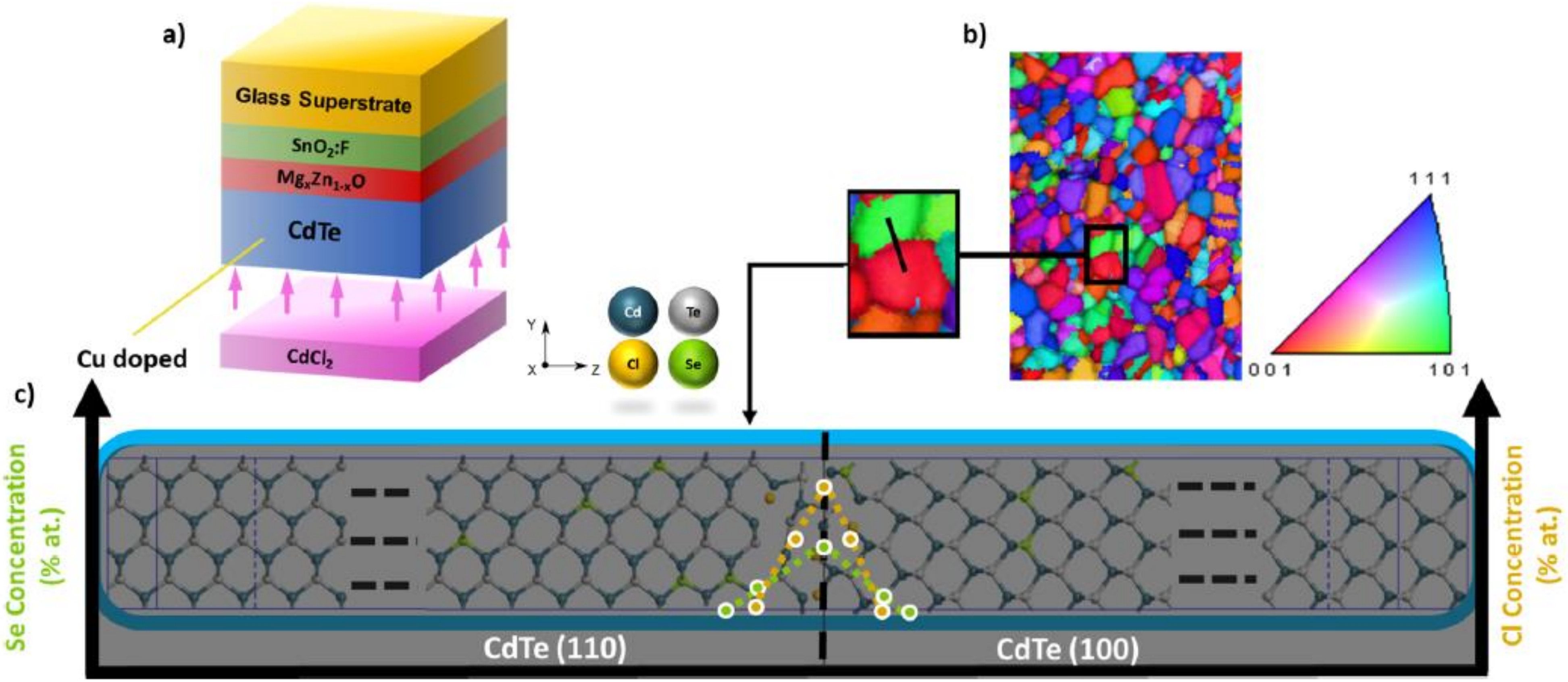


CST and CdTe grain boundaries under CL



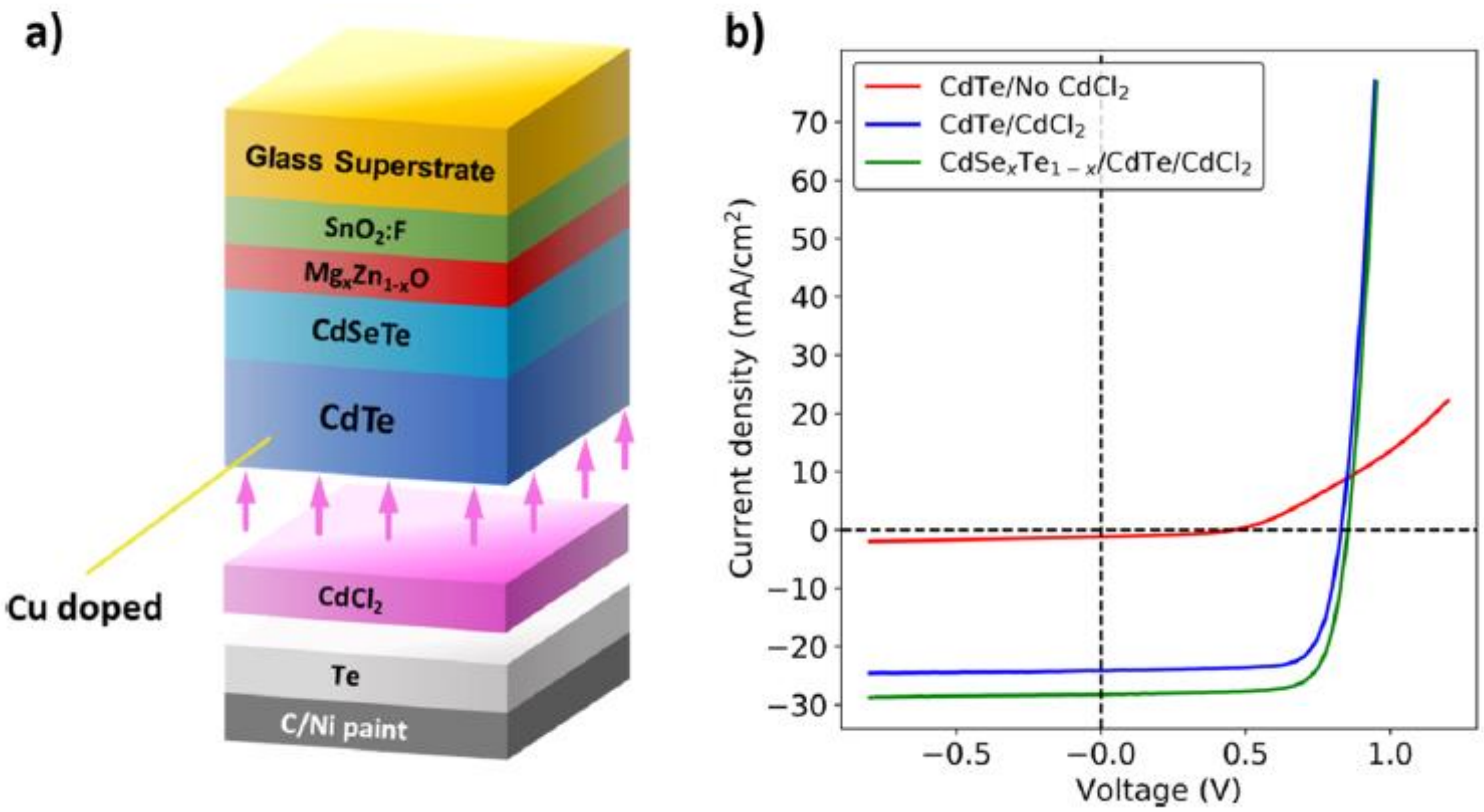
T.A.M. Fiducia, et al., Nat. Enrg., Vol 4 – 504-511

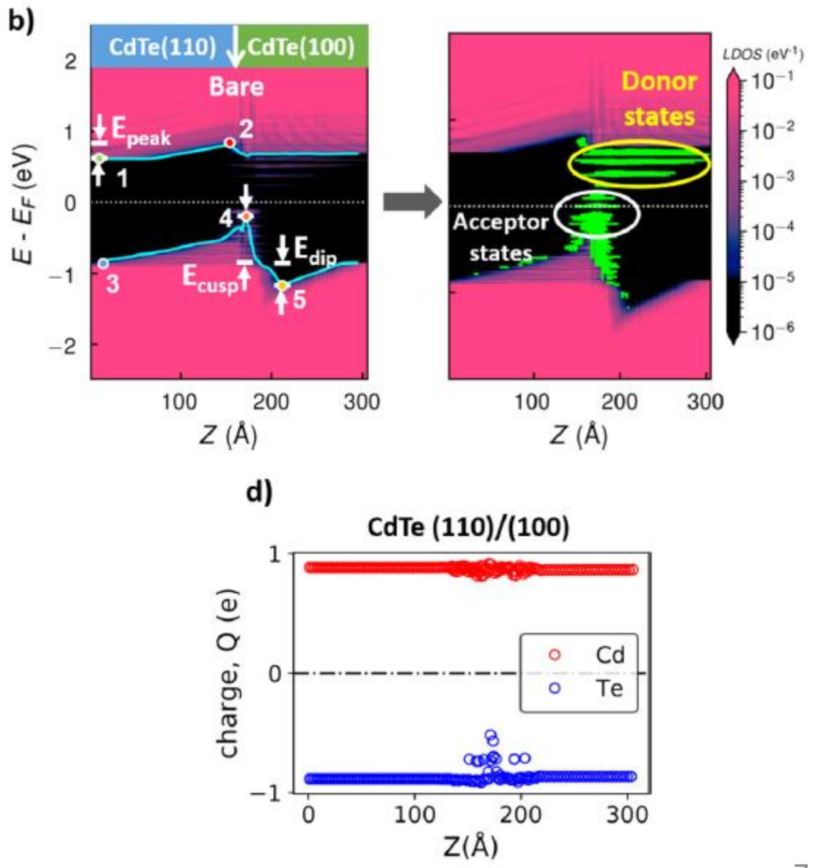
EBSD data used to set simulation parameters



Shah, Akash, et al. "Understanding the copassivation effect of Cl and Se for CdTe grain boundaries." *ACS Applied Materials & Interfaces* 13.29 (2021): 35086-35096.

Device performance with Cl, Se, and Cl+Se





Shah, Akash, et al. "Understanding the copassivation effect of Cl and Se for CdTe grain boundaries." *ACS Applied Materials & Interfaces* 13.29 (2021): 35086-35096.

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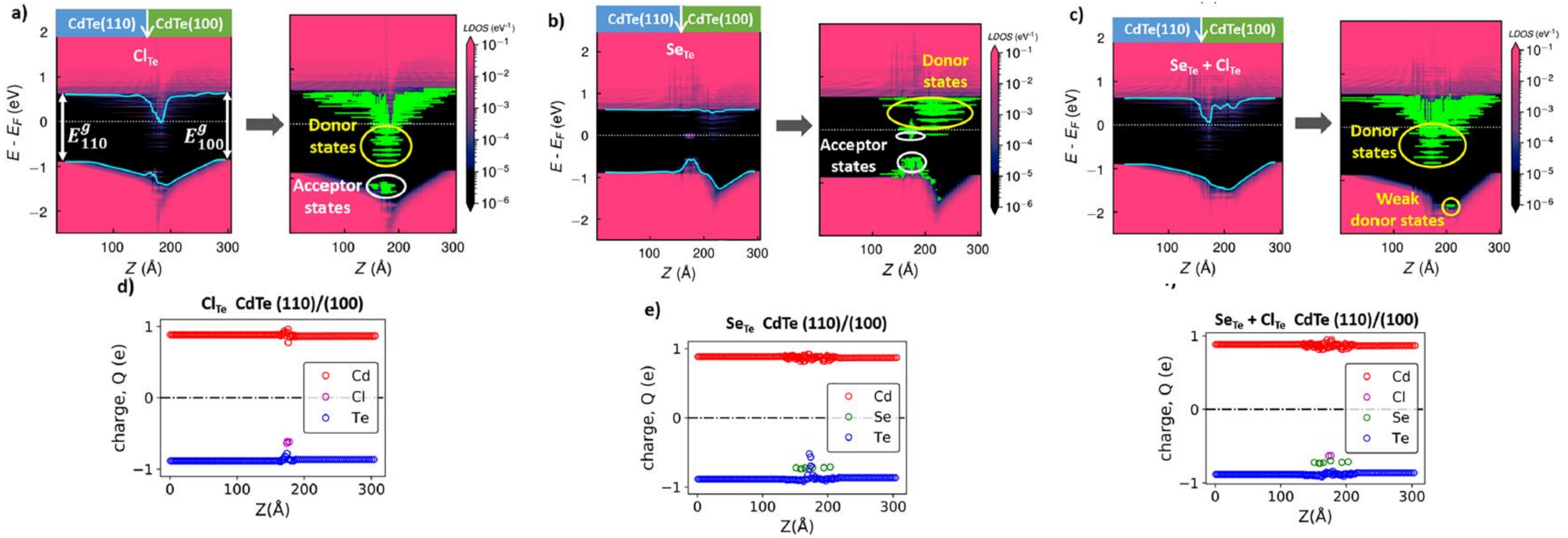
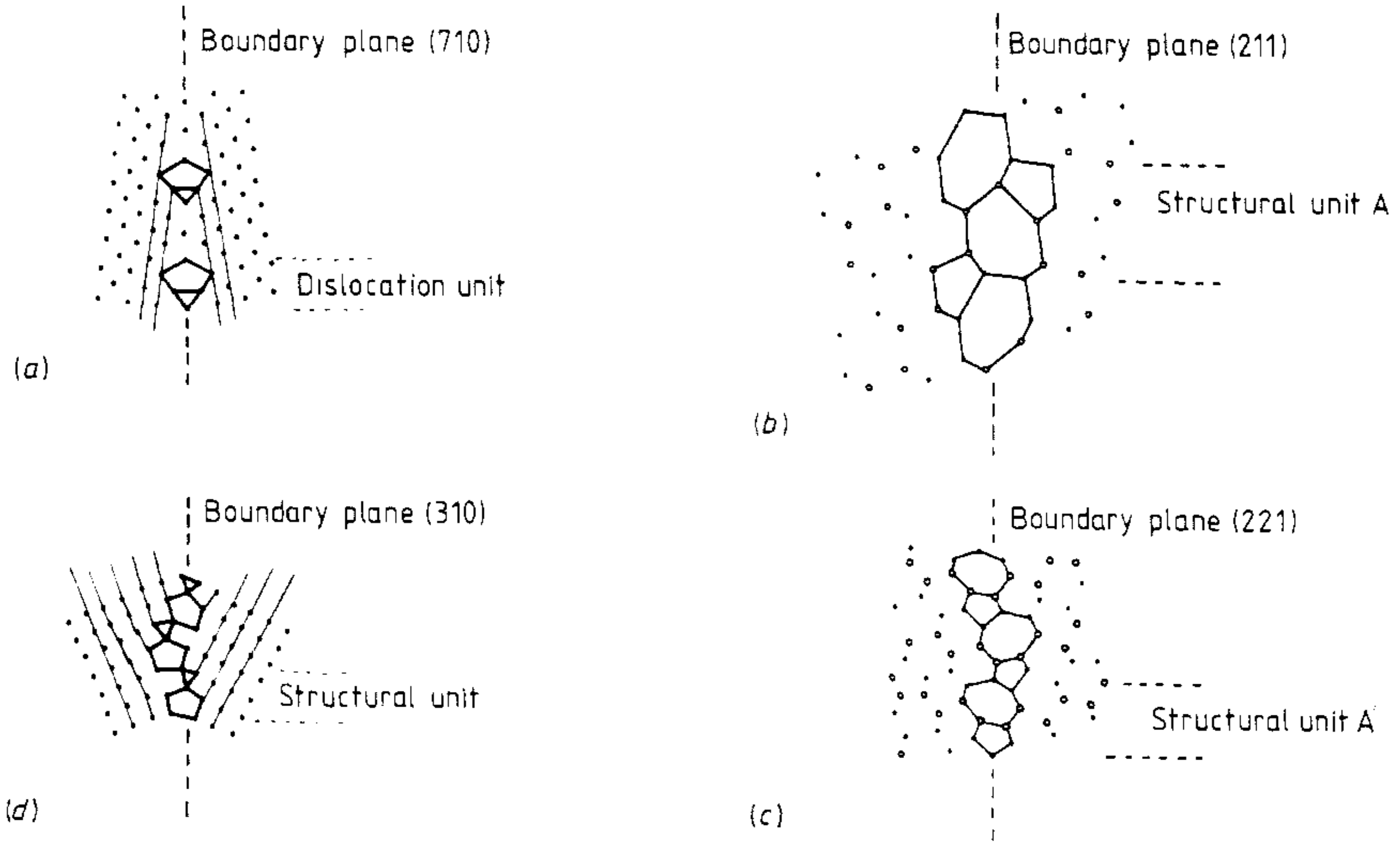


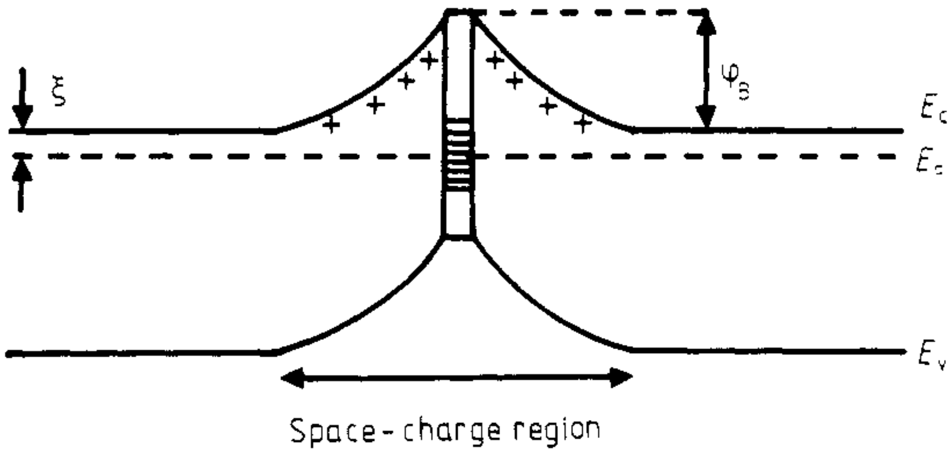
Shah, Akash, et al. "Understanding the copassivation effect of Cl and Se for CdTe grain boundaries." *ACS Applied Materials & Interfaces* 13.29 (2021): 35086-35096.

Relationship between GB structure to electronic behavior significantly under investigated

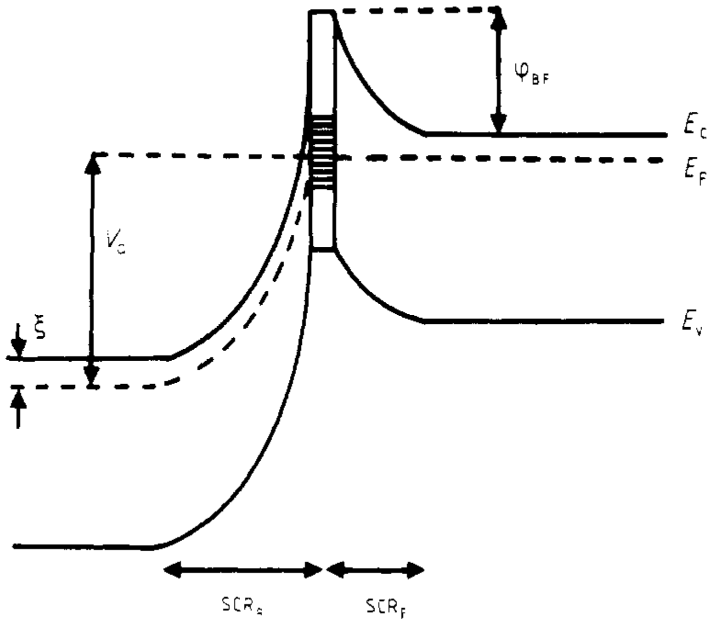


Grovenor, C. R. M. "Grain boundaries in semiconductors." *Journal of Physics C: Solid State Physics* 18.21 (1985): 4079.

Effects of GB and voltage bias in n-type px semiconductors



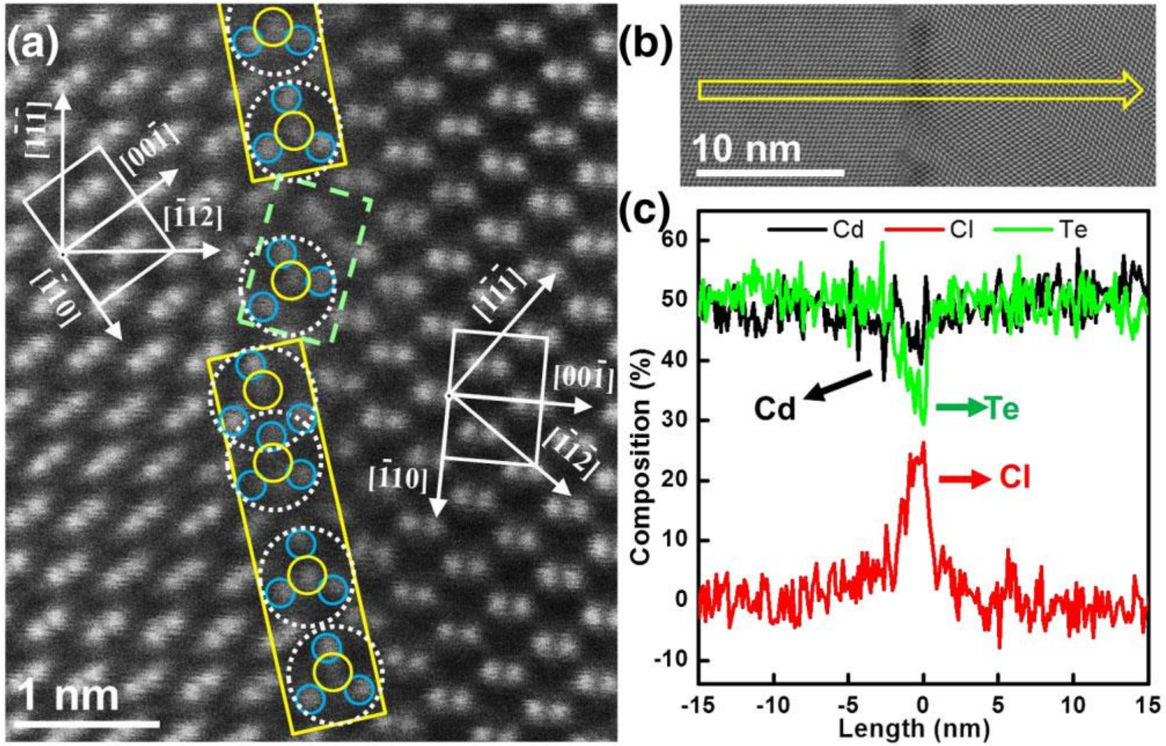
A schematic one-dimensional representation of the band-bending around a grain boundary, containing a high density of interface states, in an n-type semiconductor. Here the boundary region is shown as having the same bandgap as the bulk semiconductor, and the boundary is modelled as a Symmetric Schottky Barrier.

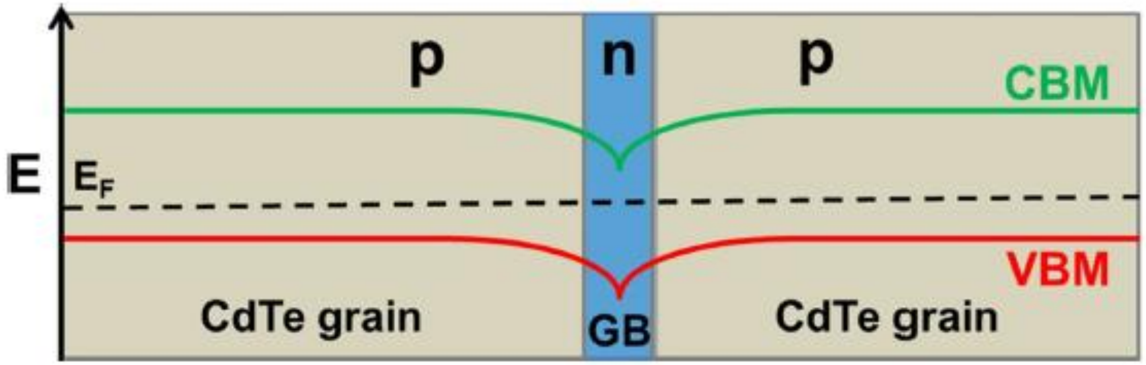


A schematic representation of the bandbending around a biased grain boundary. The band-bending on the forward-biased side of the **SSB, qgFi,**s relatively independent of the applied voltage, *V,,* because of the pinning of the Fermi level by the interface states.

Grovenor, C. R. M. "Grain boundaries in semiconductors." *Journal of Physics C: Solid State Physics* 18.21 (1985): 4079.

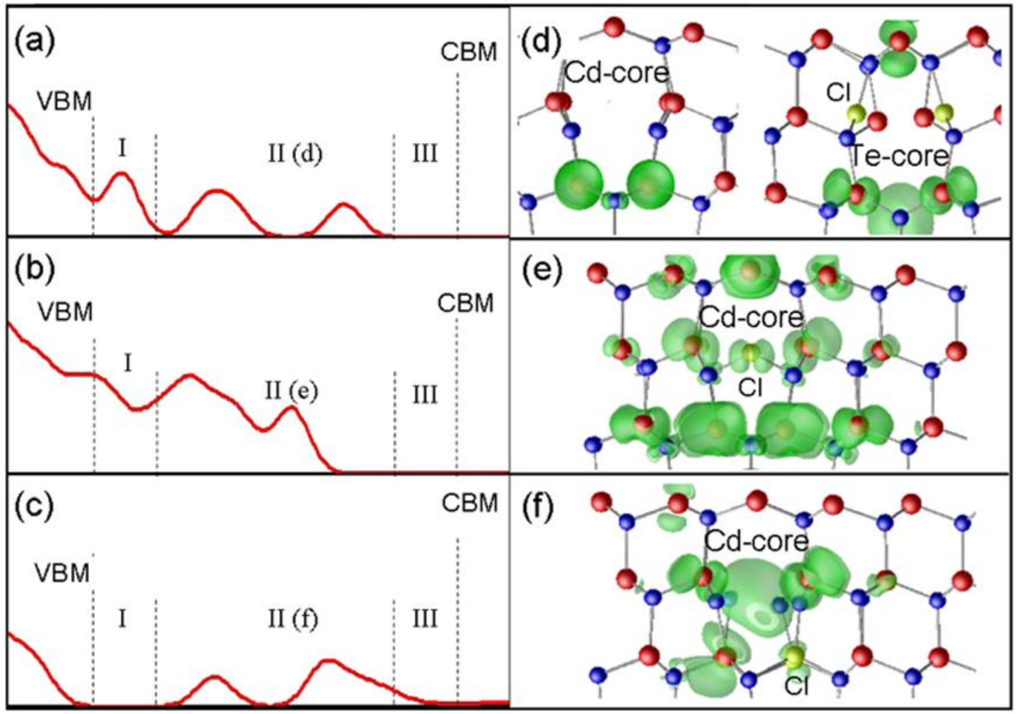
Formation of p-n-p junction at grain boundaries

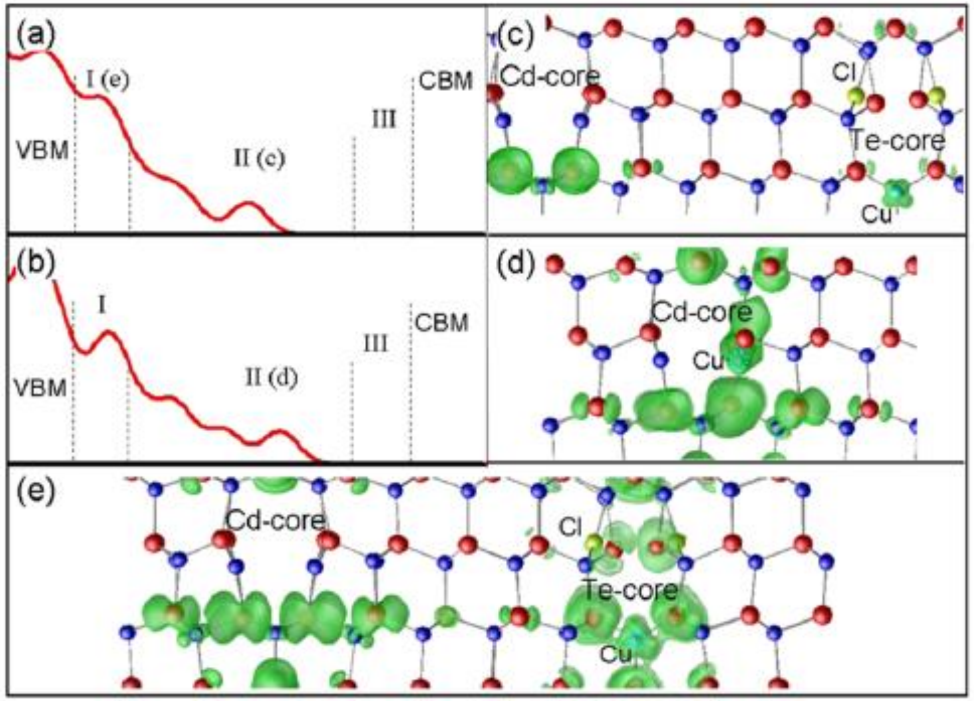




Li, Chen, et al. "Grain-boundary-enhanced carrier collection in CdTe solar cells." *Physical review letters* 112.15 (2014): 156103.

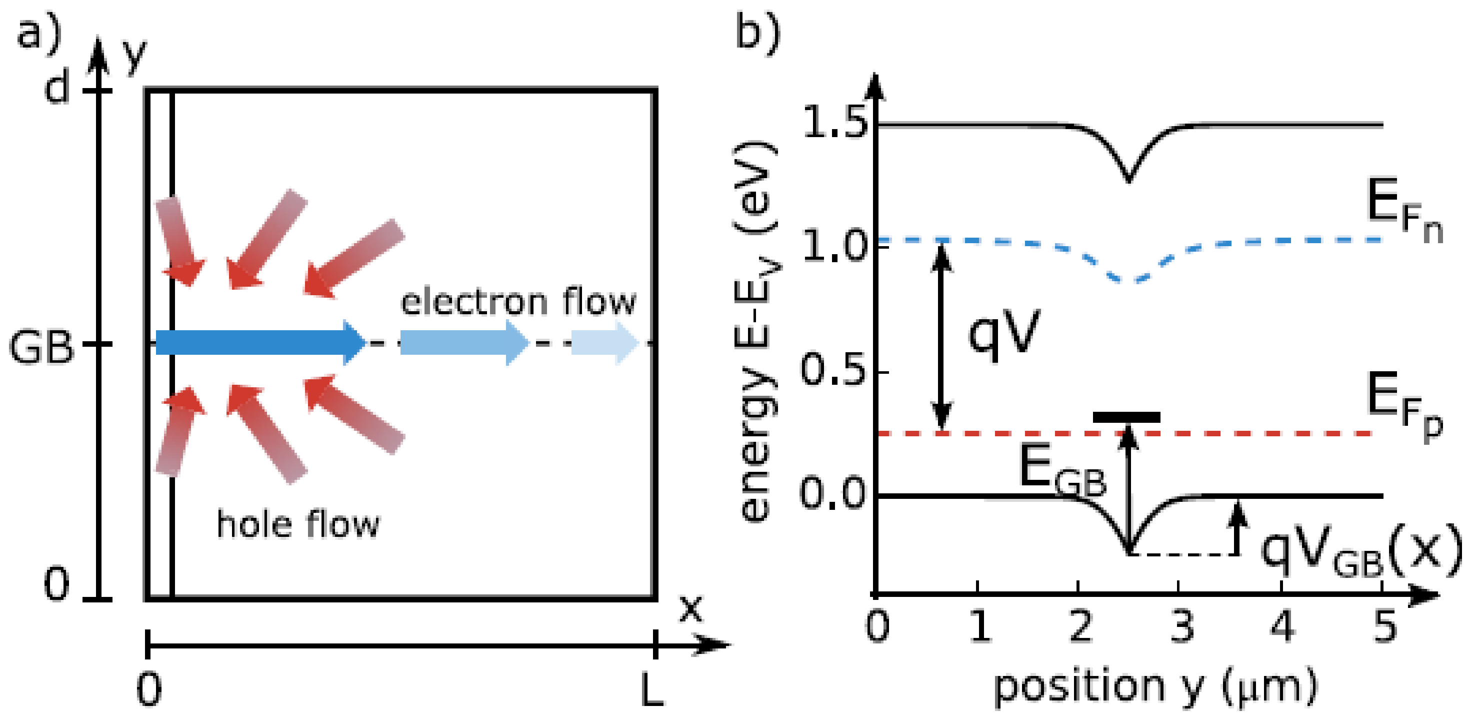
Role of Cl as a dopant requires greater attention





Zhang, Lixin, et al. "Effect of copassivation of Cl and Cu on CdTe grain boundaries." *Physical review letters* 101.15 (2008): 155501.

Grain boundaries limiting Voc in px Semiconductors



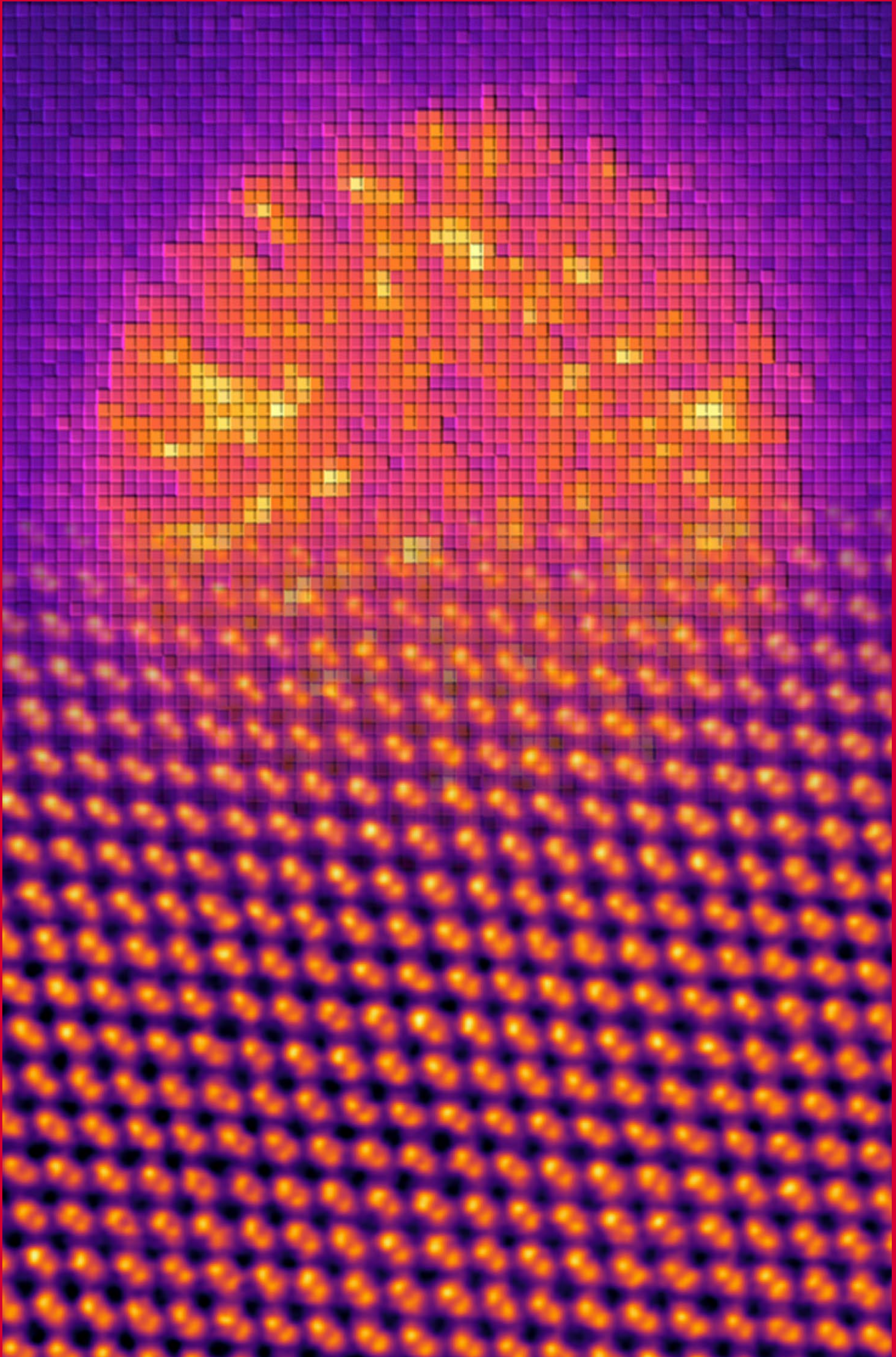
Charged grain boundaries reduce the opencircuit voltage of polycrystalline solar cells—
An analytical description

Orellana, Walter, Eduardo Menéndez-Proupin, and Mauricio A. Flores. "Self-compensation in chlorine-doped CdTe." *Scientific reports* 9.1 (2019): 9194.

“Particularly, the $(Cl_{Te})^+$ shallow donor would be compensated by the $[(Cl_{Te}-V_{Cd})(C_{3v})]^-$ shallow acceptor, ***leading to the Fermi level pinning at VBM + 0.92 eV.*** *In addition, our results show that the formation of the $Cl_{Te}-Te_{Cd}$ complex passivates the deep level associated to the Te antisite (Te_{Cd}), confirming to some extent the beneficial effect of chlorine in CdTe.”*

Acknowledgments

- W.S. Sampath and J.R. Sites
- US Department of Energy SETO and CTAC
- NSF IUCRC for Solar Powered Future 2050 (and the Industrial Advisory Board)
- Past and current, students and colleagues at CSU



Characterizing hetero-interfaces at high spatial resolution using scanning transmission electron microscopy

Arashdeep Thind, Noah Kamm, Robert F. Klie

Department of Physics

University of Illinois Chicago

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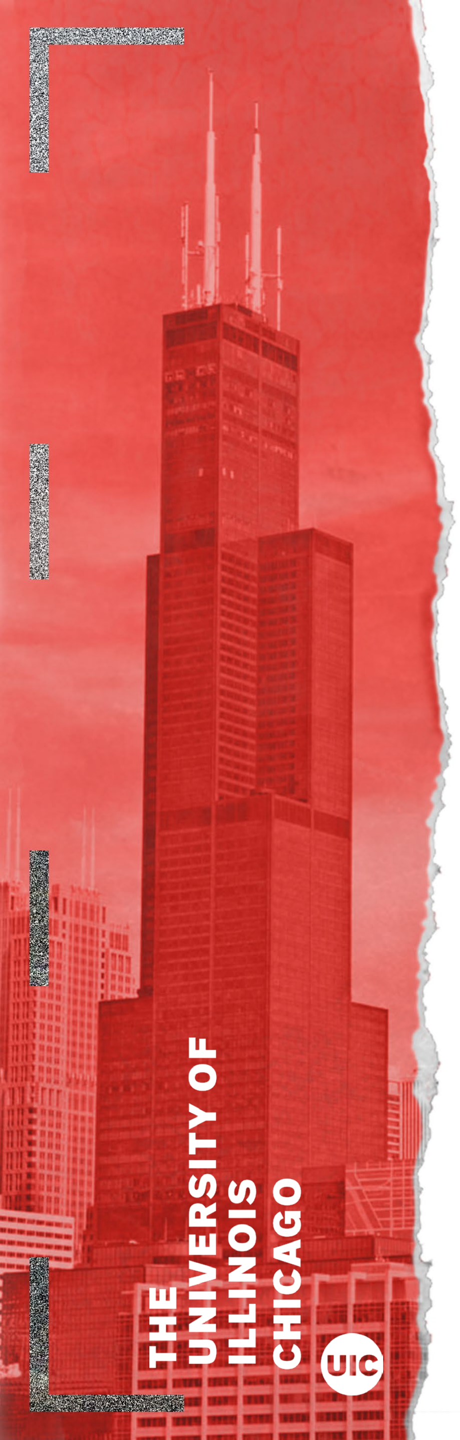

Outline

1) Defect Characterization and Elemental Diffusion at CdSeTe/CdTe interfaces

3) Machine Learning for Anomaly Detection in CdSeTe

4) Characterization Challenges of Back-Contact Passivation Layers

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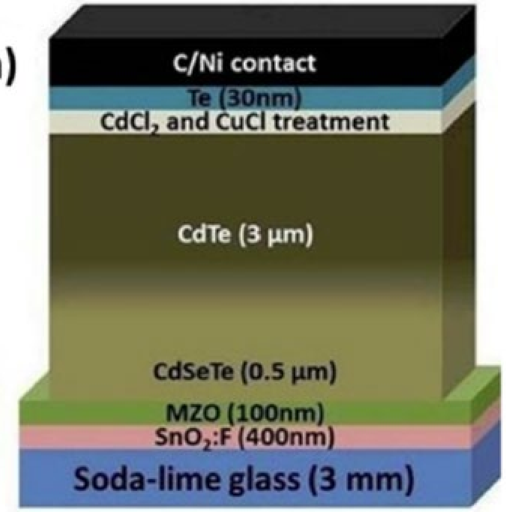
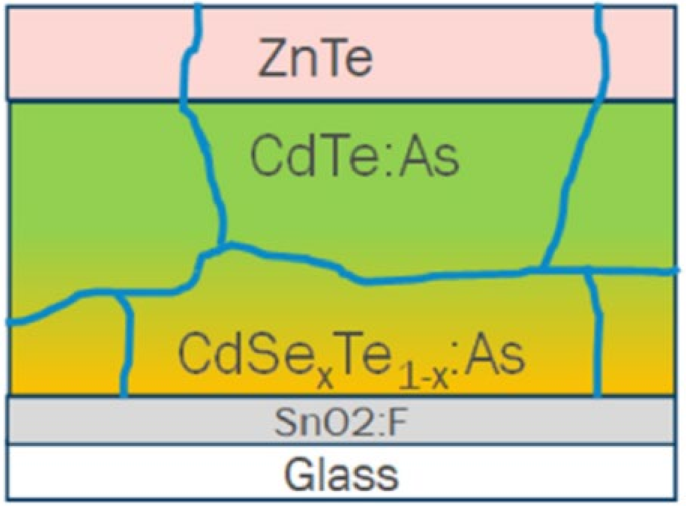
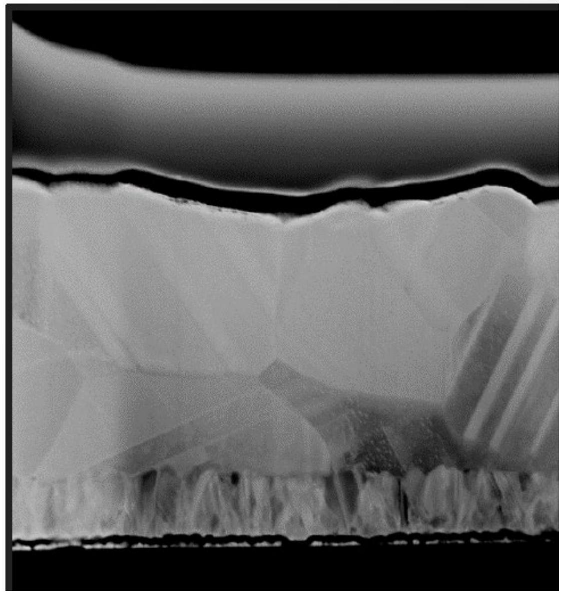
CdTe Solar Cells

(a)



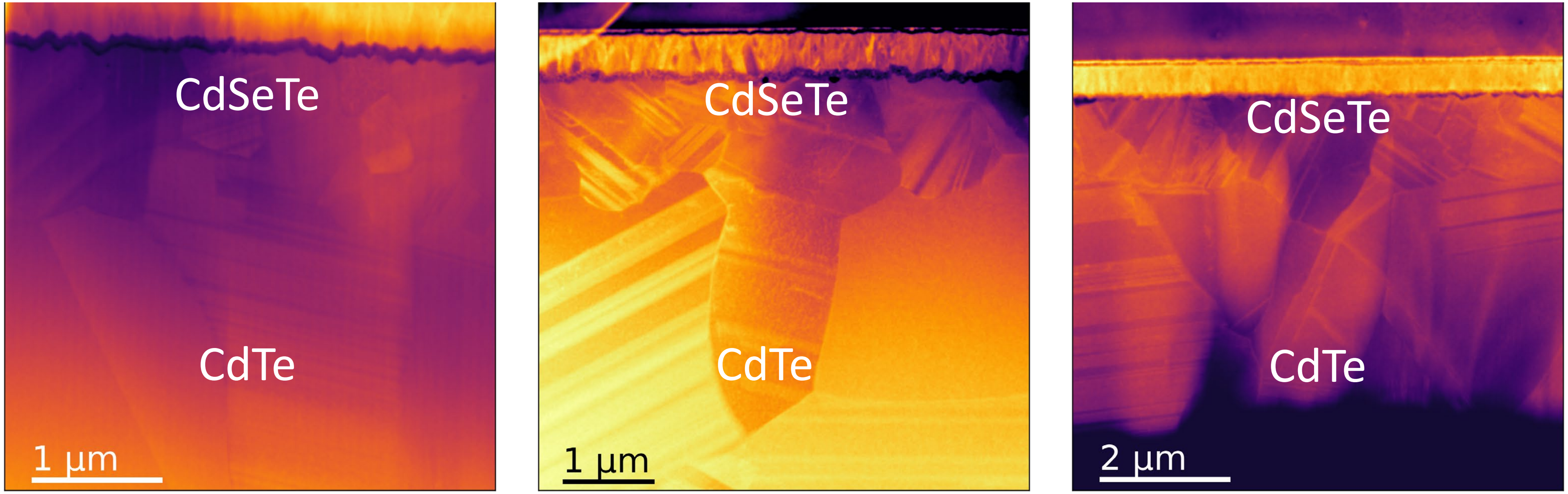
(b)





- **Interfacial Se diffusion and structural defects vary during device lifetime.**
- **Atomic-structure and stability of back-contact surface are challenging to quantify.**

Morphology of CdSeTe photovoltaics



- CdSeTe-based photovoltaics retain high photovoltaic efficiency despite a high concentration of grain boundaries and defects.
- CdSeTe layer has a smaller grain size and hence a higher density of planar defects than the CdTe layer.

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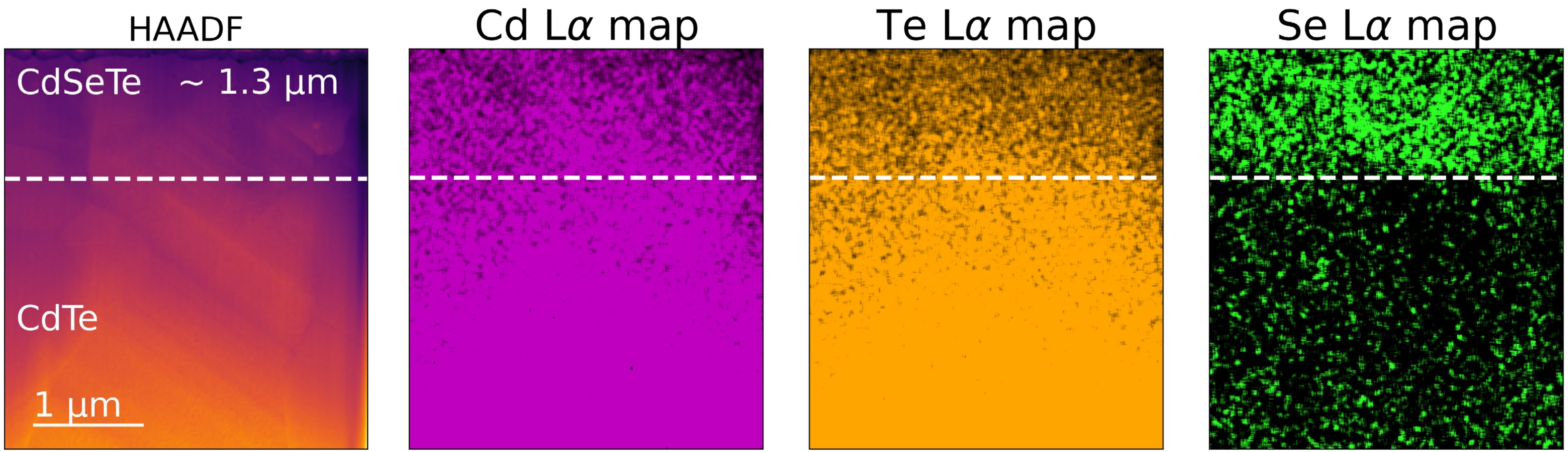
CdSeTe photovoltaics



- Se doping yields optimal band structure for optimal photovoltaic efficiency.
- Se doping lowers the band gap.
- Electrons and holes can be intrinsically separated because of band grading.

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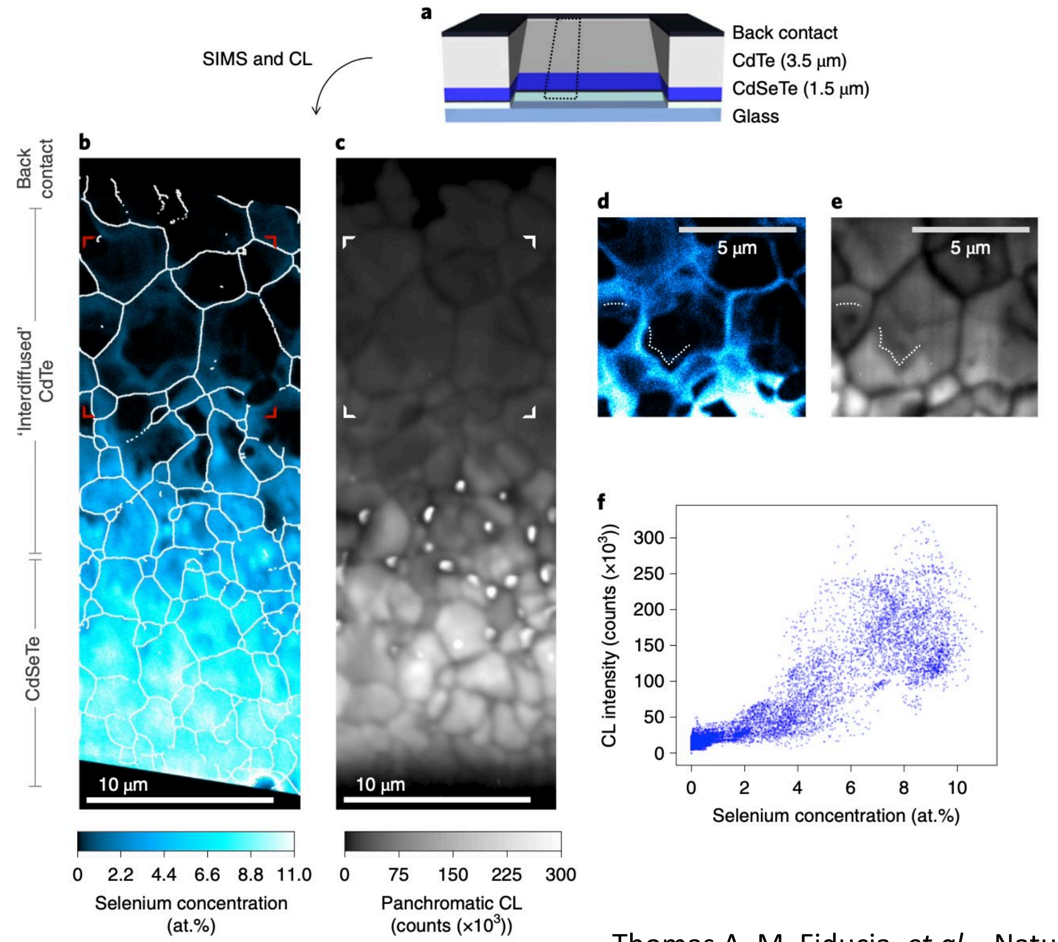
CdTe-based photovoltaics



Thomas A. M. Fiducia, *et al.*, Nature Energy, DOI: 10.1038/s41560-019-0389-z

- **Cathodoluminescence confirms that Se passivates grain boundaries as well as grain interiors.**

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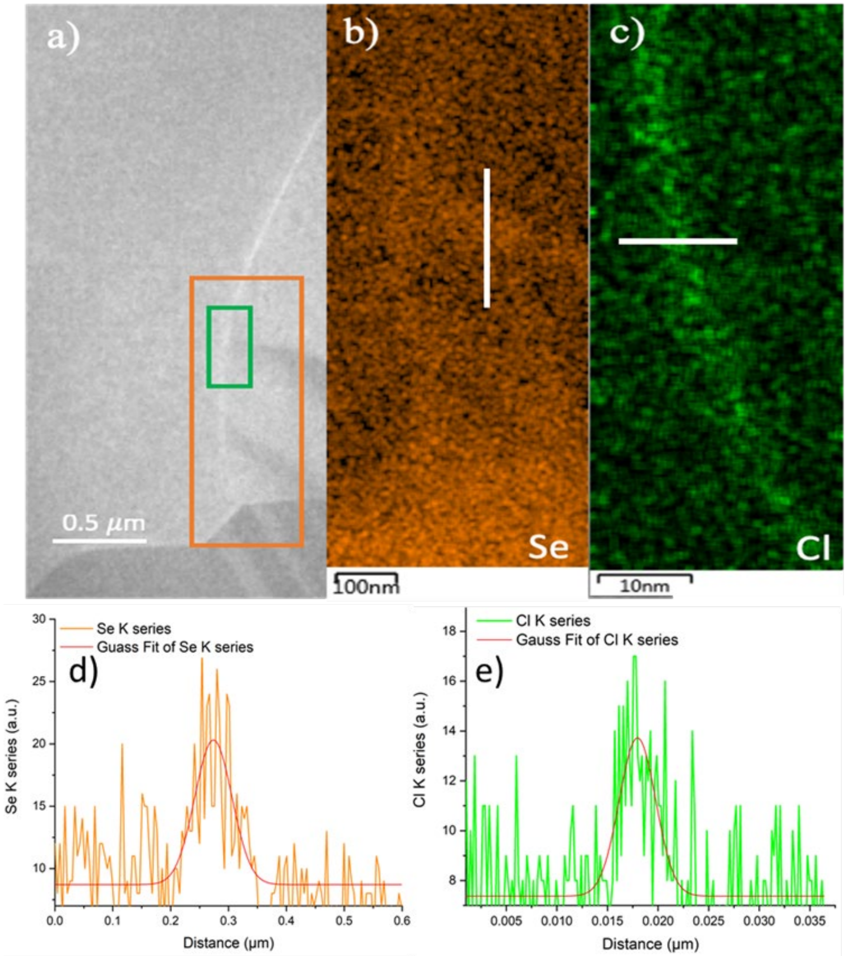
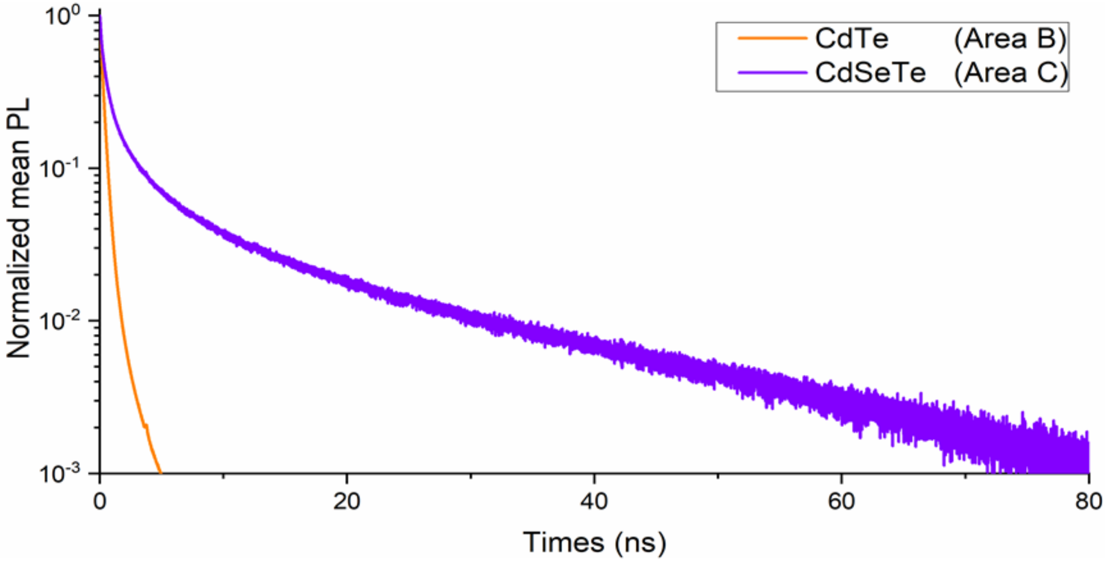
Grain boundary effects





- Presence of Se and Cl detected using EELS and EDX.
- Cl concentration profile is 20 times more narrow compared to Se.
- Significant improvements in carrier lifetimes are measured in co-passivated devices.

"Effect of selenium and chlorine co-passivation in polycrystalline CdSeTe devices ," J. Guo, A. Mannodi-Kanakkithodi; F.G. Sen; E. Schwenker; E. S. Barnard; A. Munshi, W. Sampath; M.K.Y. Chan; R. F. Klie; *Appl. Phys. Lett.* **115**, 153901 (2019)

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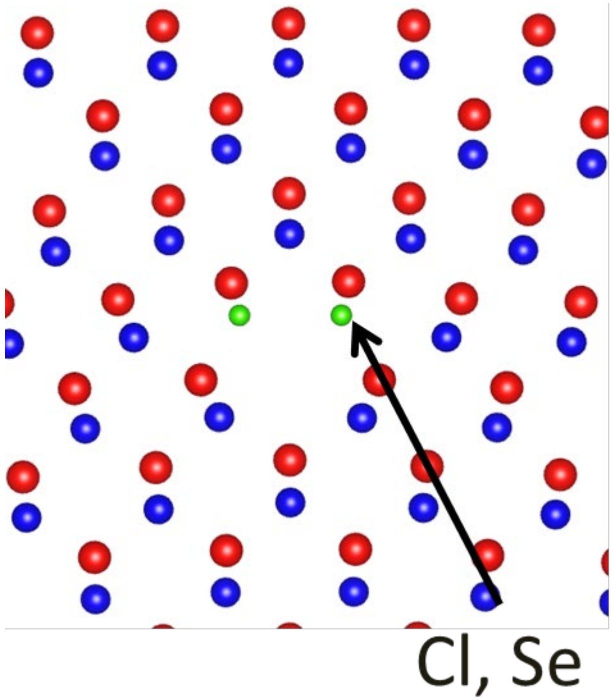
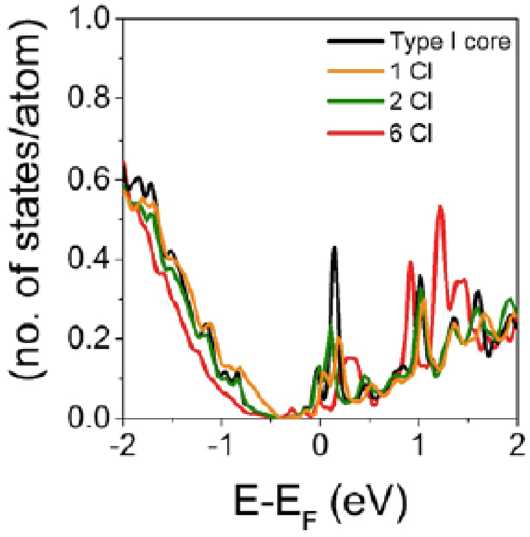
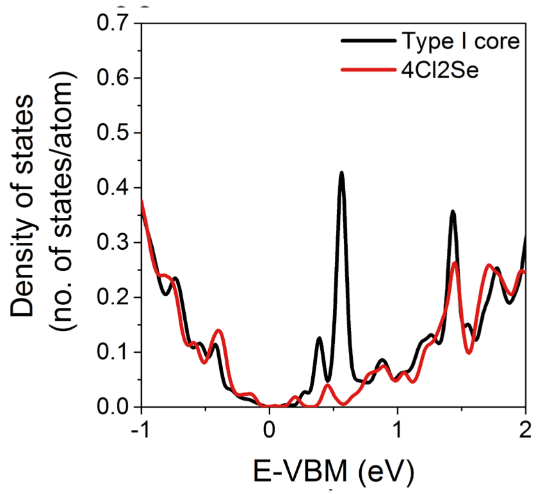
CdTe Modeling







- Cl , Se can passivate defect states in the mid-gap.
- Cl and Se segregation of dopants to grain boundaries is thermodynamically favorable.
- Co-doping Se+Cl further reduces mid-gap states when substituted to dislocation core.

"Effect of selenium and chlorine co-passivation in polycrystalline CdSeTe devices ," J. Guo, A. Mannodi-Kanakkithodi; F.G. Sen; E. Schwenker; E. S. Barnard; A. Munshi, W. Sampath; M.K.Y. Chan; R. F. Klie; *Appl. Phys. Lett.* **115**, 153901 (2019)

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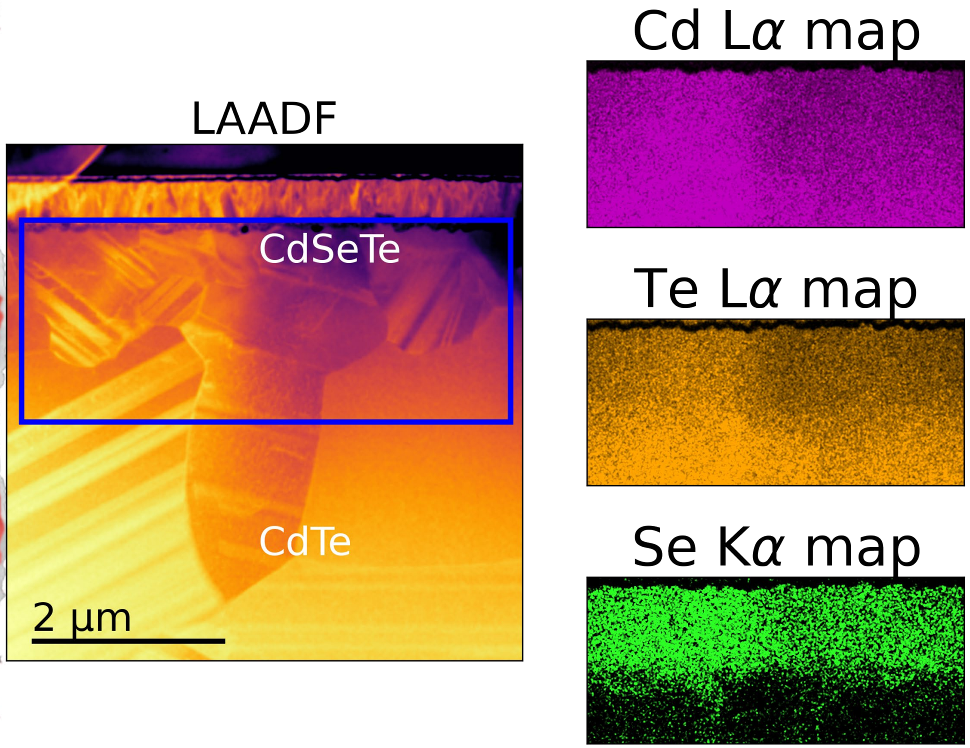
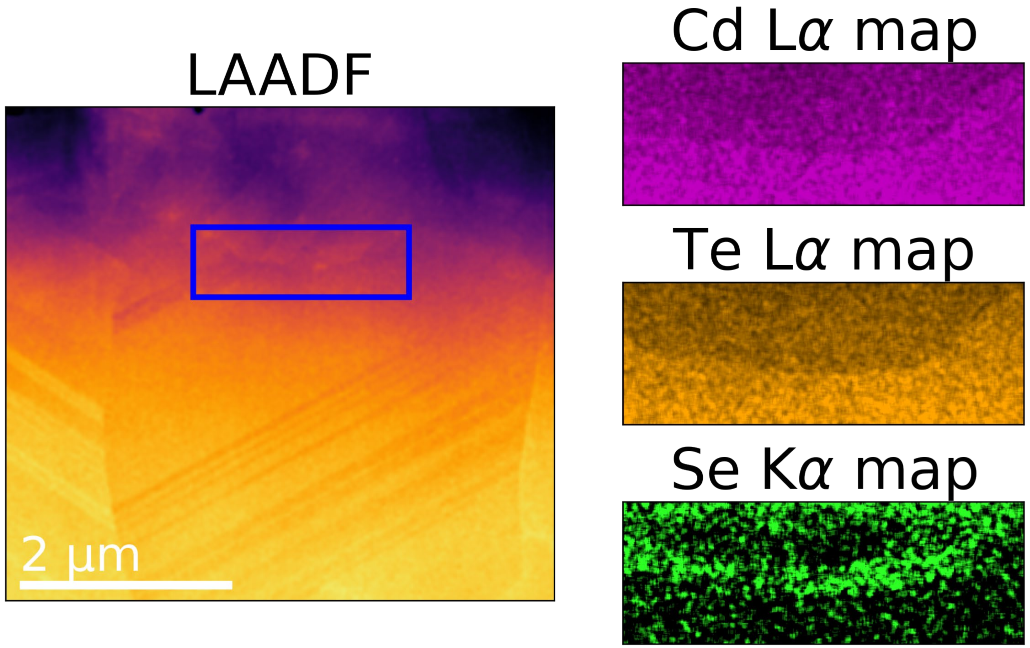
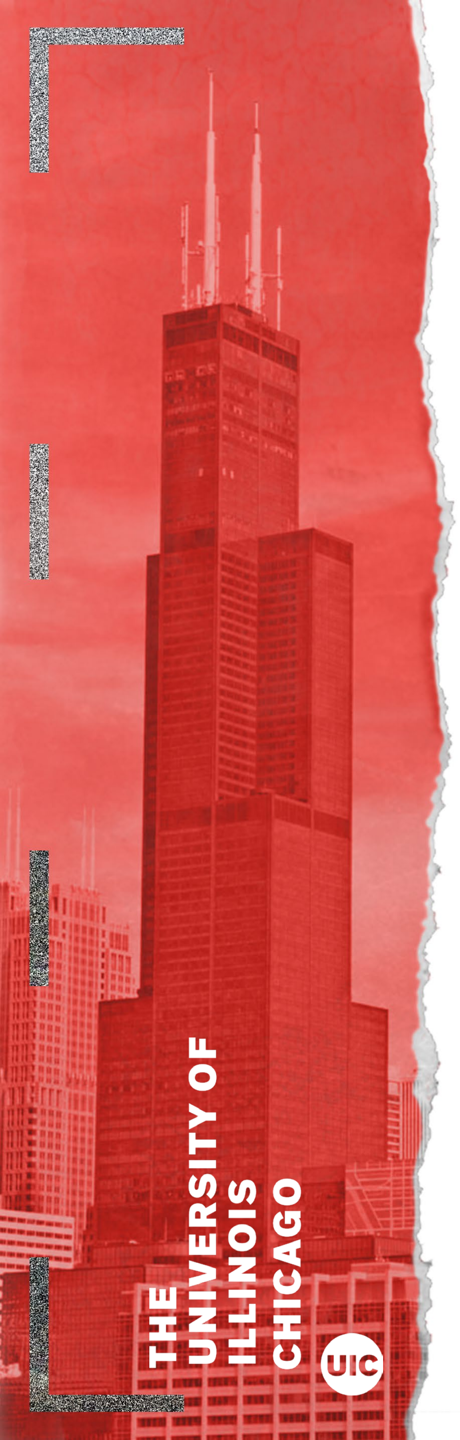
Low temperature Se diffusion





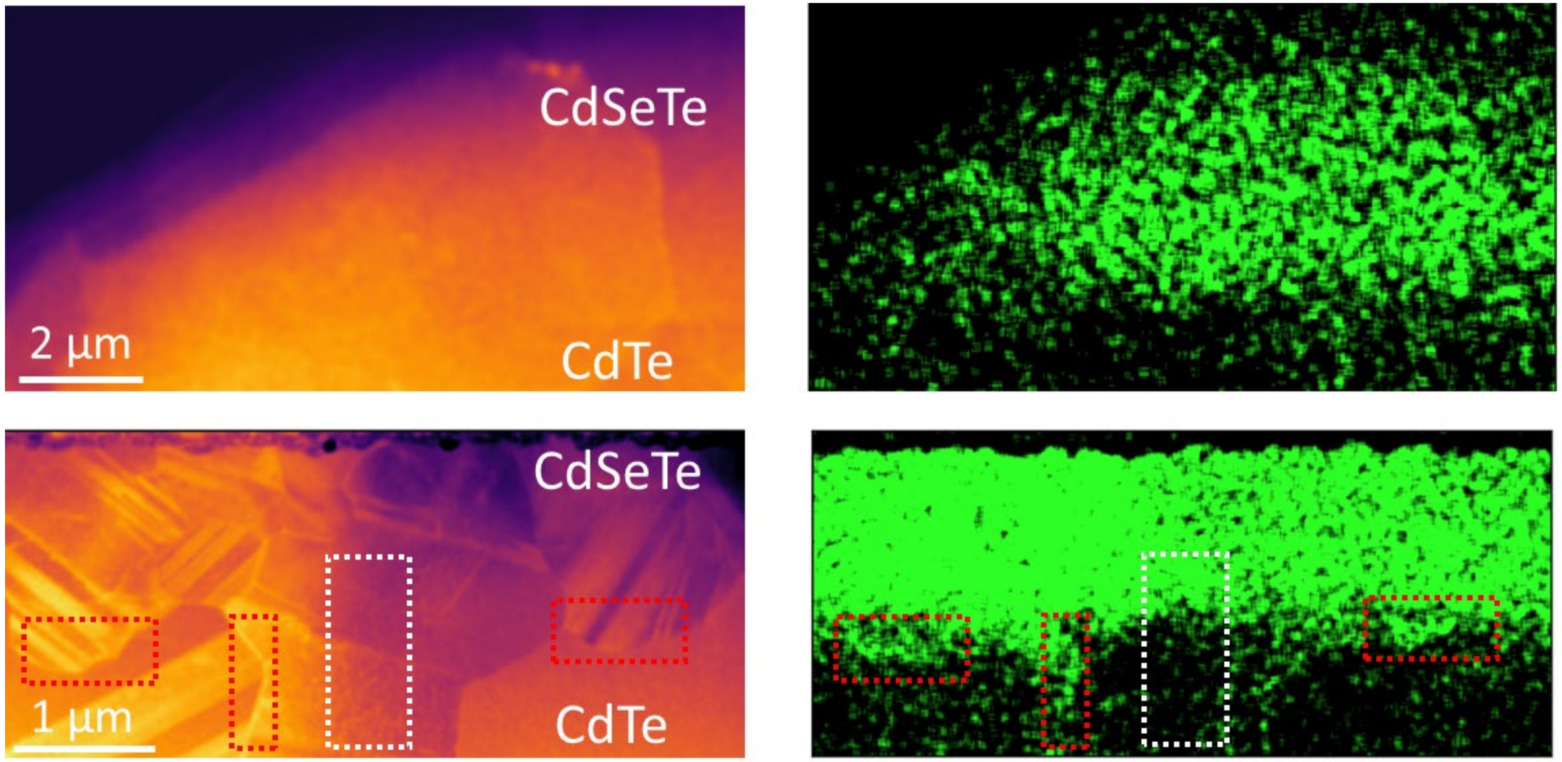
- **Se diffusion via grain boundaries at the CdSeTe/CdTe interface at operational conditions.**
- **How does Se diffusion impact electronic performance?**



Se diffusion at the interface

Intragranular interface

Intergranular interface



- Sharp interface for intragranular regions.
- Se diffusion between CdSeTe and CdTe grains via grain boundaries for intergranular regions.

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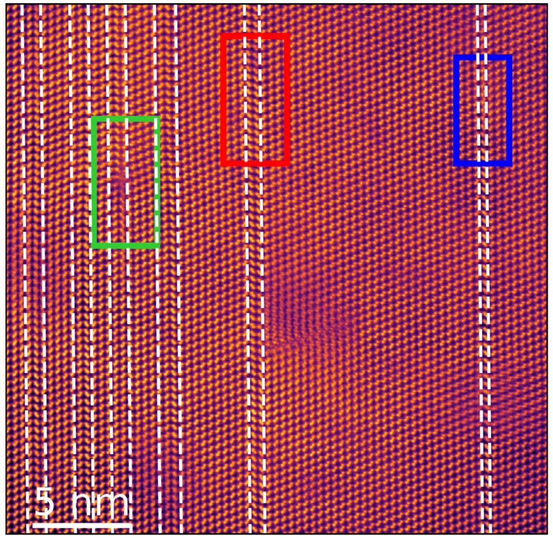
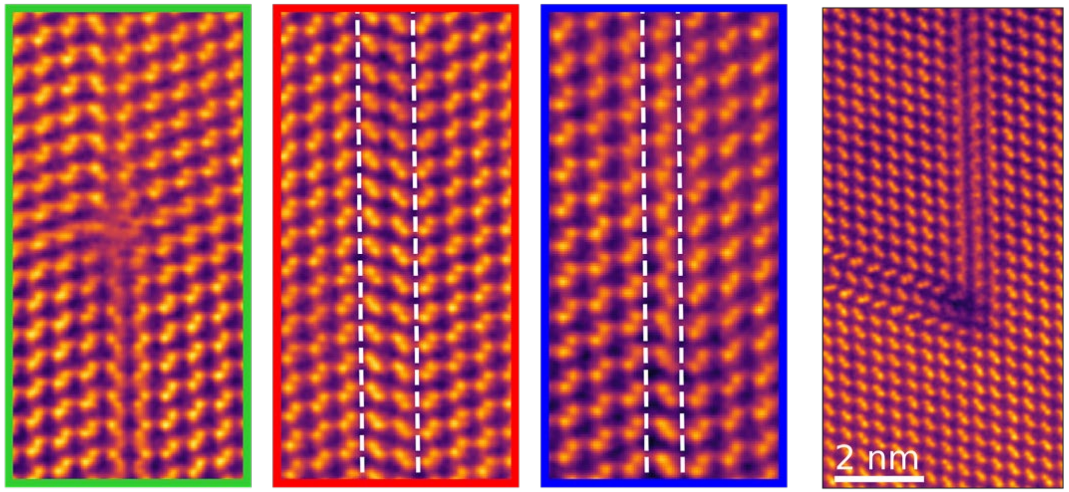
Defect Diversity in CdSeTe/CdTe interface

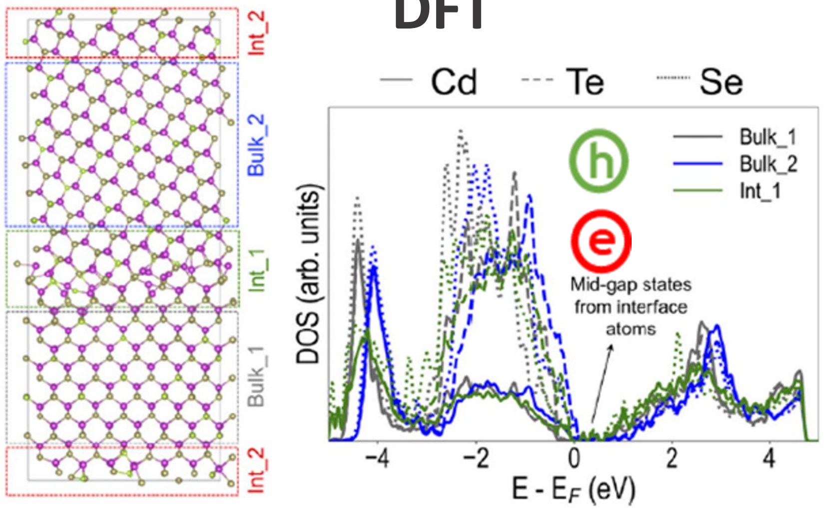
High defect density





- Wide variety of defect types detected in bulk CdSeTe and grain boundaries.
- Se and Cl co-passivation of grain boundaries.

DFT



7th CdTe Workshop
October 26th, 2023

Klie, R. F., Appl. Phys. Lett. 2019, 115 (15), 153901.

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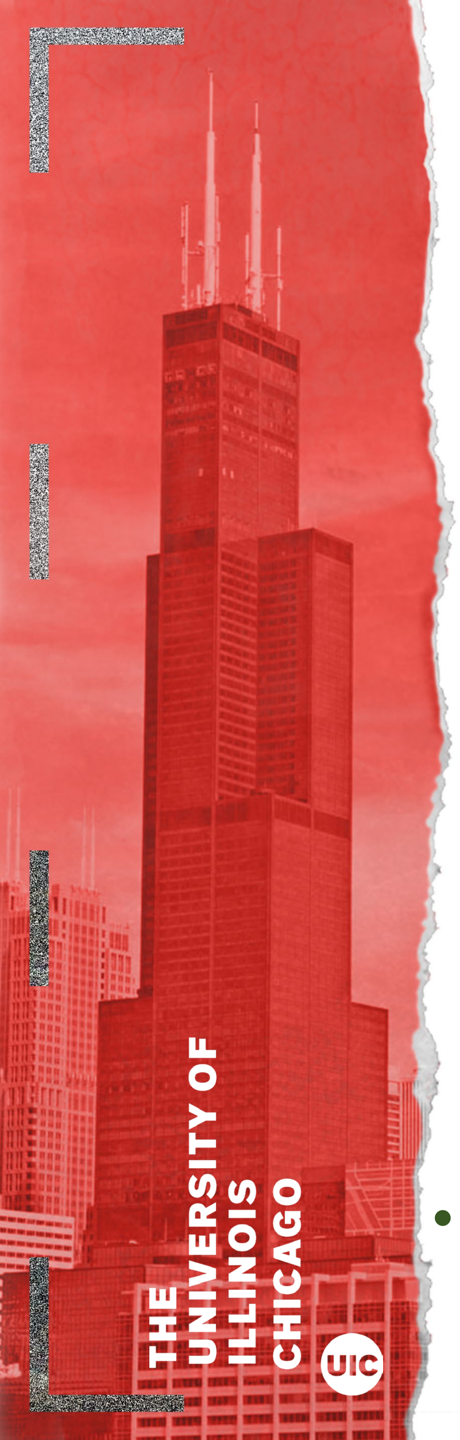
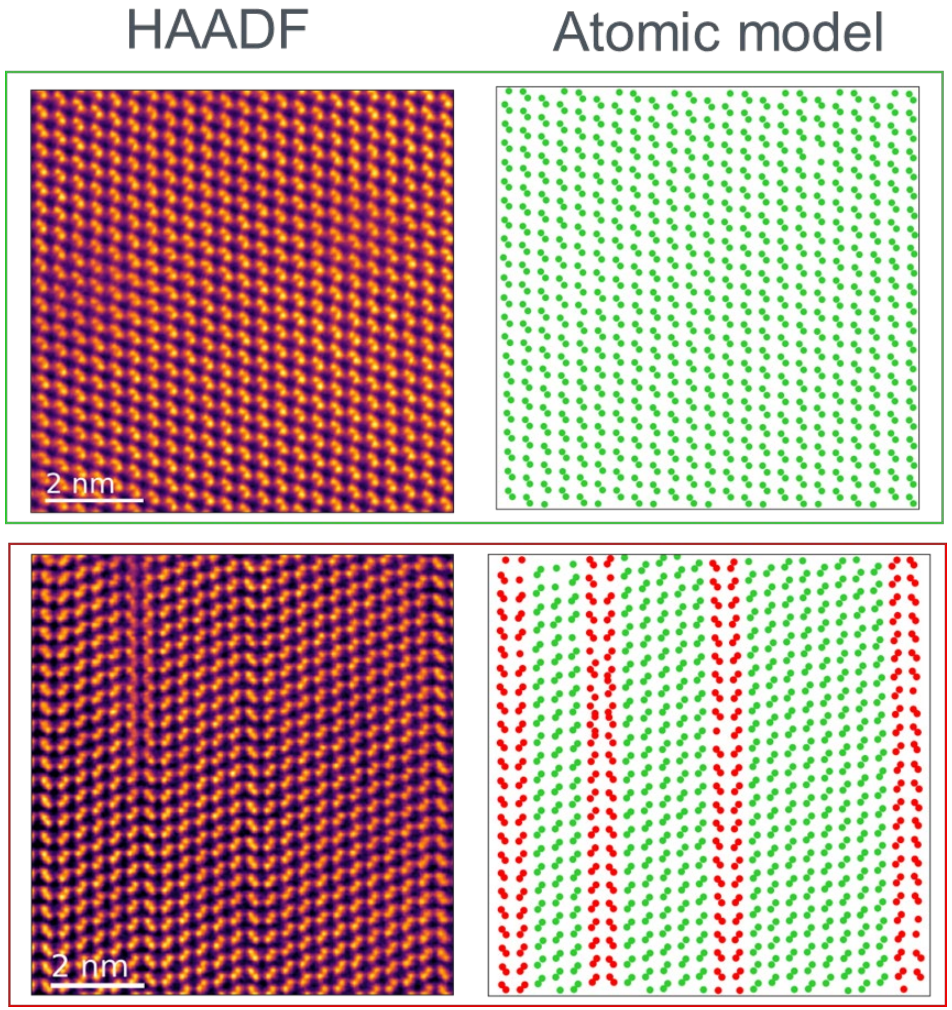
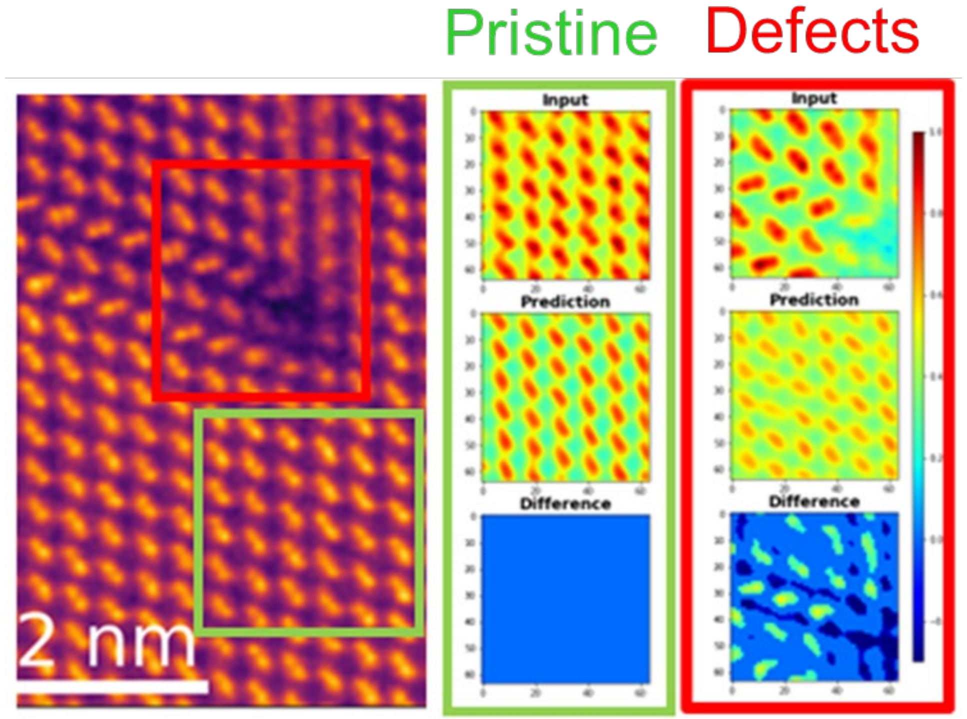


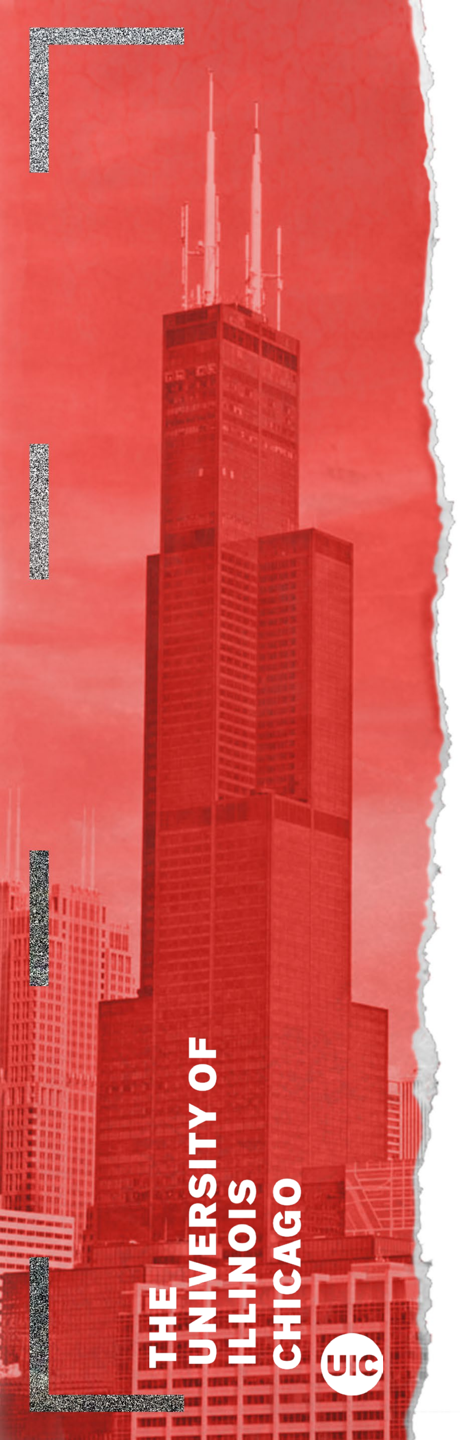
Automated Anomaly Detection





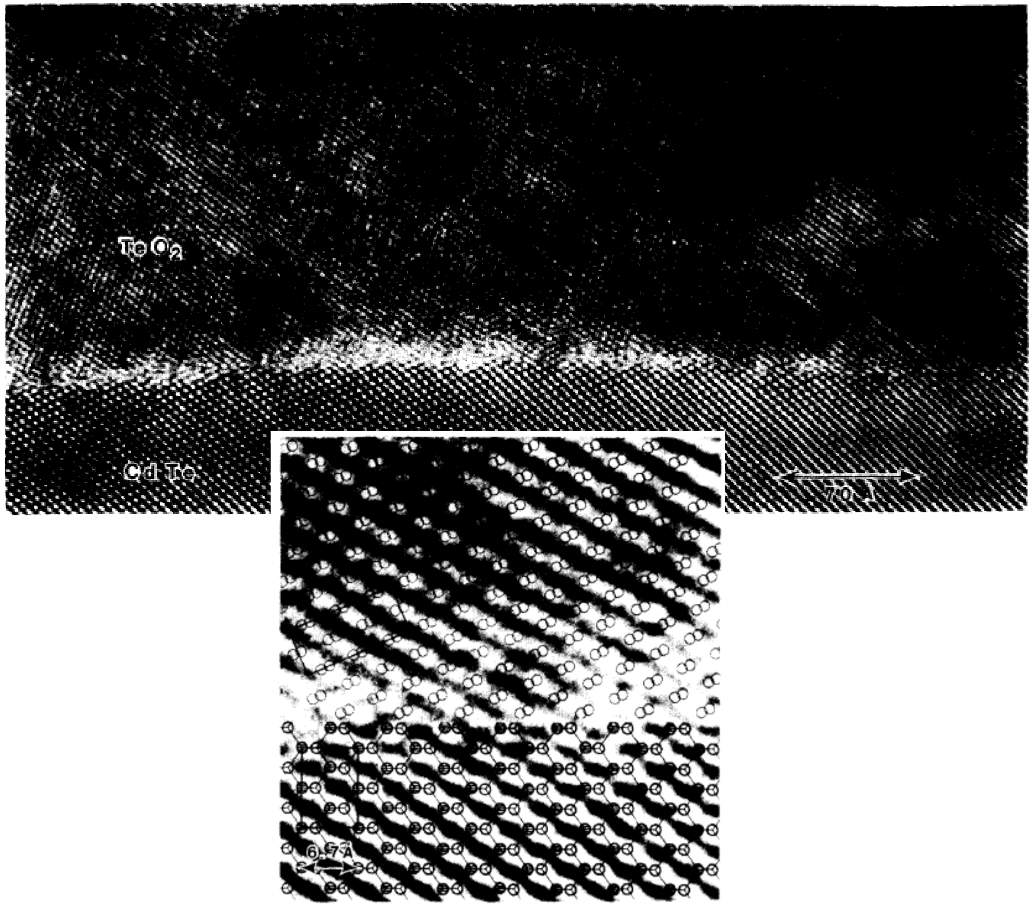
E. Prifti, J.P. Buban, A.S. Thind, R.F. Klie. *Small*, 2205977 (2023)

- **Develop Variational Autoencoder Convolutional Neural Network for automated defect detection and classification.**



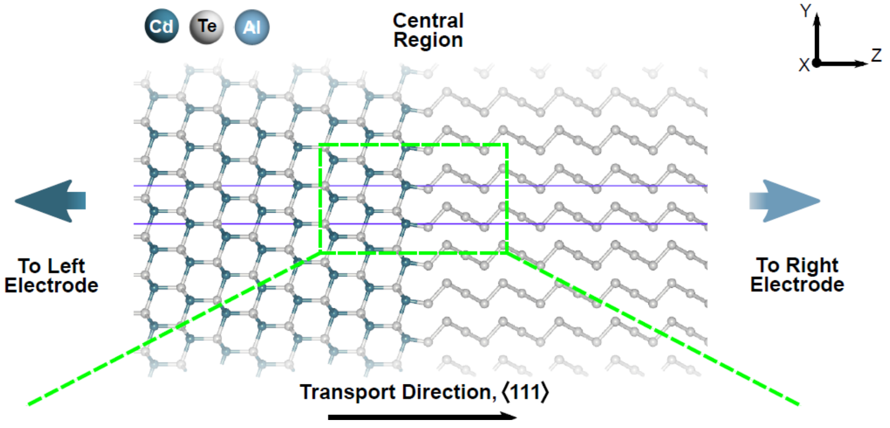
Back-Surface Passivation

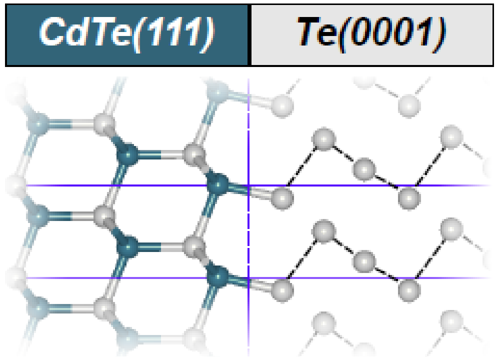
First sighting of CdTe/TeO_2 crystalline interface

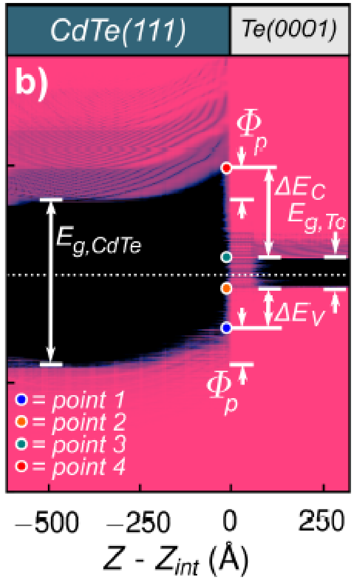


"Native tellurium dioxide layer on cadmium telluride: A high-resolution electron microscopy study," F. A. Ponce; R. Sinclair; R. H. Bube, Appl. Phys. Lett. 39, 951–953 (1981)

DFT predictions of crystalline interfaces

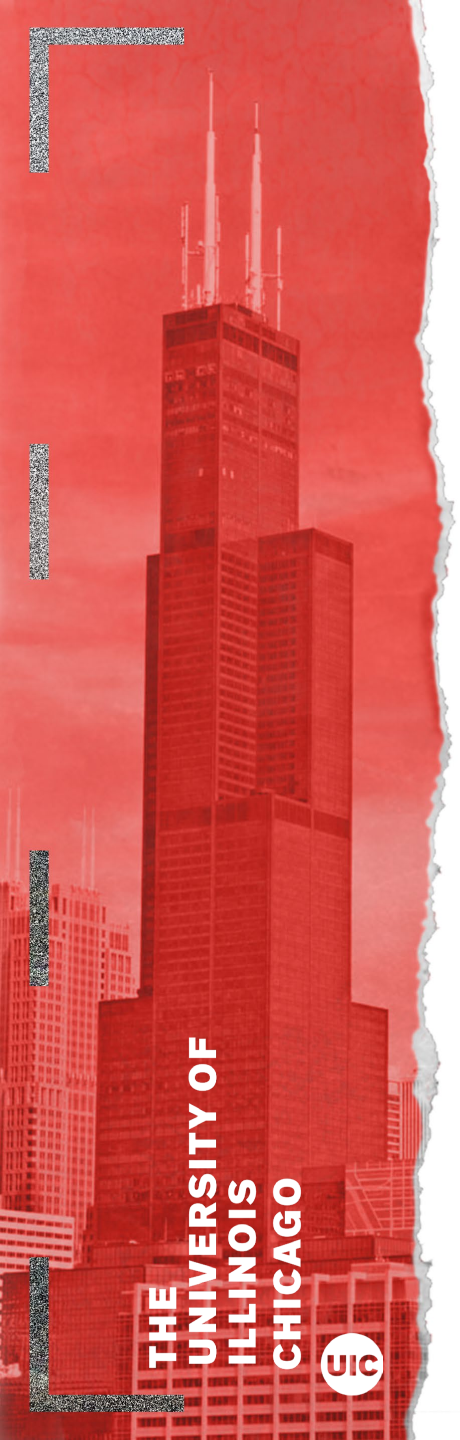


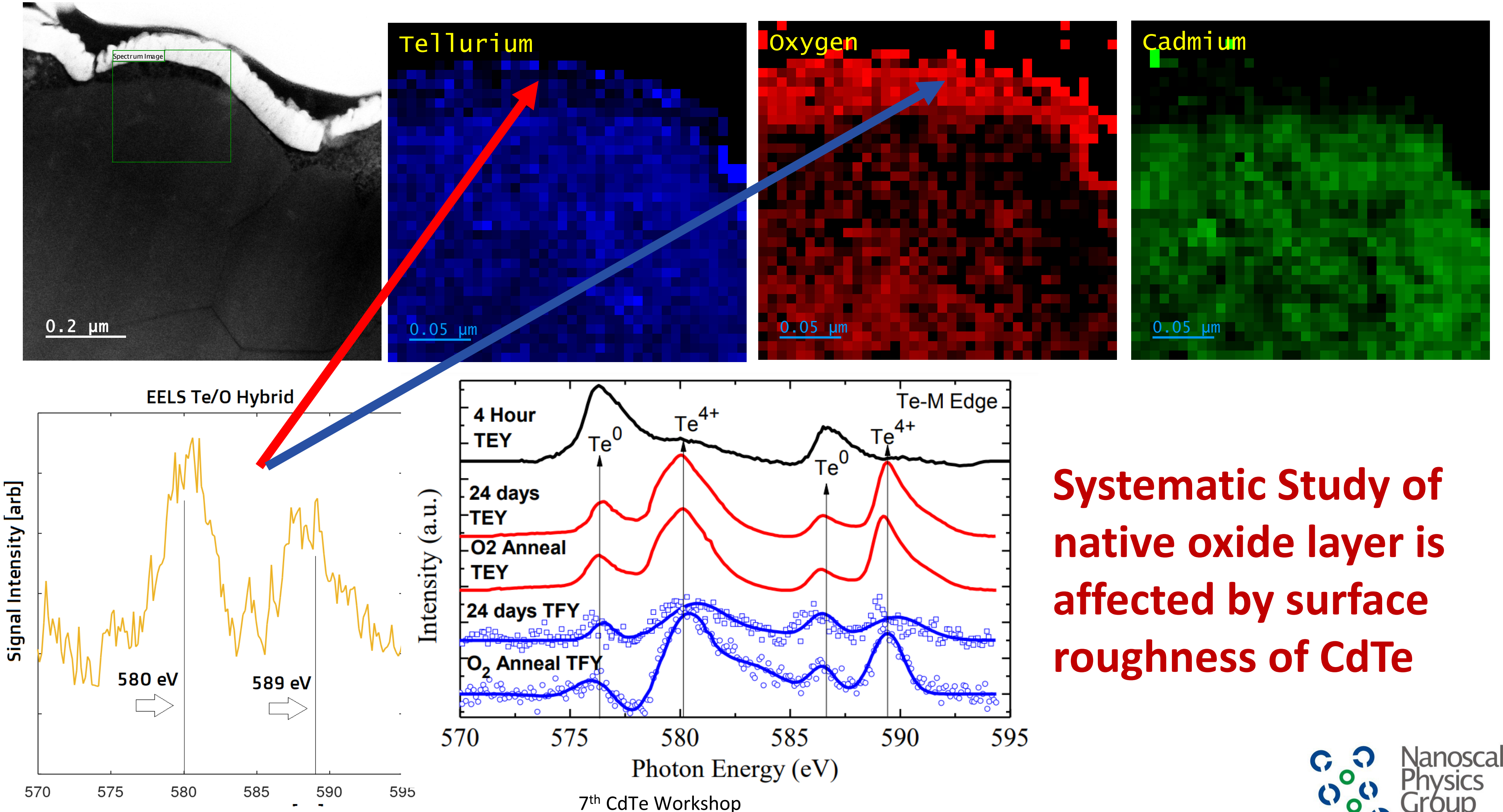




A. Nicholson et al., *ACS Applied Materials & Interfaces*, **14(25),** 29412-29421 (2022)

Back-Surface Passivation





Systematic Study of native oxide layer is affected by surface roughness of CdTe

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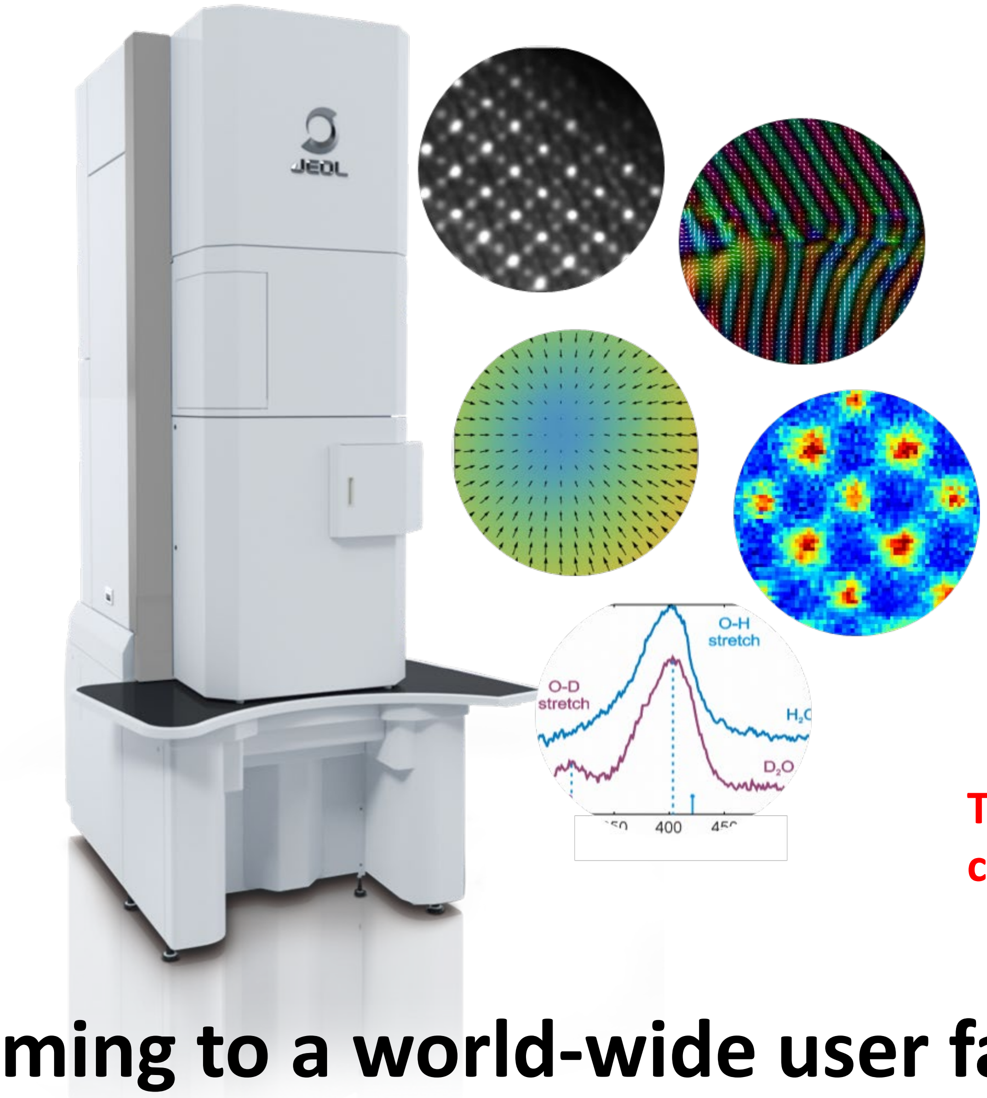
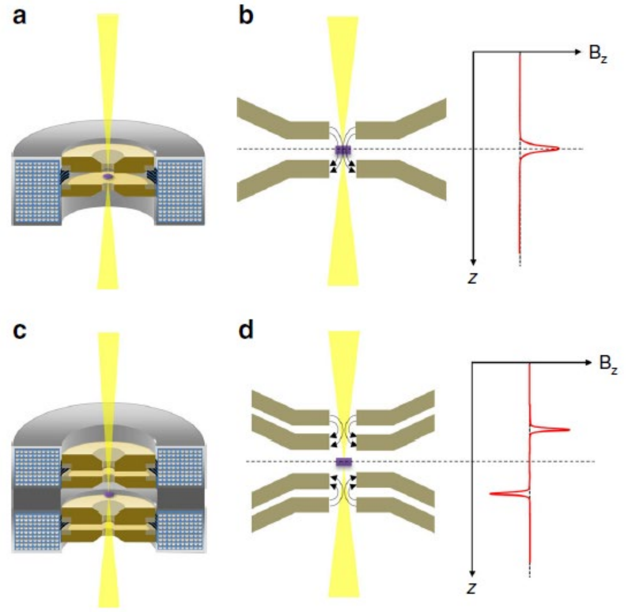
Outlook

- Develop $CdTe/TeO_2$ model systems to study atomic and electronic structures of crystalline interfaces
- Study diffusion of Se after accelerated aging experiments as a function of CdSe/CdTe interface type
- Machine Learning and novel acquisition approaches allow for fast defect analysis
- 4D STEM for multi-dimensional defect and interface analysis

New Instrumentation





The world's first monochromated, aberration-corrected, magnetic-field-free STEM

Coming to a world-wide user facility in 2024 at UIC!

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M. Heben,
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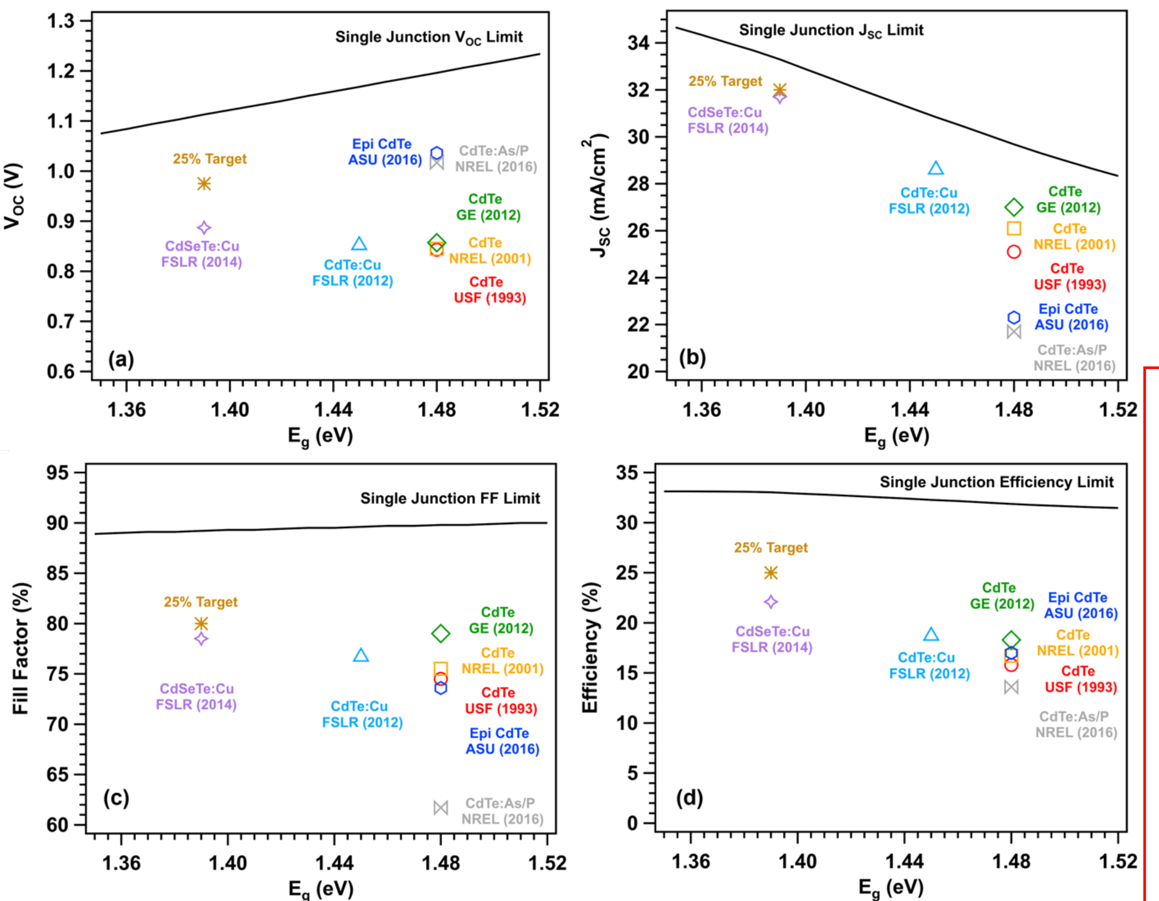
Surface Photovoltage Spectroscopy: Shining New Light on Back Contacts

Mike Scarpulla, Nathan Rock

MSE & ECE University of Utah

Funding: DOE as part of CTAC

Path for CdTe is Still to Improve V_{oc} and FF



Origins of ~900 mV V_{oc} ceiling ?

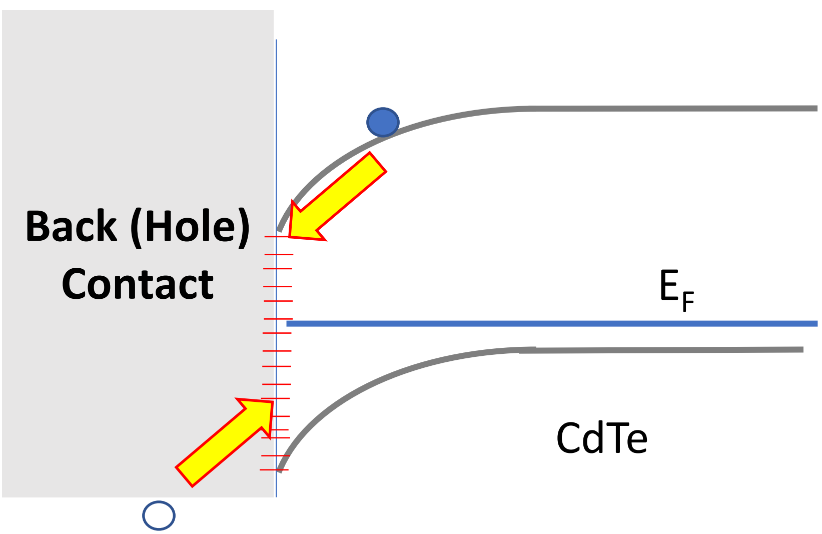
- Bulk & GB SRH
- Band tails (rad or nonrad rcomb)
- Contact / interface recombination (maybe linked to band bending too)
- Contact carrier selectivity
- Contact V losses (energy offsets, V=IR)

Courtesy of Alex Bothwell – from Scarpulla et al., SEEMSC **255** 112289 (2023)

Ideal and Real Hole Contacts

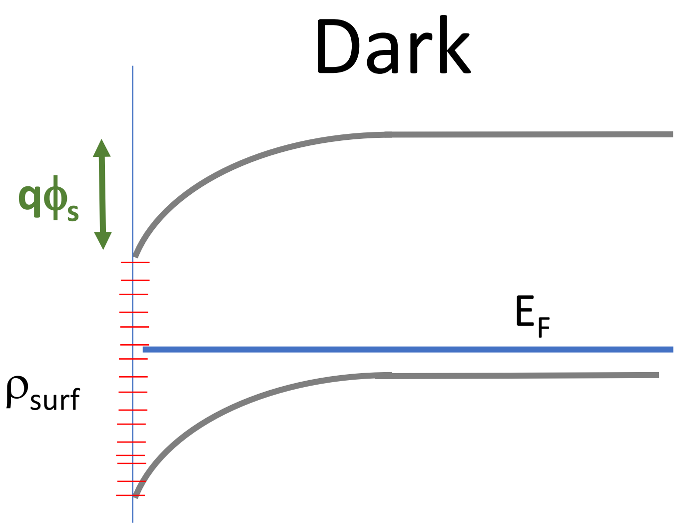
Want: Reversible, hole-selective, low-resistance, bifacial-enabling back contact

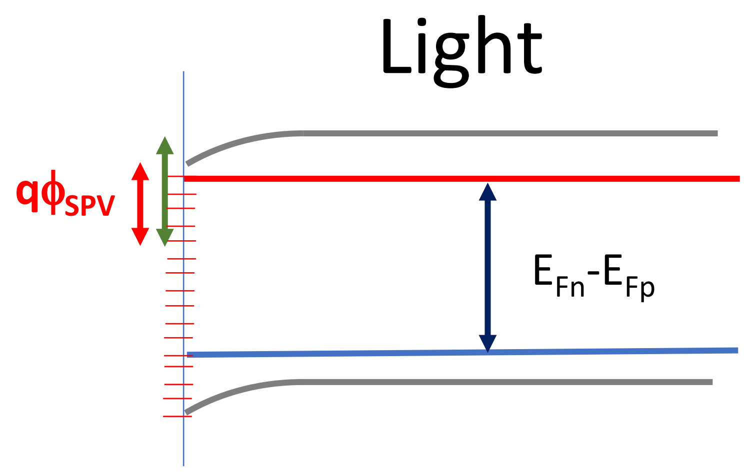
• Extract holes at E_{Fp} reversibly	Energy level alignment near V_{oc}
• Reject e-	Upwards band bending (charge) or CB offsets
• Suppress interface recombination	Passivate traps or keep e- away



How to characterize?

Surface Photovoltage



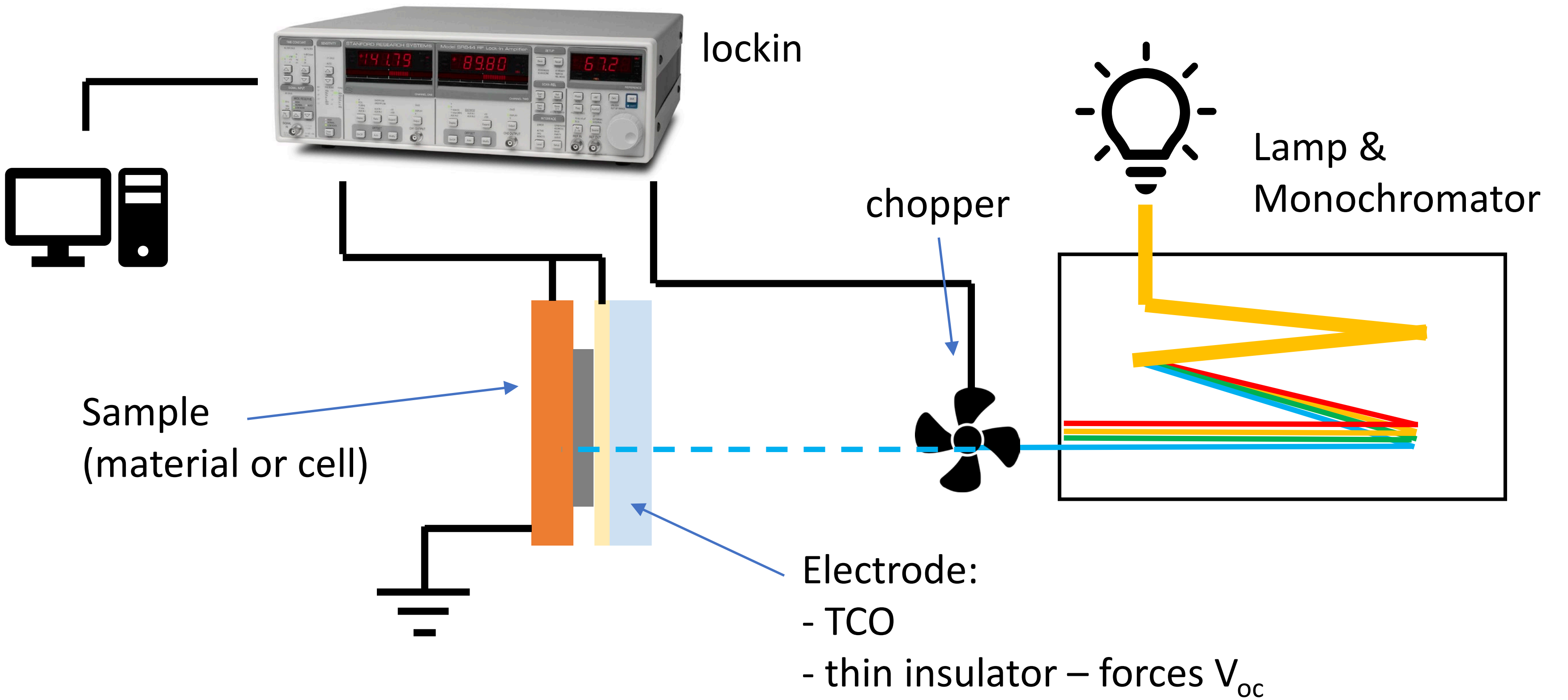


CdTe surface with E_F pinning from traps
ϕ_S = surface built-in voltage

Excess carriers bias surface/bulk junction towards flatband
ϕ_{SPV} magnitude depends on:
ϕ_S, τ_{bulk}, μ_{bulk}, SRV, ρ_{surf}, $I_{light}(\lambda,t)$, …

- SPV: same origin and physics as PV operation. Thus sensitive to all the same factors
- **Surface photovoltage spectroscopy: like IQE, but at V_{oc} rather than J_{sc}**
- Adds orthogonal information to JV, IQE, CV, etc
- Works for structures for which current is not an option: e.g. thick Al_2O_3 passivation

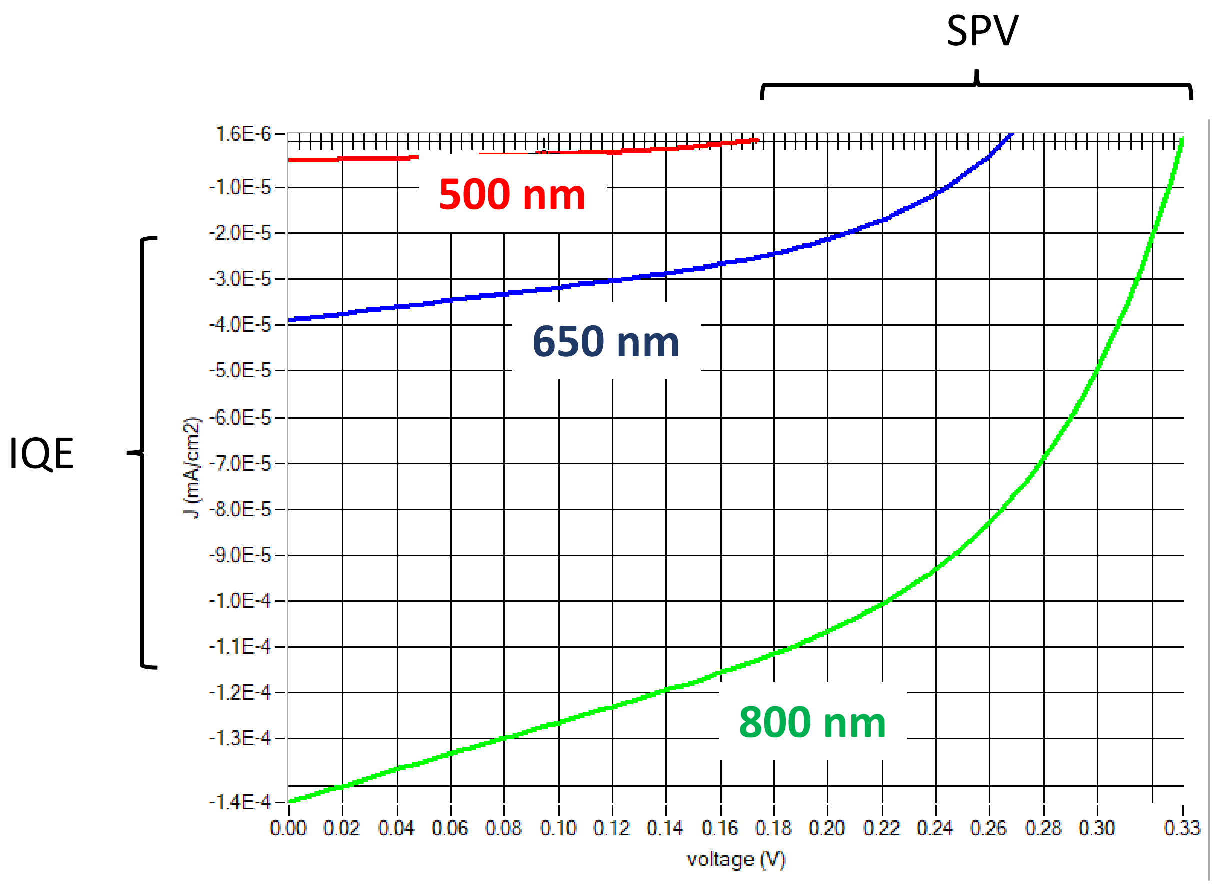
Our Photovoltage Spectroscopy Setup



- Transparent electrode forms MIS structure with sample
- Chopped monochromatic light (can add other sources and AM1.5 bias light)
- Can vary V, light spectrum, intensity, time modulation
- Can measure bifacial cells without separate electrode

Direct Simulation & Relation of IV, IQE, and SPV

SCAPS Direct Simulation



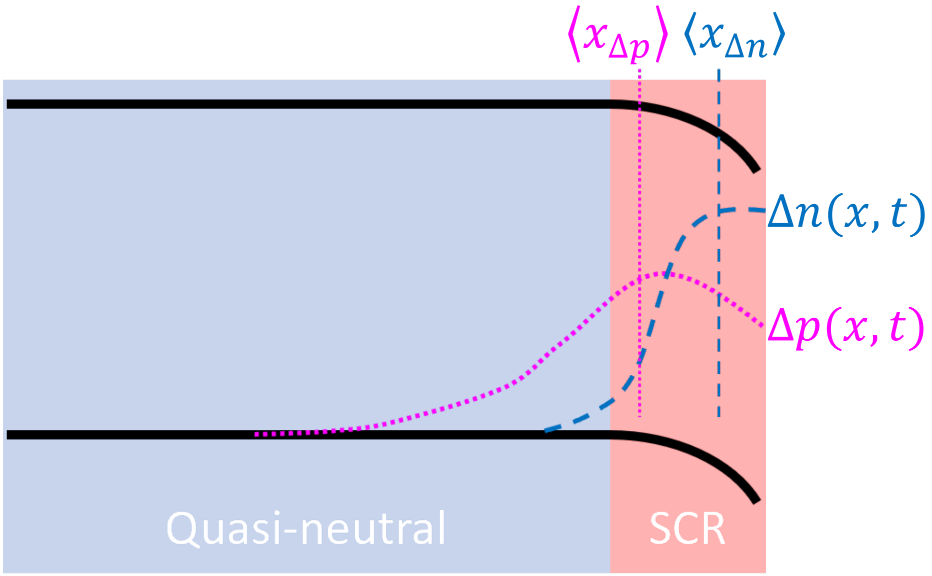
Monochromatic illumination
Each λ: 10^{16} ph cm^{-2} s^{-1}

Undoped CdTe Cell

E_f pinned by mid-gap states at back interface

IQE: Collection of Each Carrier (yes/no)
SPV: Utilization of Voltage from Each Carrier (shades of grey)

Intuitive Understanding of SPV: Difference in Excess Carriers' Centers of Mass



Asymmetry in band diagram (e.g. any SCR) separates Δn and Δp distributions

Treating excess carrier distributions as a parallel plate capacitor gives good approximation

$$SPV = \frac{q}{\varepsilon_r \varepsilon_o} \Delta n \left[\langle x_n \rangle - \langle x_p \rangle\right]$$

Must model Δn(x,t), Δp(x,t) distributions: analytical or numerical

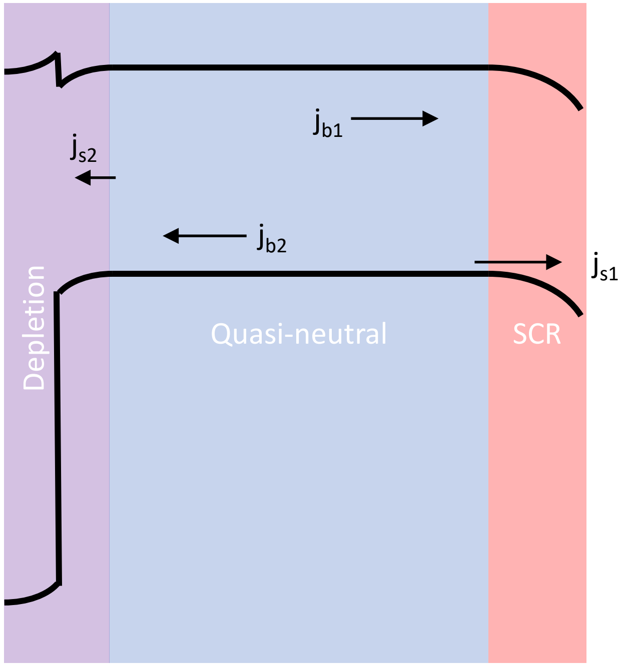
Analytical Model of SPV

Analytical model of Toušek and Toušková (2001,2008,2014)
Can handle thin or thick bulk, SCR and depletion regions
Splits device into layers: front junction, QNR, back SCR

$J_{ph1} = j_{QNR1} + j_{SCR1}$
$J_{ph2} = j_{QNR2} + j_{SCR2}$

$$V_{oc1} = \frac{k_B T}{q} ln\left(1 + {}^{j_{ph1}}\!/_{j_{01}}\right)$$ V from back

$$V_{oc2} = -\frac{k_B T}{q} ln\left(1 - {}^{j_{ph2}}\!/_{j_{02}}\right)$$ V from front



Linear for small excitation intensities

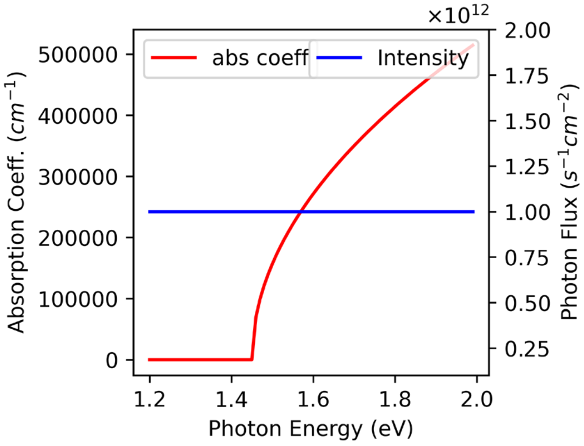
$$V_{oc1} \cong \frac{k_B T}{q} {}^{j_{ph1}}\!/_{j_{01}}$$

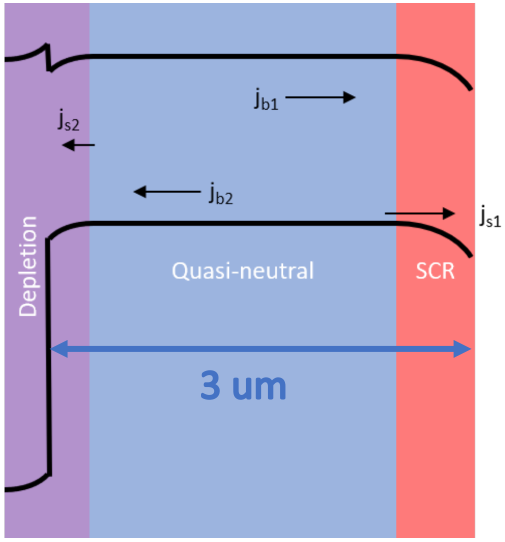
$$V_{oc1} \cong \frac{k_B T}{q} {}^{j_{ph1}}\!/_{j_{01}}$$

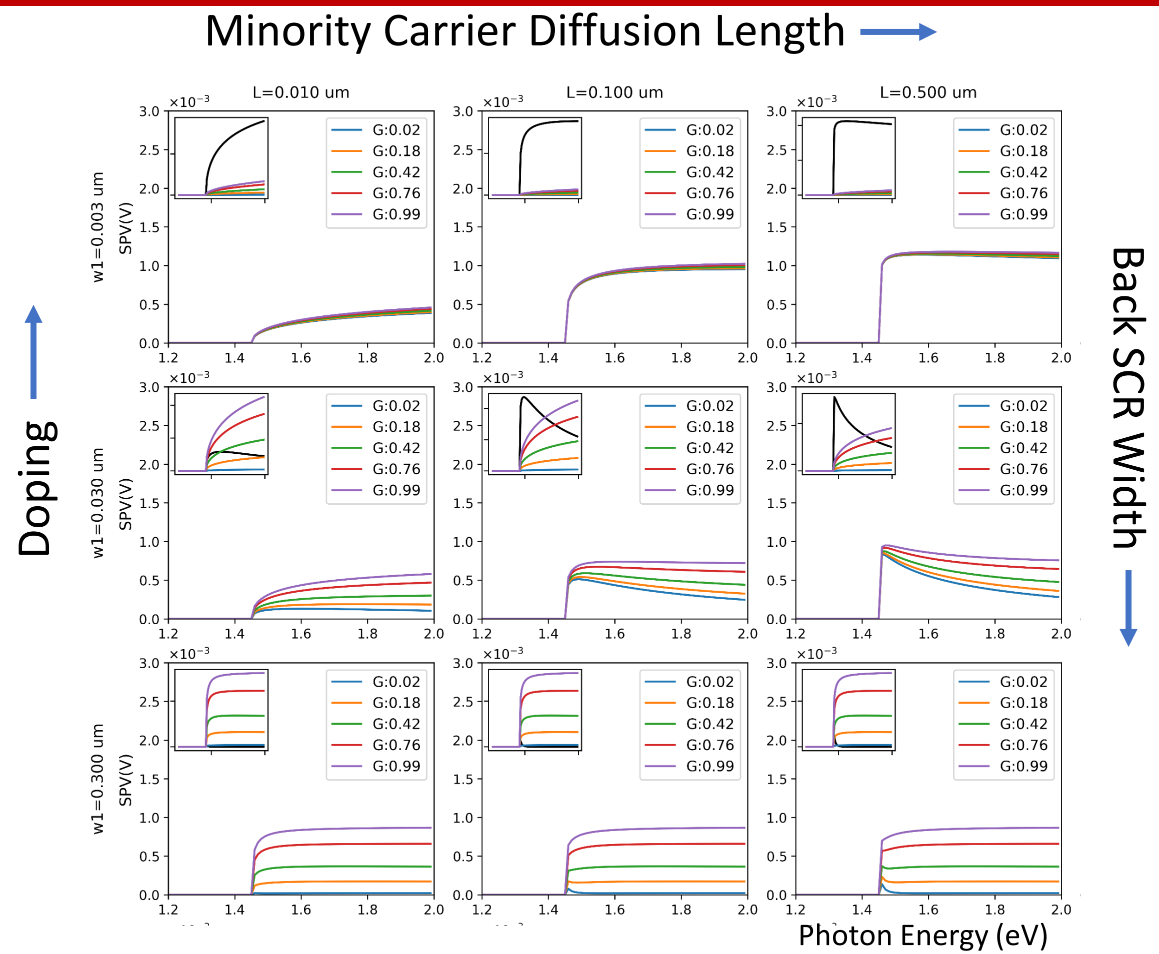
$$SPV \cong \frac{k_B T}{q}\left({}^{j_{ph1}}\!/_{j_{01}} + {}^{j_{ph2}}\!/_{j_{02}}\right)$$

Toušek, et al. 2001. https://doi.org/10.1063/1.1332418.
Toušek, J., and J. Toušková. 2008. https://doi.org/10.1016/j.solmat.2008.02.033.
Toušek, J., and J. Toušková. 2014. https://doi.org/10.1063/1.4893973.

Understanding Parameter Effects: Analytical



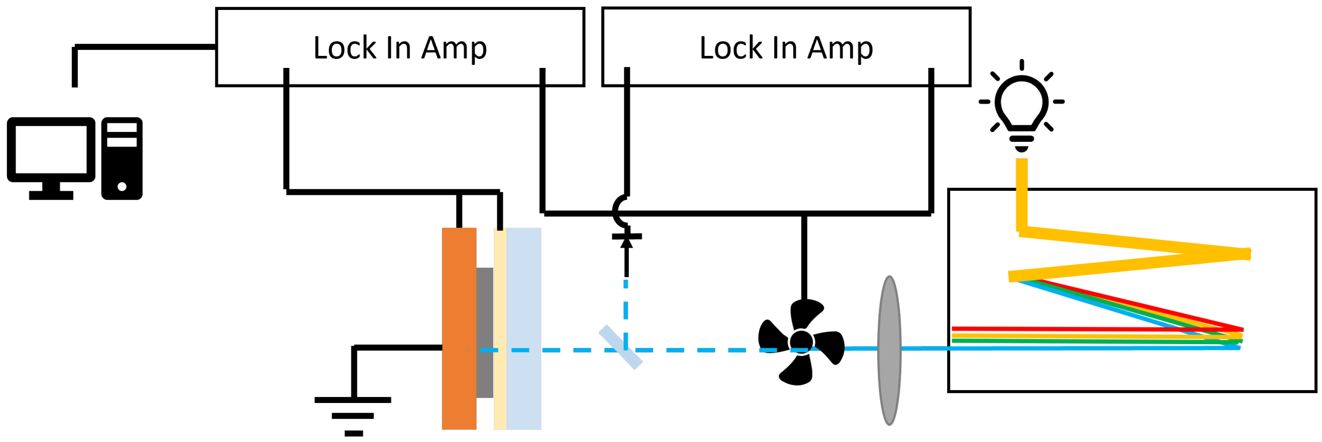




Like IQE, SPV spectral shape reflects generation, bulk recombination, surface recombination, …

*note these SPV shapes assume uniform incident spectrum

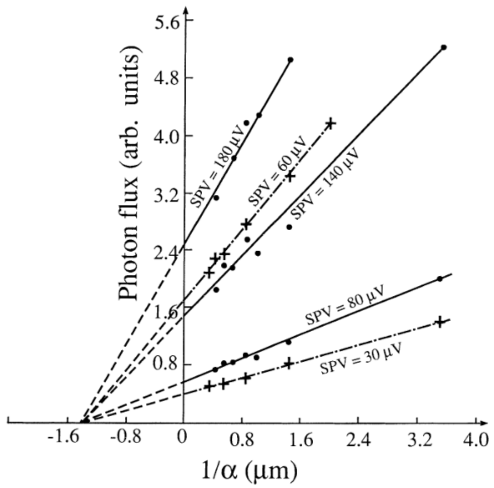
Can Goodman Method Be Used for CdTe?



Method for extracting *short* minority carrier diffusion lengths

Assumptions:
- Minority diffusion length (L) << absorber thickness (d)
- SCR width w << 1/α (absorption coeff.)

$$I(\lambda) = const \cdot \left(\frac{1}{\alpha(\lambda)} + L\right)$$



Need more complete modelling for modern CdSeTe devices

Goodman, JAP **32** 2550 (1961)

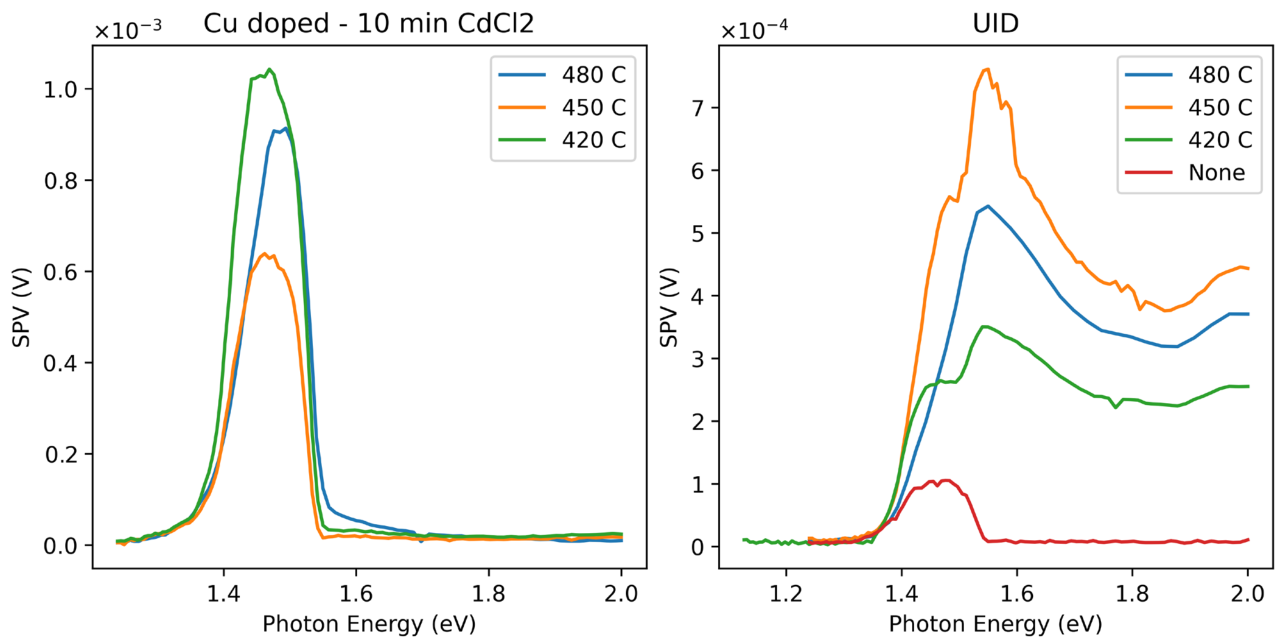
Kronik, L. 1999. https://doi.org/10.1016/S0167-5729(99)00002-3.

Example Data

Thank you U Toledo and NREL for providing samples on fast turnaround!

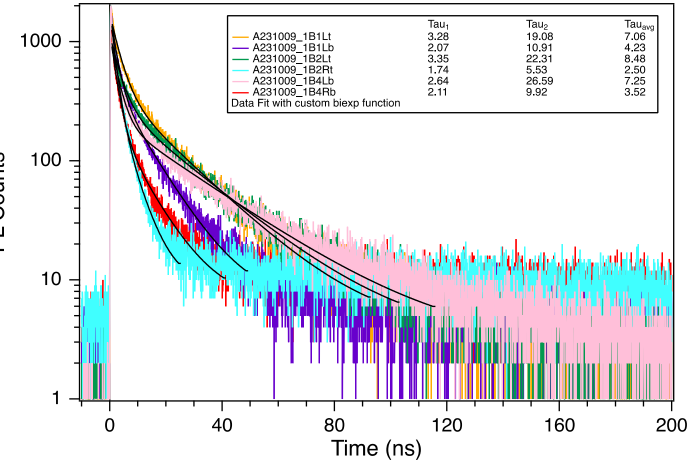
NREL:
Cu Doped vs Undoped
$CdCl_2$ Treated – 420 C, 450 C, 480 C

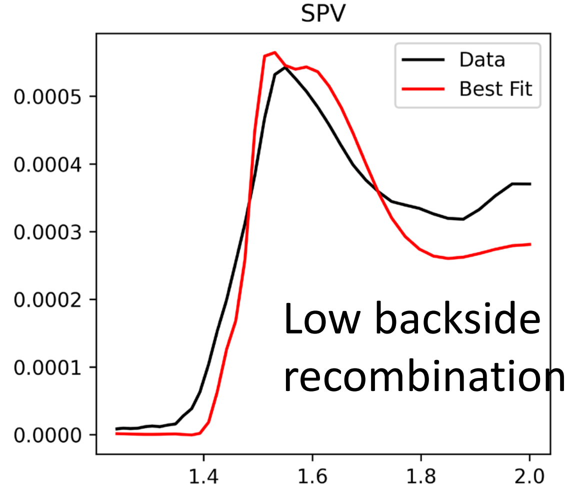
Stack: TEC12d Glass / 500 nm CST (30% Se) / 3 um CdTe



Signals in mV because of weak, monochromatic illumination

Modelling SPS Combining TRPL Lifetimes

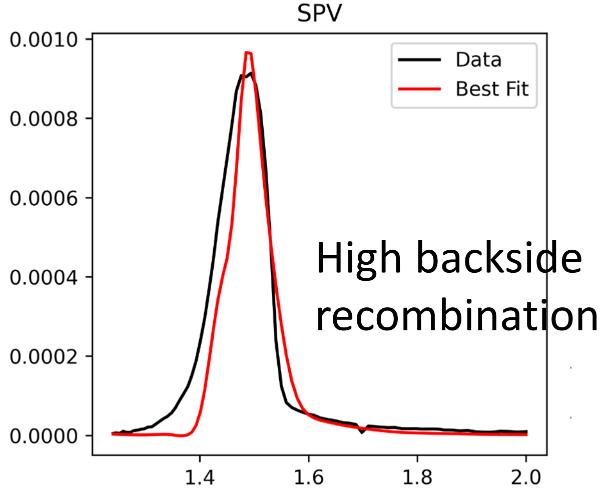




No Cu

480 °C $CdCl_2$

	w1(um)	Tau_2(ns)	G(x=0)
UID	2.0	19.1	0.5
CuCl2	1.5	10.9	$5x10^{-4}$



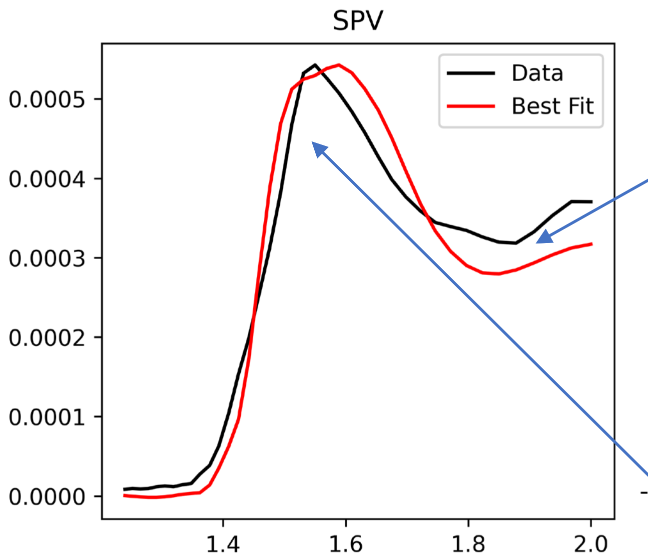
Cu doped

480 °C $CdCl_2$

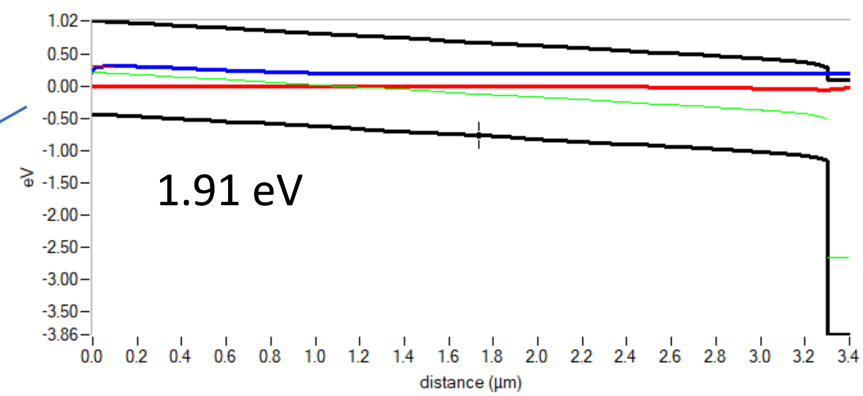
- *Both devices have significant back surface SCR's*
- *Significantly higher SRV for $CuCl_2$ sample*
- *Imperfect data for absorption and spectral fluxes preventing perfect agreement*

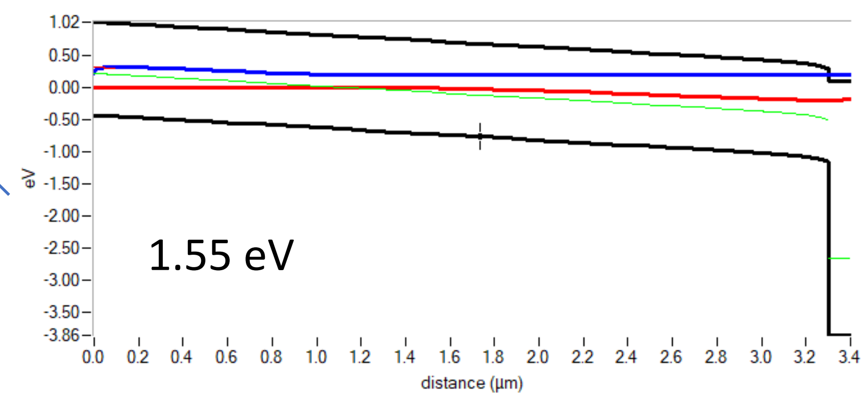
NREL Undoped, $CdCl_2$ 480 °C

Analytical Model



SCAPS Model

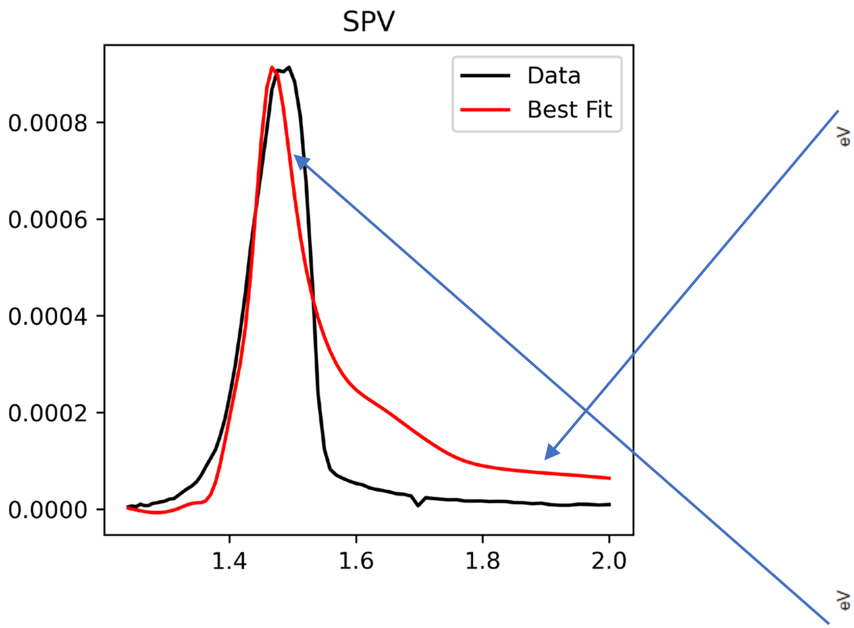


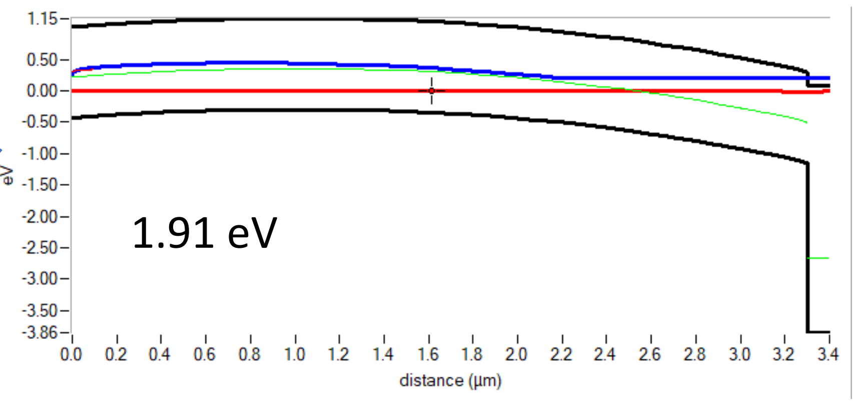


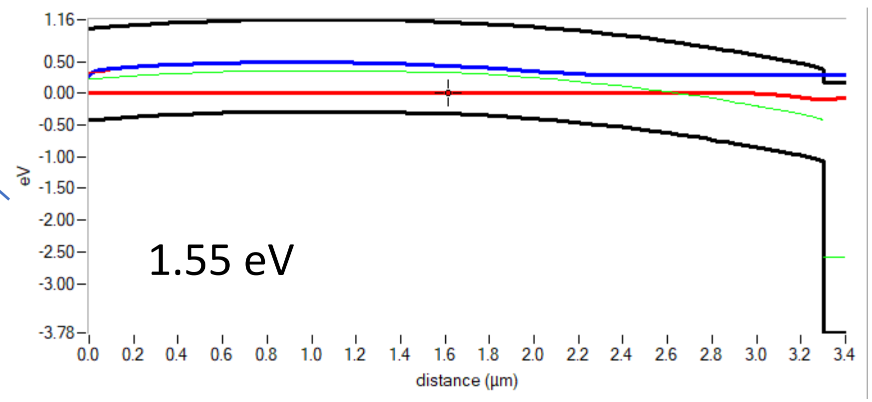
NREL Cu soak, $CdCl_2$ 480 °C

Analytical Model

SCAPS Model





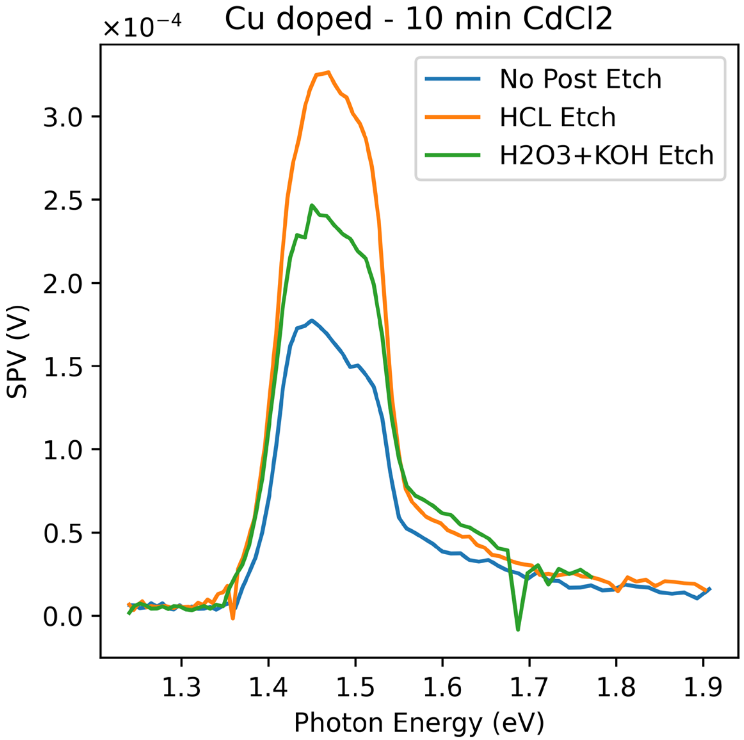


SPS and Wet Etchants

University of Toledo:
All are CdCl2 treated and Cu doped ~2x10^{14} cm^{-3}

No etch
HCL (Te rich)
H2O2+KOH (Cd rich)

Stack: TEC12d Glass/130 nm CST (30% Se)/3.5 um CdTe



Next Steps

- SPS yields some orthogonal data on devices and processing
- Intuitive and numerical models of SPV / SPS compared to data
- Next: add realtime light monitor. Add DC AM1.5 light bias
- Open for collaborations – we welcome new sample sets!

Thank you to CTAC funding, UToledo, and NREL for samples

Extraction of Key Metrics to Help Track Cell-Level Progress

Jim Sites, Colorado State University

CdTe Workshop, October 26, 2023

Many metrics are important; three examples advocated here:

(1) Fully calibrated luminescence efficiency of near-band-gap and sub-gap absorber peaks.

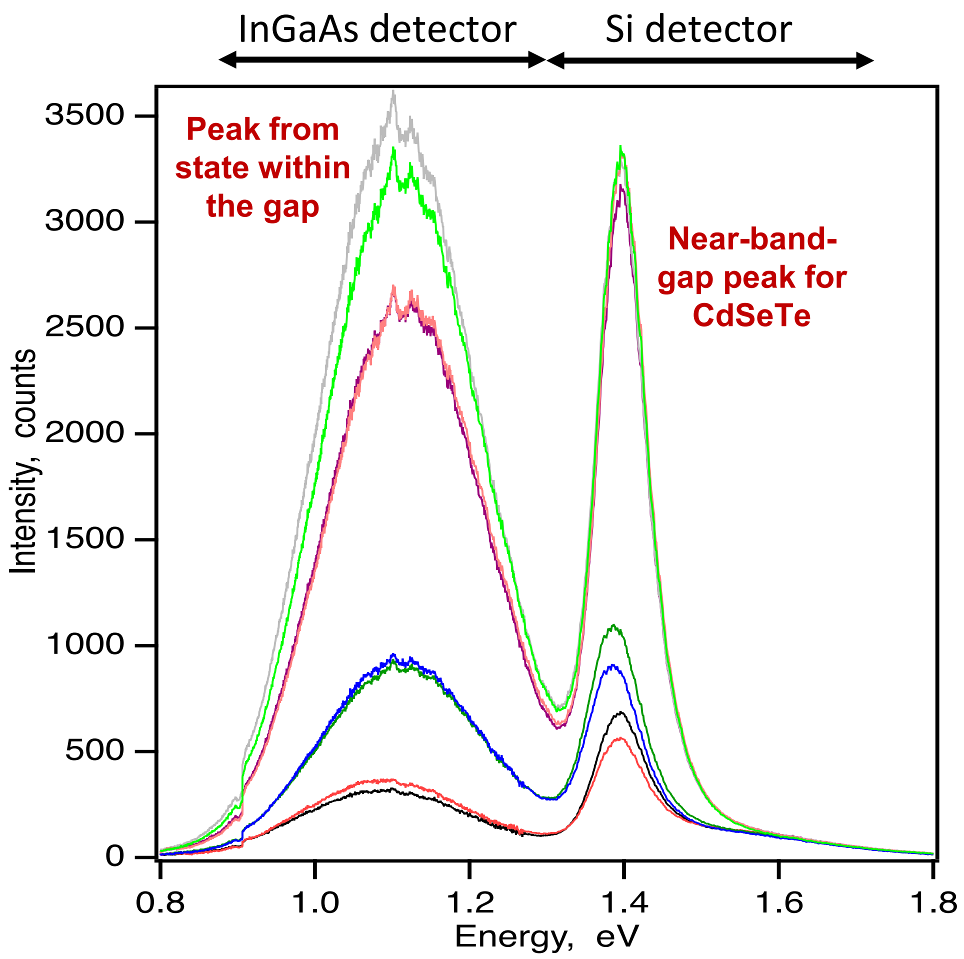
(2) Diode equation parameters, especially diode quality factor, that limit fill-factor.

(3) Back-contact hole barrier from temperature dependence of current-voltage curves.

Let's move towards more routine extraction and tracking of key cell parameters, and work as a community on consistent measurement and analysis procedures.

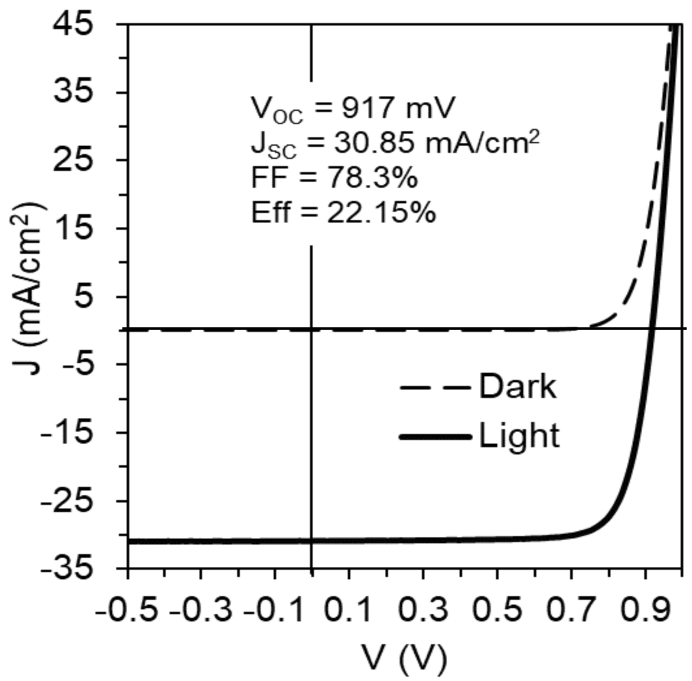
(1) Calibrated Full Luminescence Spectra

- Figure shows several full spectra from CdTe cells with CdSeTe front layer. Key point is that there is large sub-gap peak that results from defect states within the band gap, which very likely contribute negatively to solar cell performance.
- Since the traditional silicon detector has little or no sensitivity below 1.2 eV, that large peak centered at about 1.1 eV in CdSeTe is often missed. A second detector is therefore needed.
- Critical therefore to track both peaks as adjustments are made in cell fabrication. Goal is to reduce the defect peak and increase the near-gap one.
- Important also to develop transparent back contacts so that the spectra can be measured from both sides.



Spectra here from Darius Kusciaukas at NREL

(2) Diode Equation Parameters

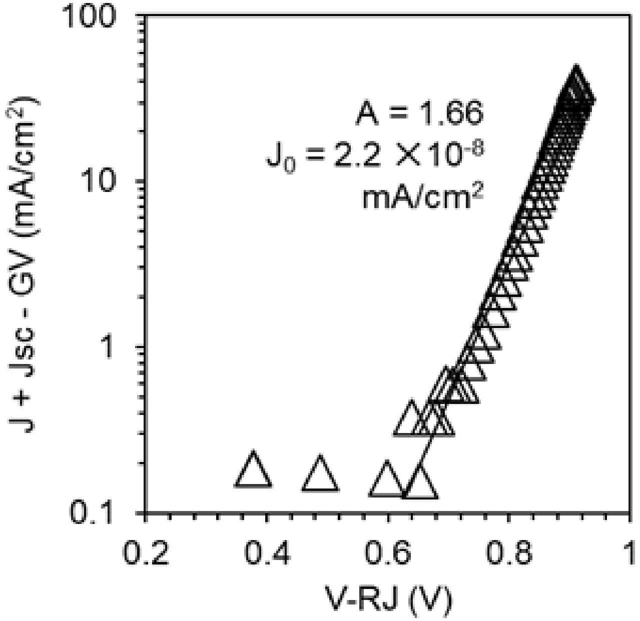


Following Hegedus and Shafarman [Prog. in Photovoltaics 155 (2004)], and assuming no significant terms outside the basic diode equation:

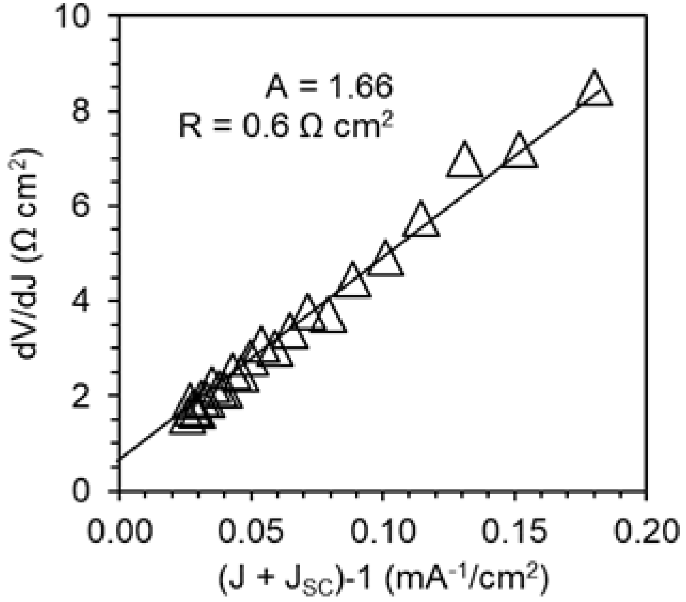
$$J = J_0 \exp\left[\frac{q}{AkT}(V - RJ)\right] + GV - J_L$$

J-V data can be plotted in different ways with judicious selection of points fitted to allows accurate determination of conductance G, series resistance R, prefactor J_0, and most important for impact on fill-factor, the diode quality factor A.

Log plot of forward current



dV/dJ for intercept R and slope AkT/q



Analysis by Ishwor Khatri

Shown here for the highest-voltage cell from R. Malick et al, IEEE J. Photovoltaics **13**, 510 (2023): J-V in the standard format, log of the shifted light curve, and linearization of the diode equation to highlight A and R.

Straightforward to calculate the fill-factor loss from each

(3) Back-Contact Barrier from J-V-T

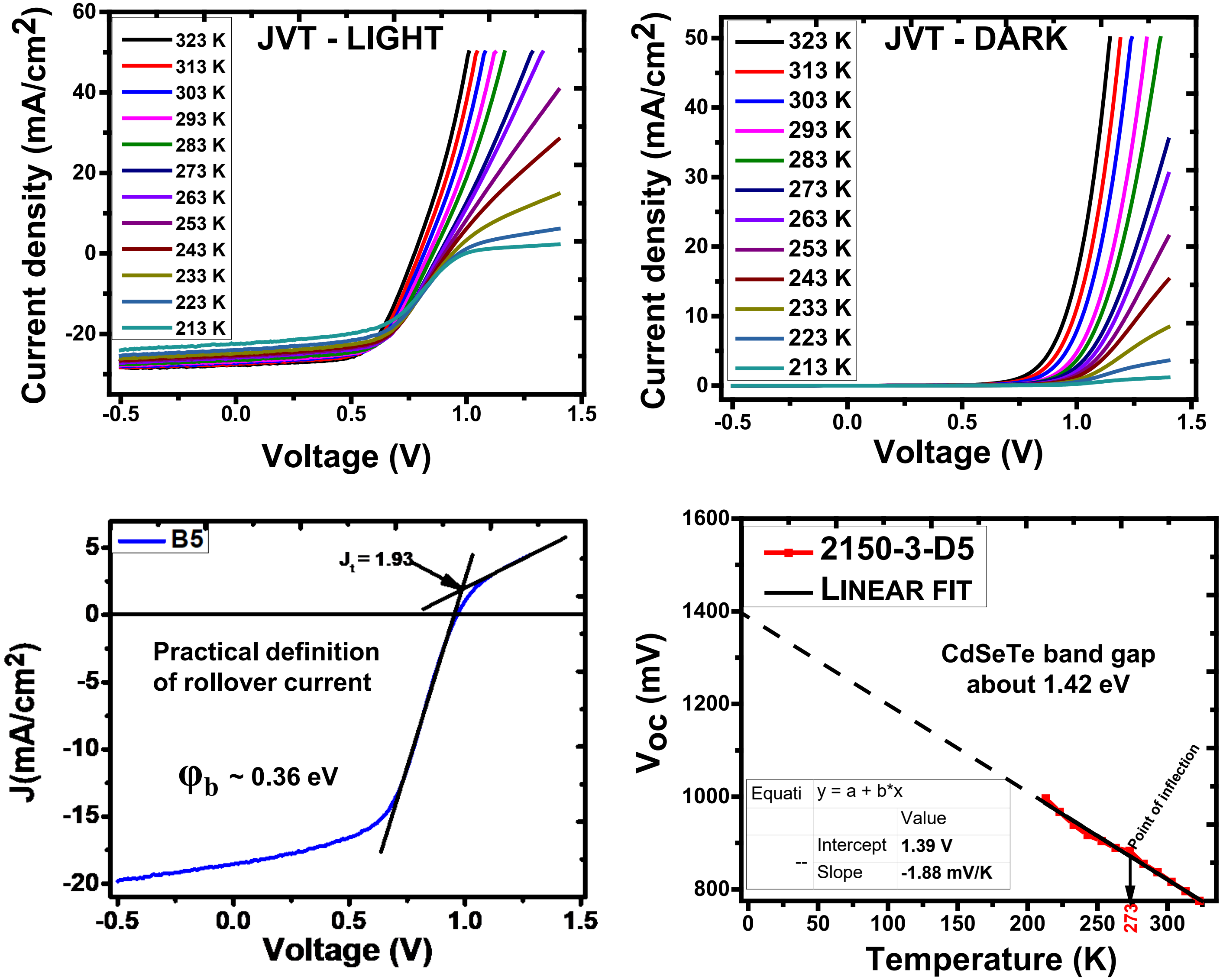
- In many cases, cells exhibit “rollover” in their current-voltage curve as the temperature is reduced. The onset is often an indication of a hole barrier at the back.
- A useful metric shown below is the current J_t at the rollover transition point, which can be related to the barrier height φ_b:

$$J_t \sim A^* T^2 e^{-q\varphi_b/kT}$$

Koishiyev et al, Proc. 33rd PVSC, 2.71 (2008)

- Best to for consistency to calculate the barrier at different temperatures.
- An additional value of J-V-T is to track V_{OC} vs T (right figure). It should be nearly linear with the T = 0 intercept near the band gap (1.4 eV in this case).

Figures from Chime Chinecherem and Katherine Zaunbrecher



Broader Picture

There are a large number of other possibilities, so as a community, let's prioritize where to adopt common procedures and direct comparisons with focus on what can be done relatively routinely at different labs.

Some of us can take the lead in coordinating at least one measurement and/or analysis area. As with joint projects in general, this requires organization and leg work, but could very well broaden our overall success.

Best to be selective: combination of group decision that an area is important and an individual commitment to bring labs together.

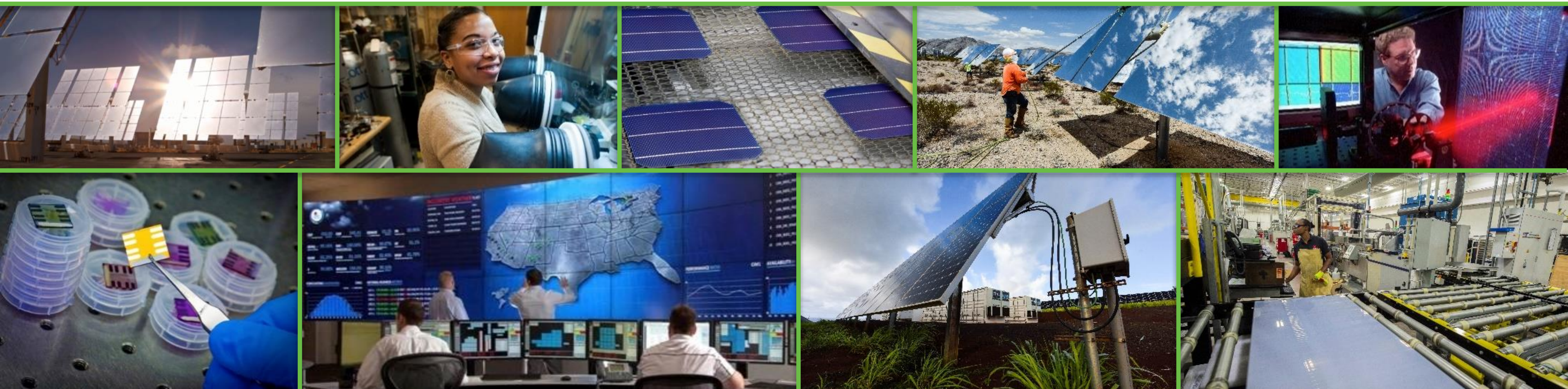
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Forces Influencing the Future of CdTe PV

Brion Bob, Solar Energy Technologies Office

October 2023

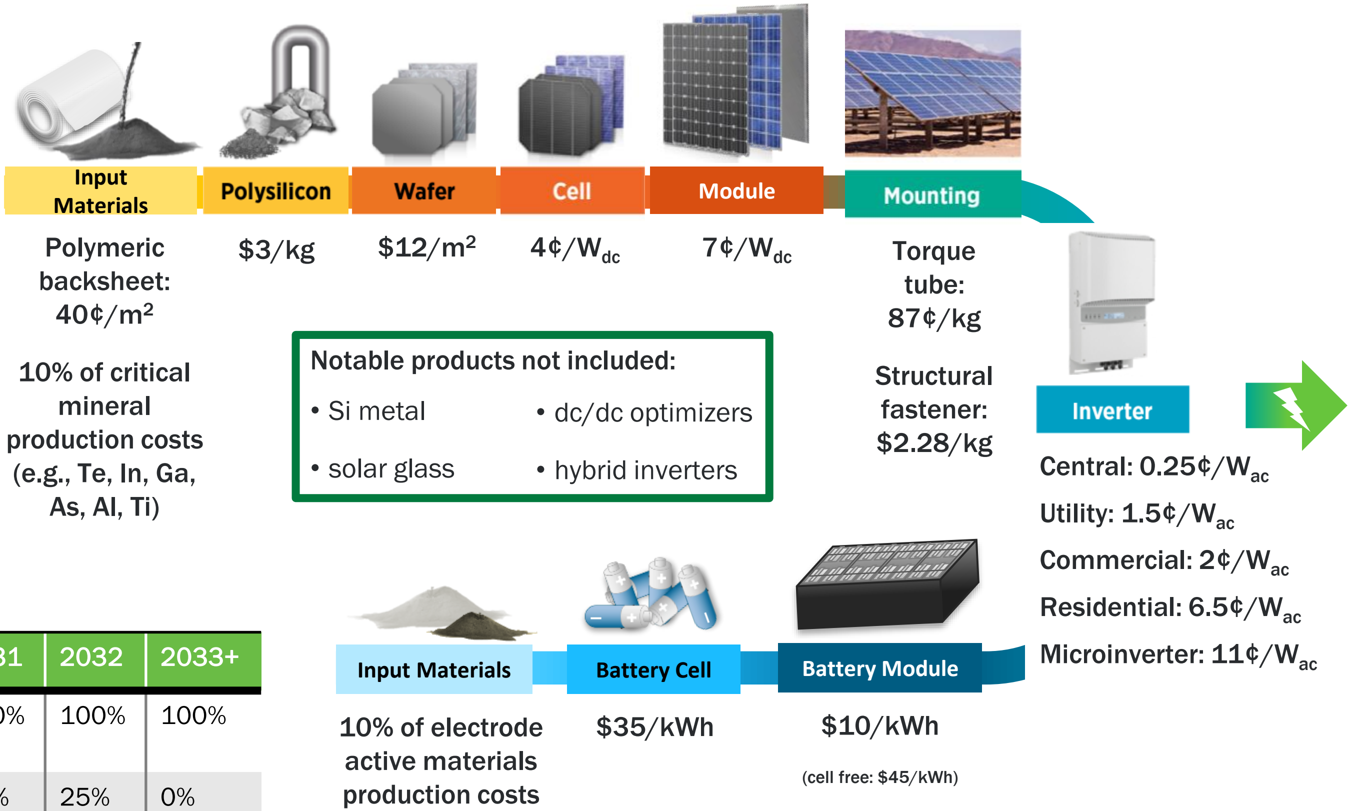


IRA's Advanced Manufacturing Tax Credit

+10% ITC/PTC Bonus for Systems that meet domestic content requirements.

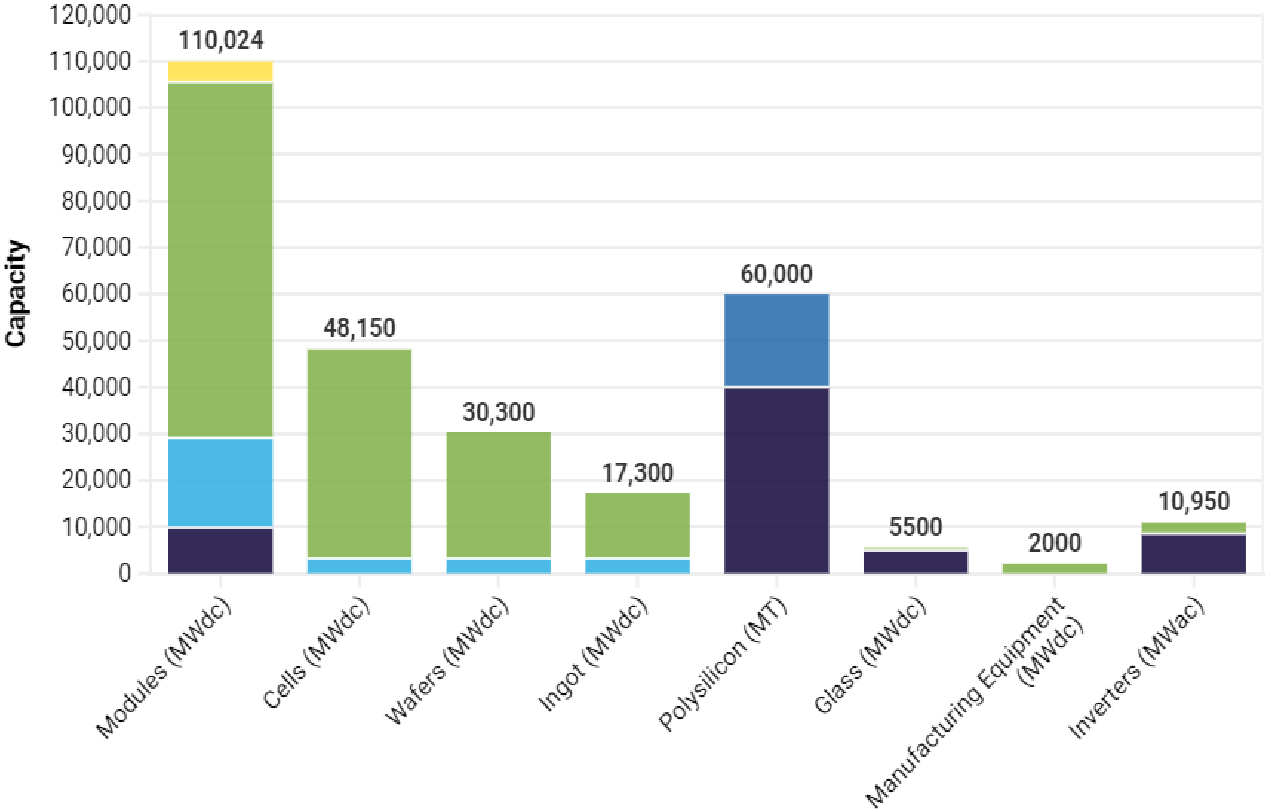
Implementation for the tax credits, grants, loans, and other provisions within IRA is ongoing.

The Department of Treasury is the authority on how these tax credits will be implemented.



Component:	2023-2029	2030	2031	2032	2033+
Critical minerals	100%	100%	100%	100%	100%
All others	100%	75%	50%	25%	0%

Onshoring of the Silicon PV Supply Chain



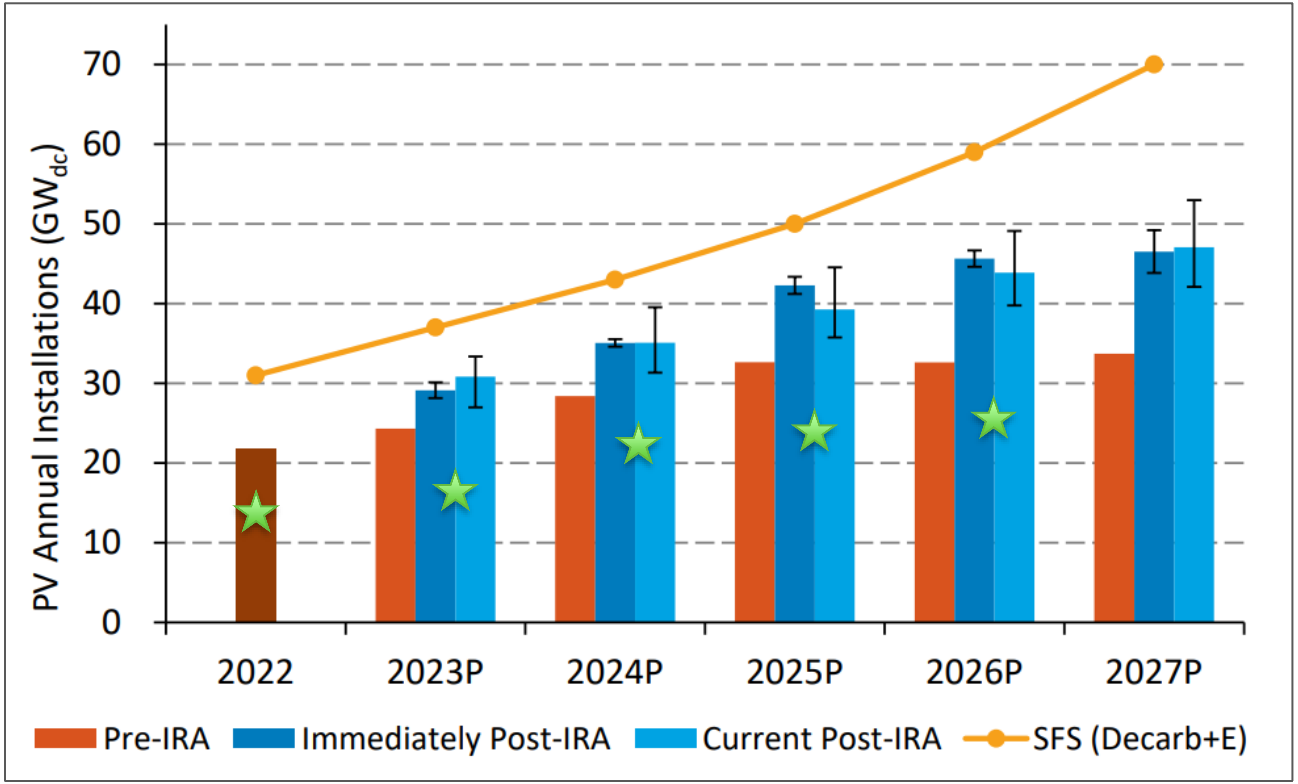
Source: SEIA Solar & Solar Supply Chain Dashboard, (October 2023)

Impact of the Manufacturing Tax Credit has been Rapidly Felt

Increasing PV System Deployment

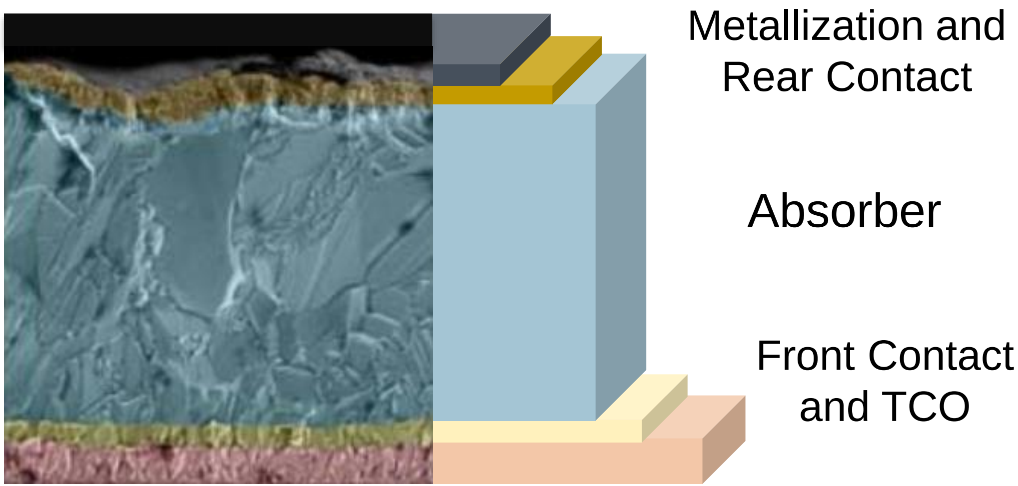
Nearly 50% Expected Annual Growth Rate in US PV Deployment from 2022 to 2023

35% of all PV Modules deployed in US Utility Scale Systems in were CdTe in 2022



Sources: NREL Solar Industry Update Q32023 and First Solar Analyst Day 2023

Open Questions and Areas of Interest



Source: NREL

- How Best to Broaden the Community
- Workforce Development
- Cell Efficiency and Bifaciality
- Incorporation into Tandems
- Tellurium Supply
- End of Life Module Recovery

QUESTIONS