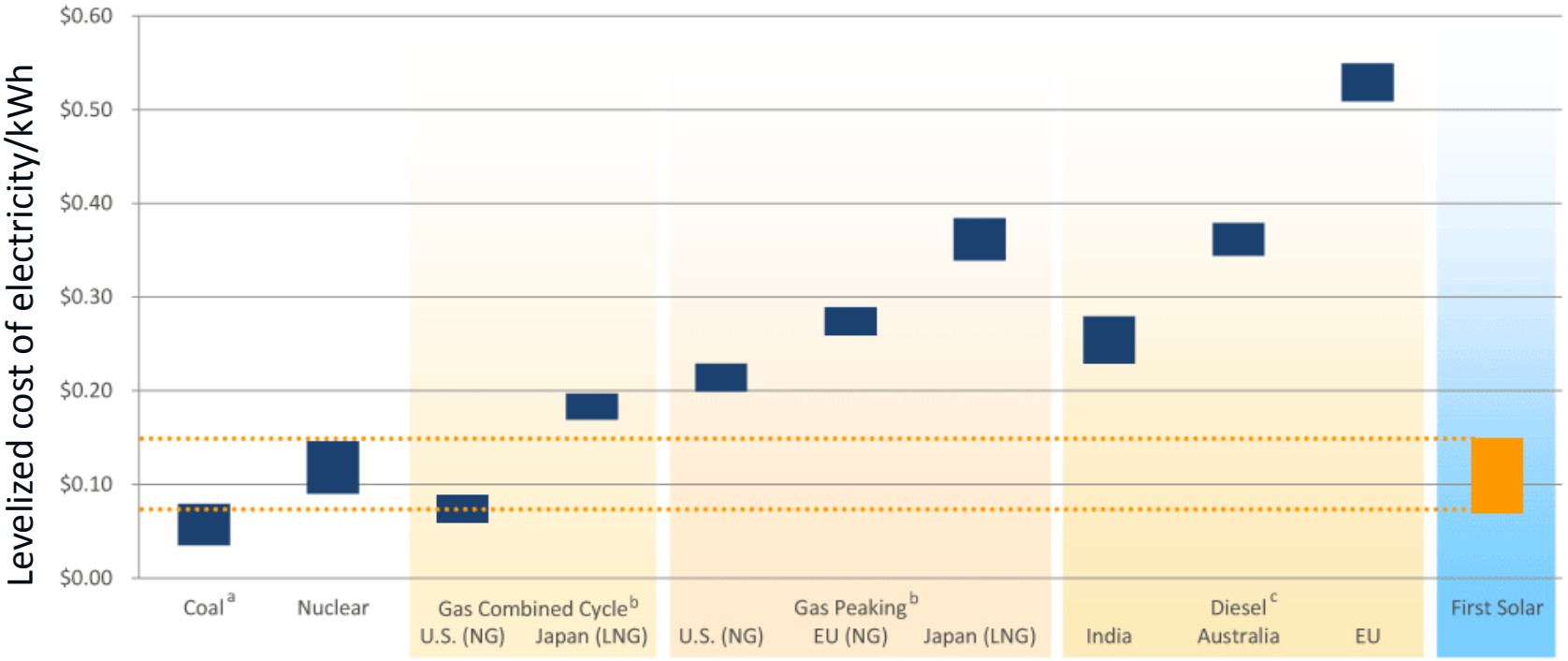
CdTe Team

SunUp Presentation

Defining Defect Chemistry and Structural Properties To Improve CdTe Photovoltaics

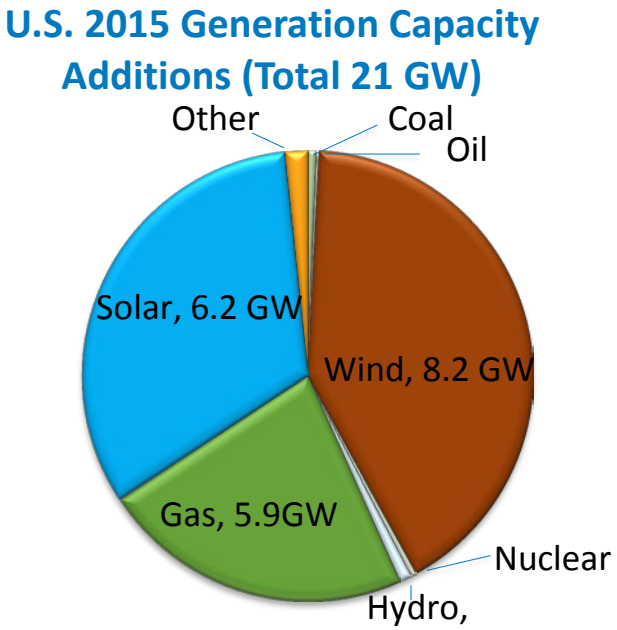
November 3, 2016

CdTe Is Competing With Conventional Fuels



http://www.firstsolar.com/en/Solutions/Utility-Scale-Generation

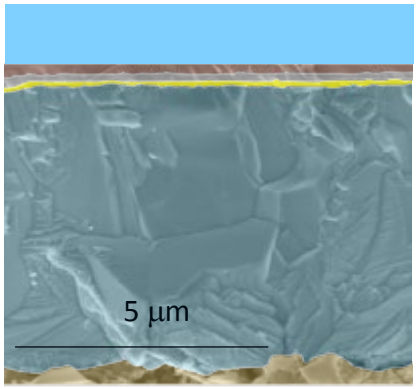
Renewables On the Rise



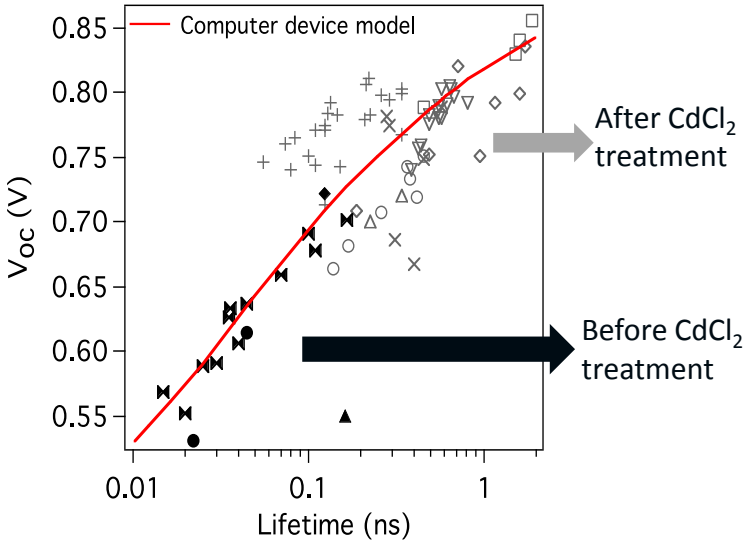
Sources: 2004-2010 (except solar): EIA.U.S installed capacity, Form 860. 2011-2013: FERC: "Office of Energy Projects Energy Infrastructure Update for December 2012/2013/2014." Solar, GTM/SEIA, U.S. Solar Market Insight Q4 2015.

- In 2015, solar and wind combined for 60% of U.S. new generation capacity
- About 10% of electricity in California and Hawaii is provided by solar
- Solar capacity is doubling every 2-3 years
- Still a lot of work to do to continue this growth

Material Challenges



Fast deposition produces small grains

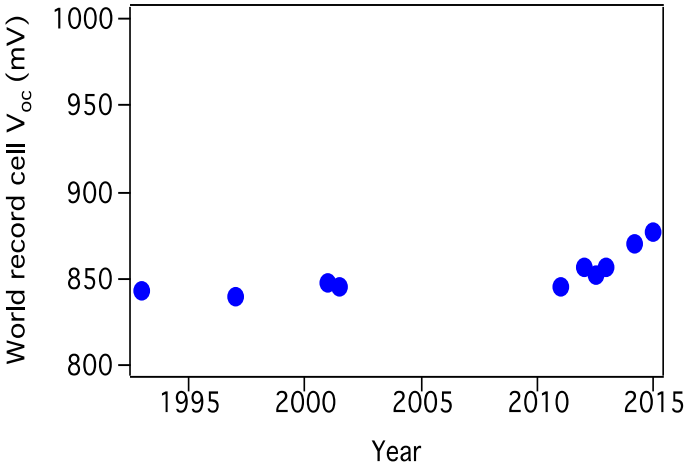


$CdCl_2$ applied to fix up bad material

Metzger et al., JAP **94** 3549

Cu applied later can help a bit, but moves and creates stability problems

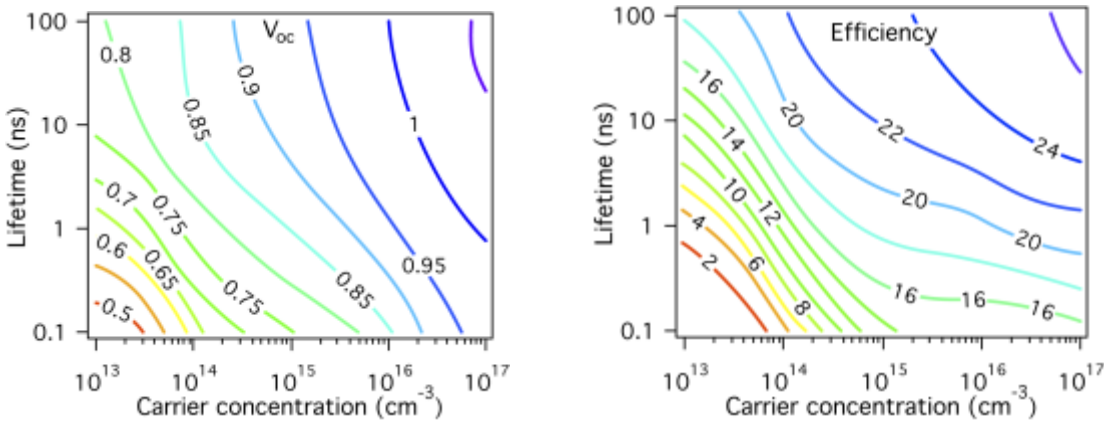
This is a stubborn defect chemistry.



Voltage has been flat for 20 years.

Result - efficiency has been maximized around a poor absorber, future gains require overcoming fundamental material issues

Headroom to Improve

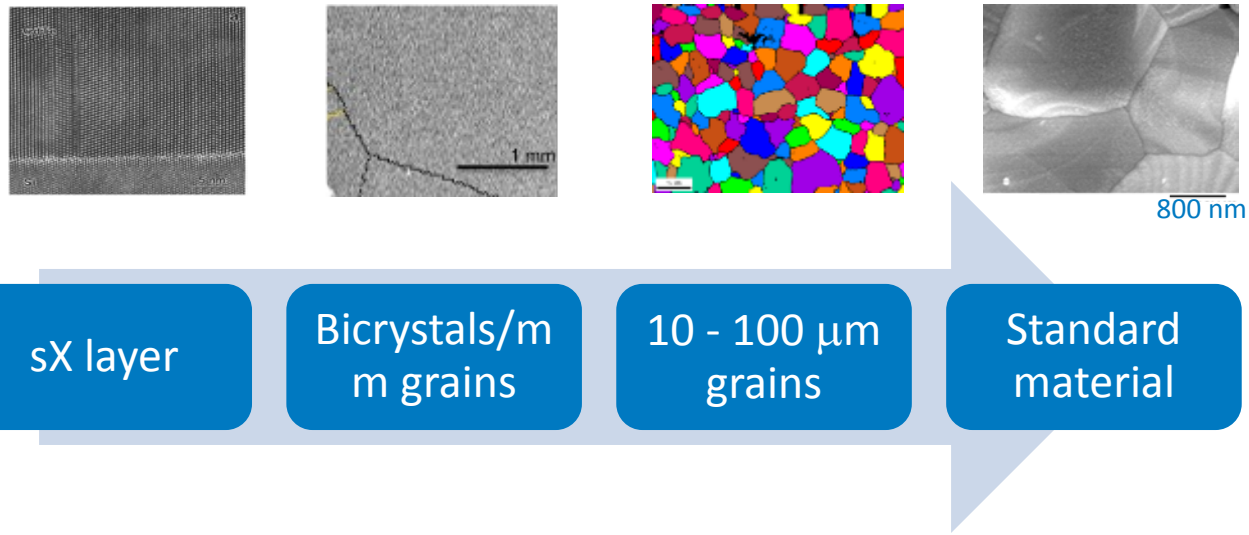


Duenow et al., JPV, DOI:10.1109/JPHOTOV.2016.2598260; Duenow *et al.*, APL **105**, 053903, 2014

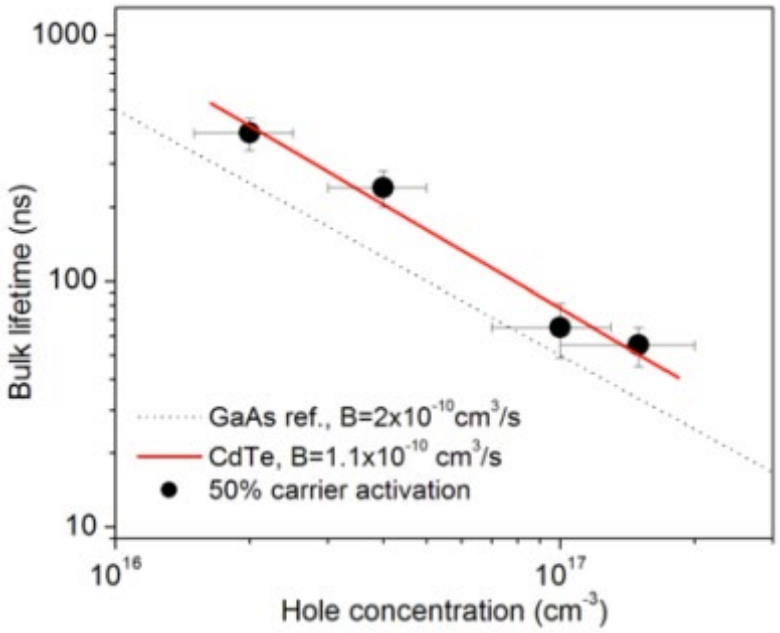
- Lifetime limited to several ns, and carrier concentration to low 10^{14} cm^{-3}
- Need to push both up by 1–2 orders of magnitude
- This can push efficiency well beyond mc-Si and toward SunShot goals of electricity at rates less than conventional sources

Materials Approach

Take a step back and work with single crystals – then shift to polycrystalline materials



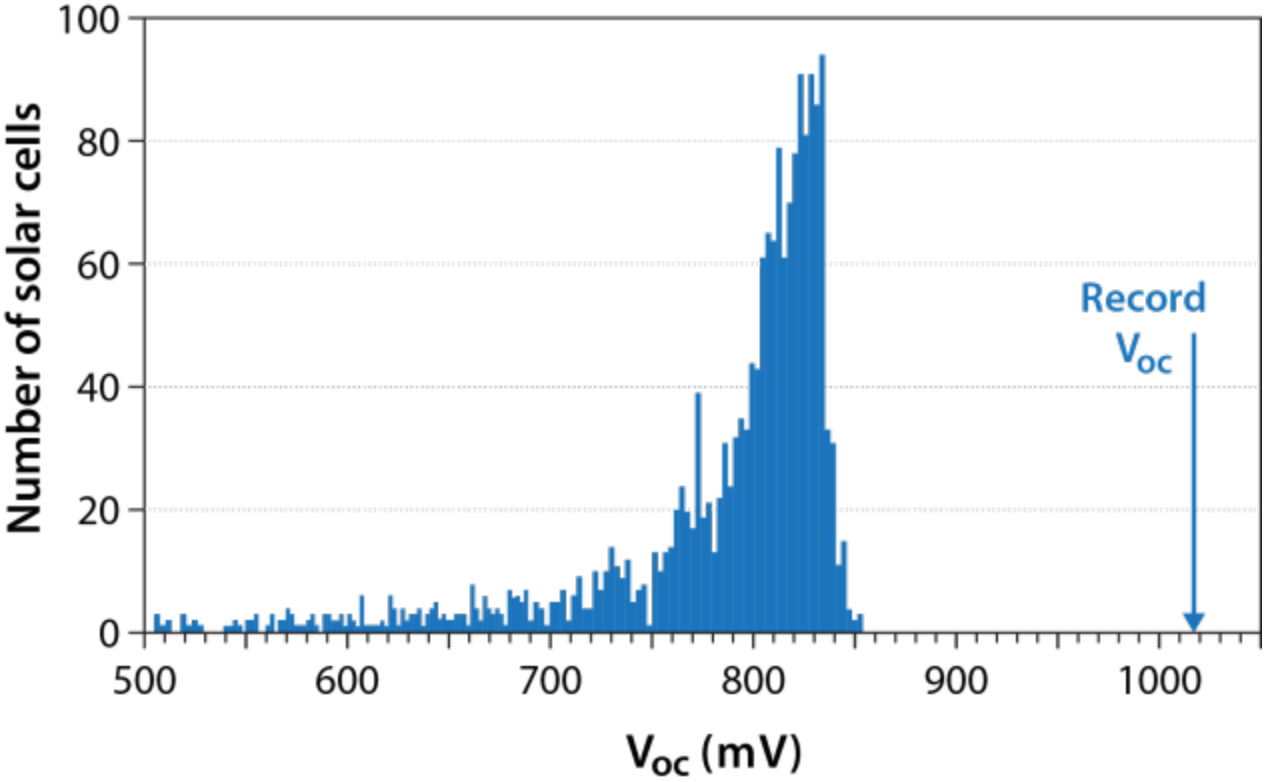
We Have Made sX CdTe Commensurate with GaAs



- V_{Cd} and Te_{Cd} antisites can decrease lifetime
- Anneal samples in Cd with P present
- Red line corresponds to CdTe
- Doping is over sweet spot for solar cells – 10^{16} to low 10^{17} cm^{-3}
- Dashed line corresponds to radiatively limited GaAs.
- We now have hole density and lifetime commensurate with top shelf GaAs

www.nature.com/articles/nenergy201615, Burst et al., Nature Energy, **1** 16015 (2016)

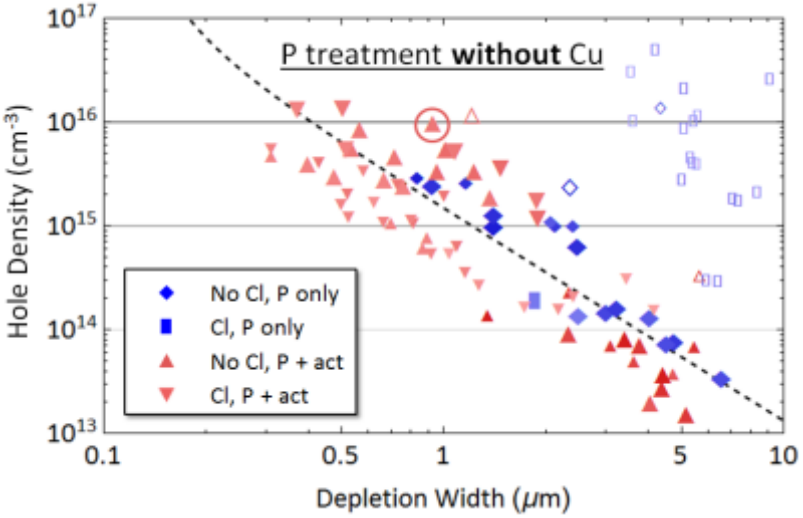
Breaking the Voltage Barrier in CdTe Photovoltaics

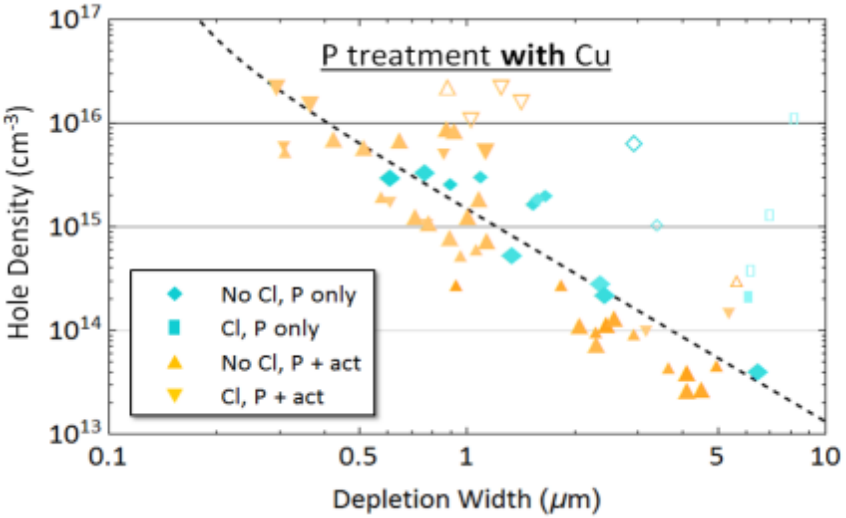


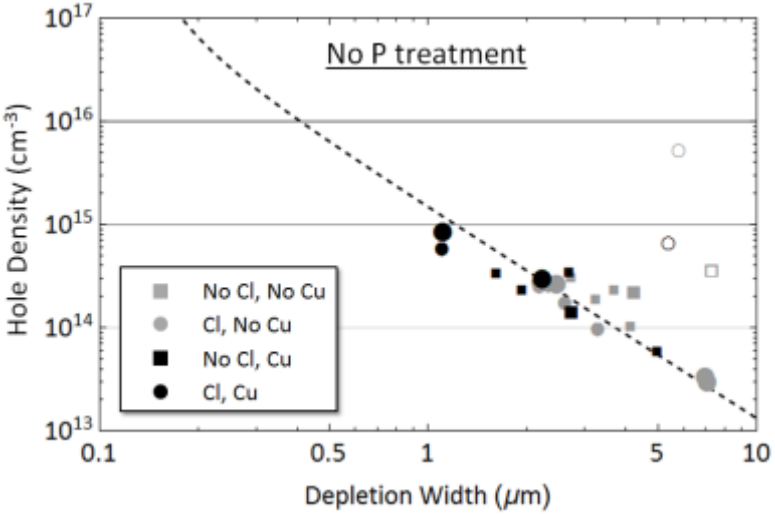
- Results for 2400 CdTe solar cells fabricated at NREL in last decade
- Representative of many more cells made by academia and industry
- Record voltage with new defect chemistry - anion doping without $CdCl_2$ treatment and interdiffusion

www.nature.com/articles/nenergy201615, Burst et al., Nature Energy, **1** 16015 (2016)

Transferring Results to Polycrystalline Films







E. Colegrove, PVSC 2015

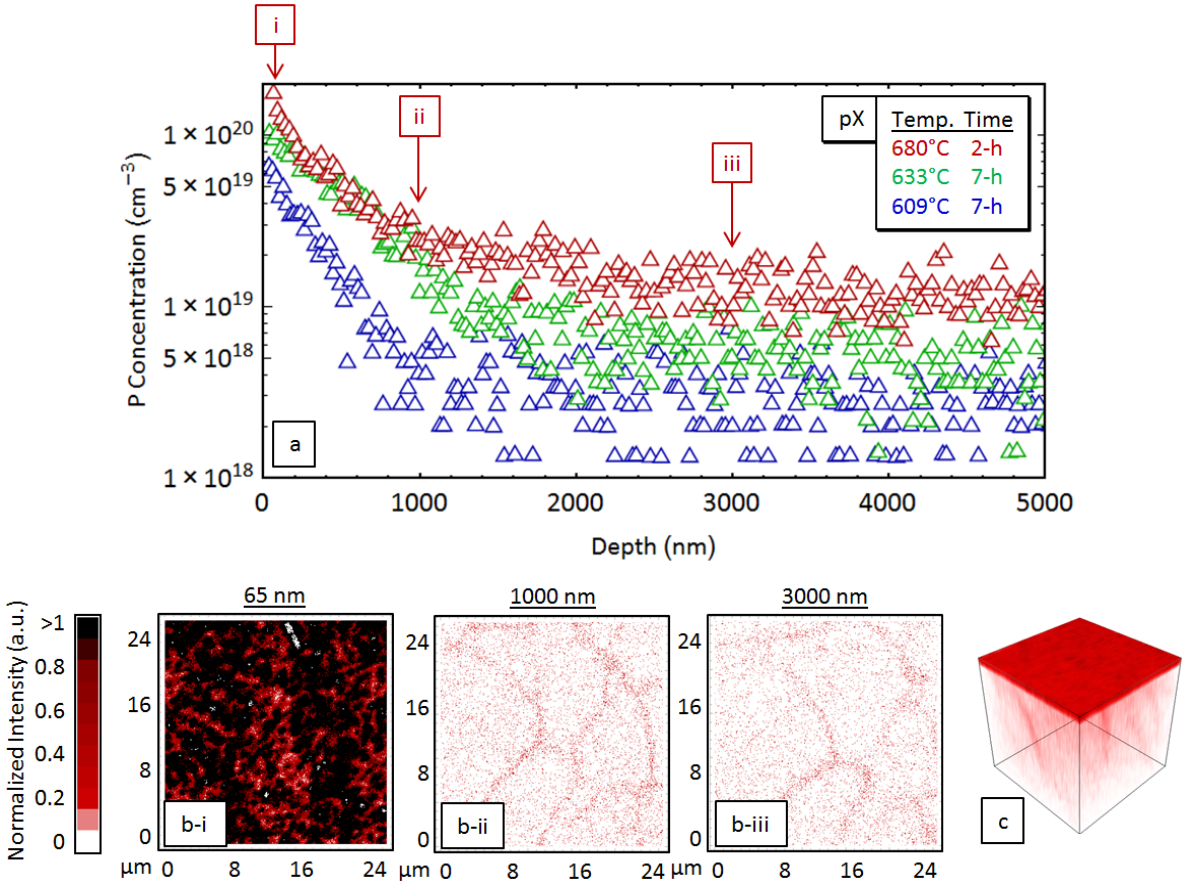
We are increasing hole density with P

Some values exceed 10^{16} cm^{-3}

Challenges are to maintain lifetime and uniformity

NREL Offers Great Techniques to Address Issues

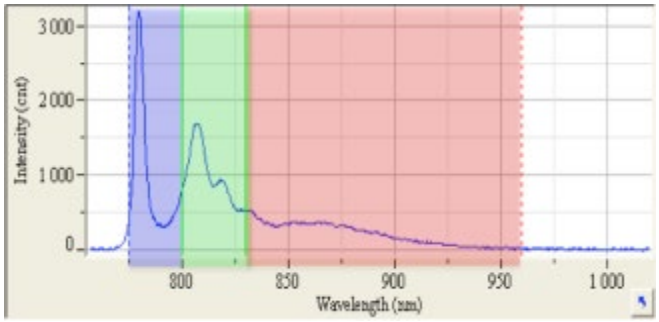
Dynamic and TOF SIMS allow us to measure three dimensional incorporation of dopants in pX and sX films to understand diffusion kinetics

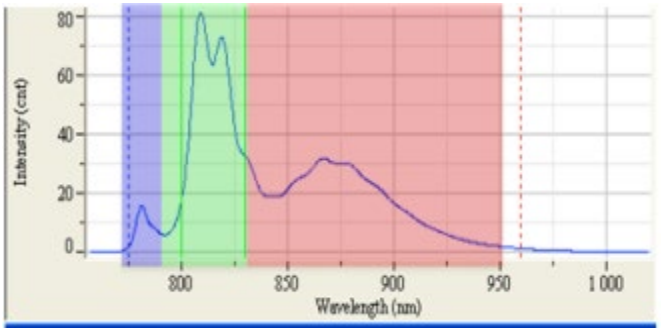


E. Colegrove *et al.*, *Physical Review Applied* Vol. 5, 054014 (2016)

Visualization of Dopant Activation

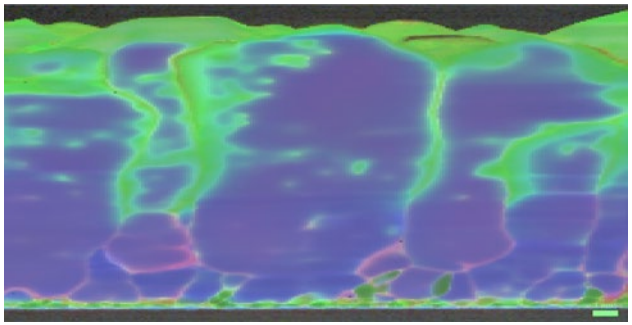
Global cathodoluminescence (CL) spectra and color coding for images

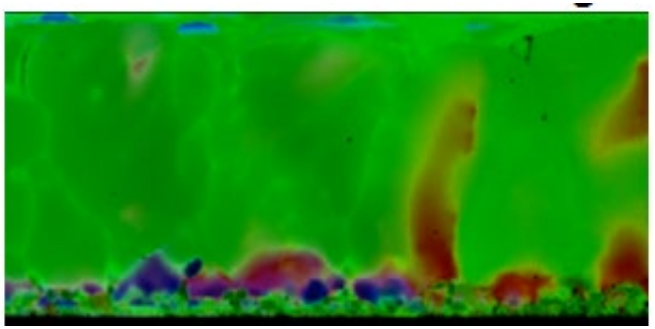




CdTe back surface

CdTe/CdS



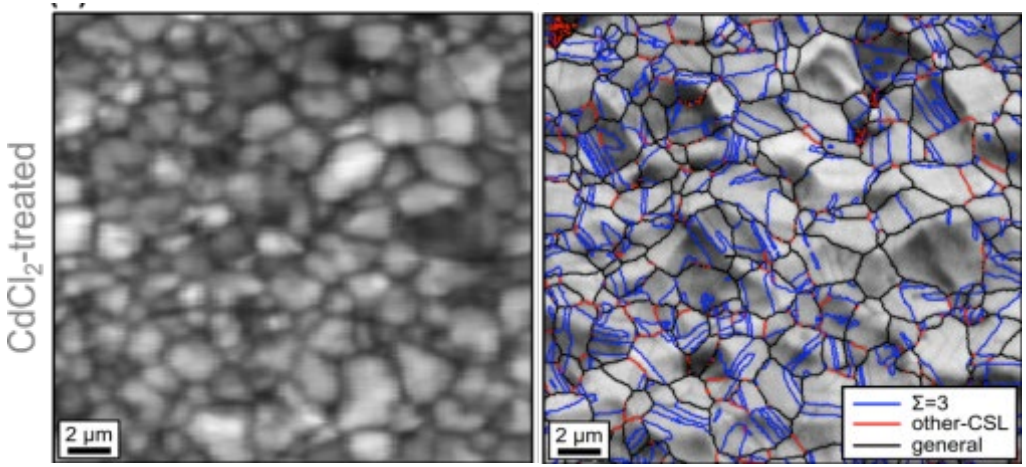


Left: doping primarily along GBs and not in the bulk
Right: doping is throughout most of the CdTe film

A challenge is to elevate doping pX CdTe to a science

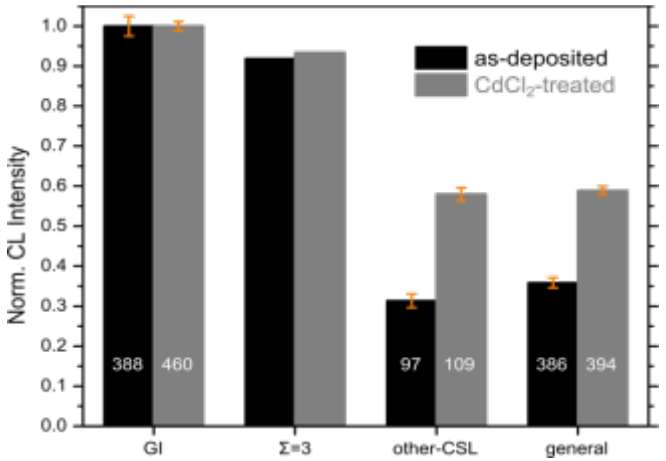
Guthrey *et al.*, JAP *submitted* (2016)

Our Work – GBs Are Recombination Centers



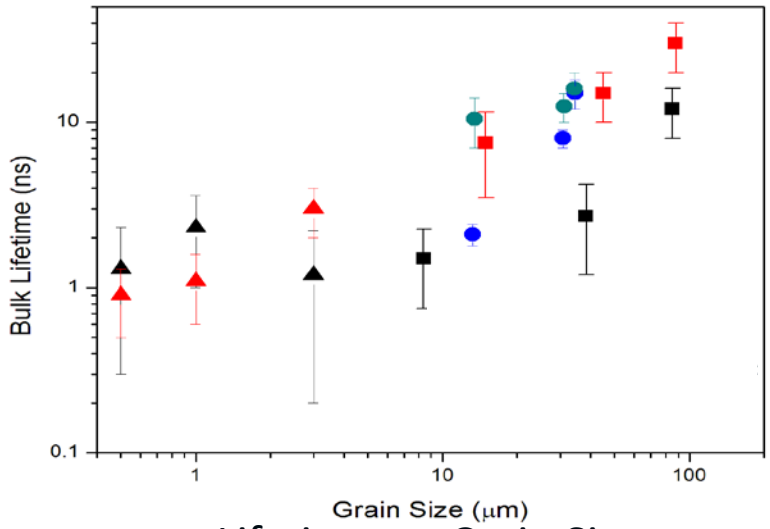
CL map

Corresponding EBSD

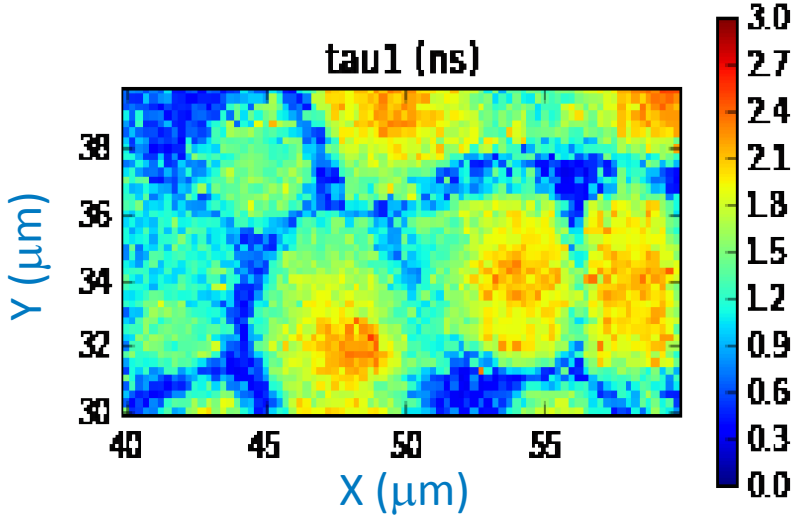


Statistical Analysis on Standard Cells

J. Moseley et al., JAP 118, 025702



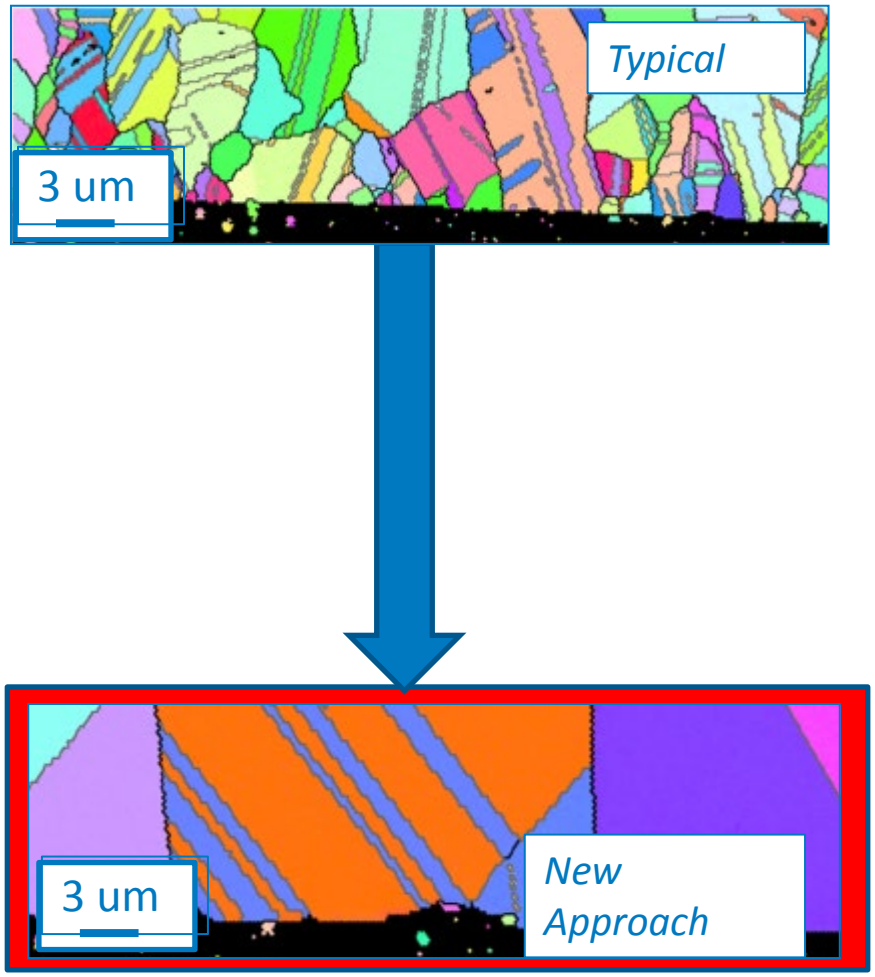
Lifetime vs. Grain Size

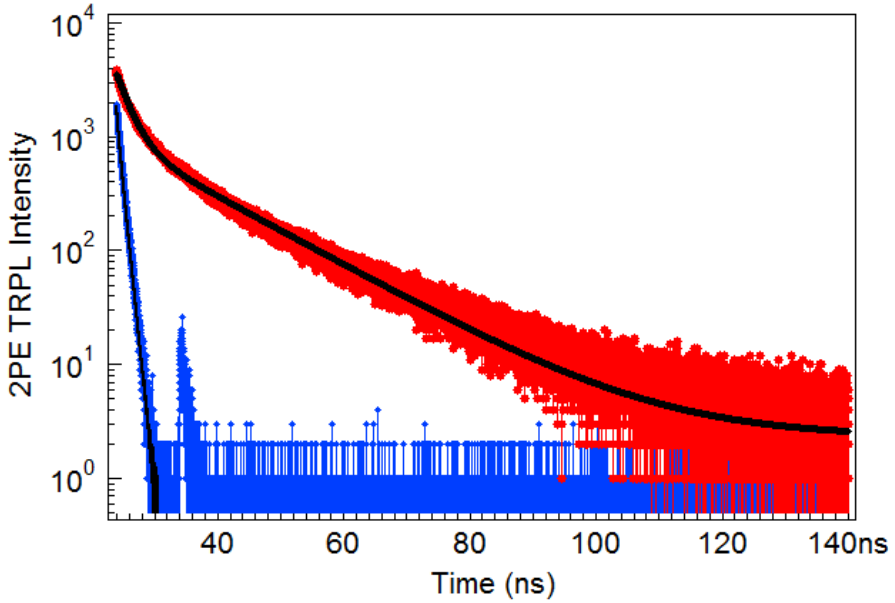


Lifetime Map (Blue corresponds to GBs)

S.Jensen et al., APL 103, 263903

Changing Grain Size





- *Large columnar grains are formed*
- *Fewer intragranular defects*
- *Very high bulk carrier lifetimes*

SunUp Opportunities

MakeCdTe photovoltaics less expensive than conventional fuels

1) Overcome historic voltage limits

2) Establish new defect chemistries

3) Increase carrier concentration while maintaining good lifetime

4) Modify GB recombination and grain size in thin films

5) Combine synthesis, characterization, and theory

If interested, please contact

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Thank you!