NREL
NATIONAL RENEWABLE ENERGY LABORATORY

SunUP – CdTe Interfaces and Contacts

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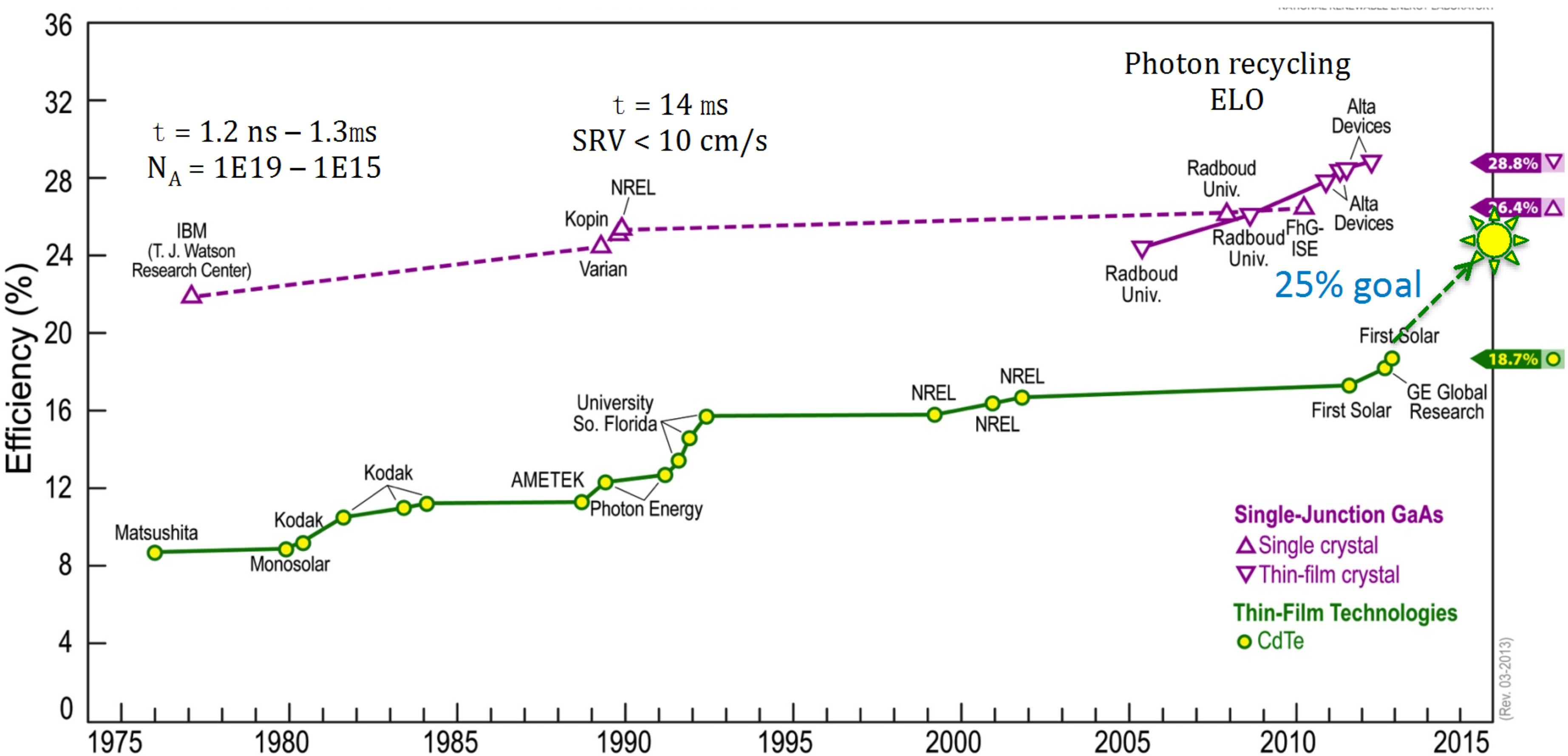
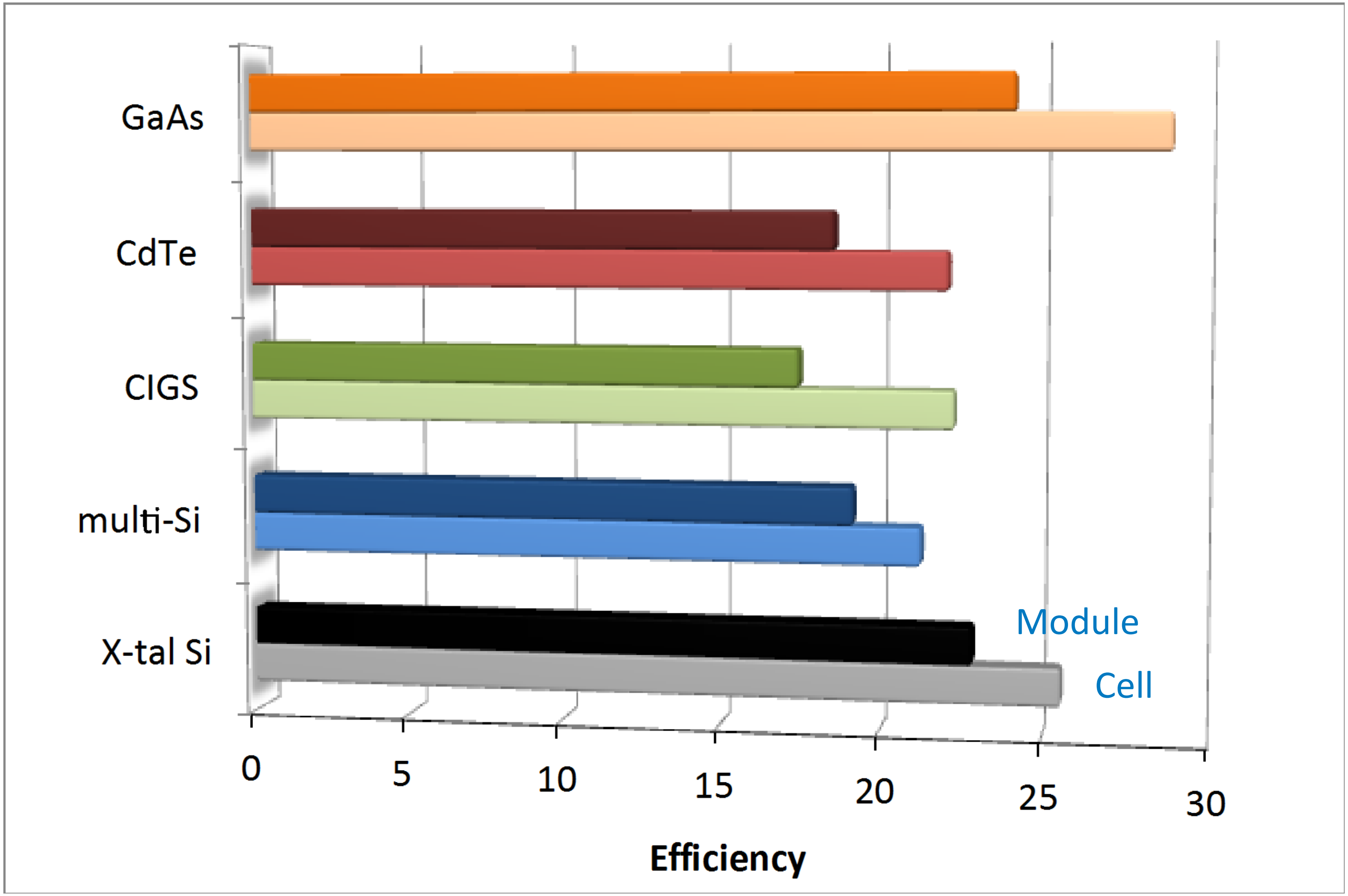
October 18, 2016

GW Production with Dramatic Efficiency Improvements

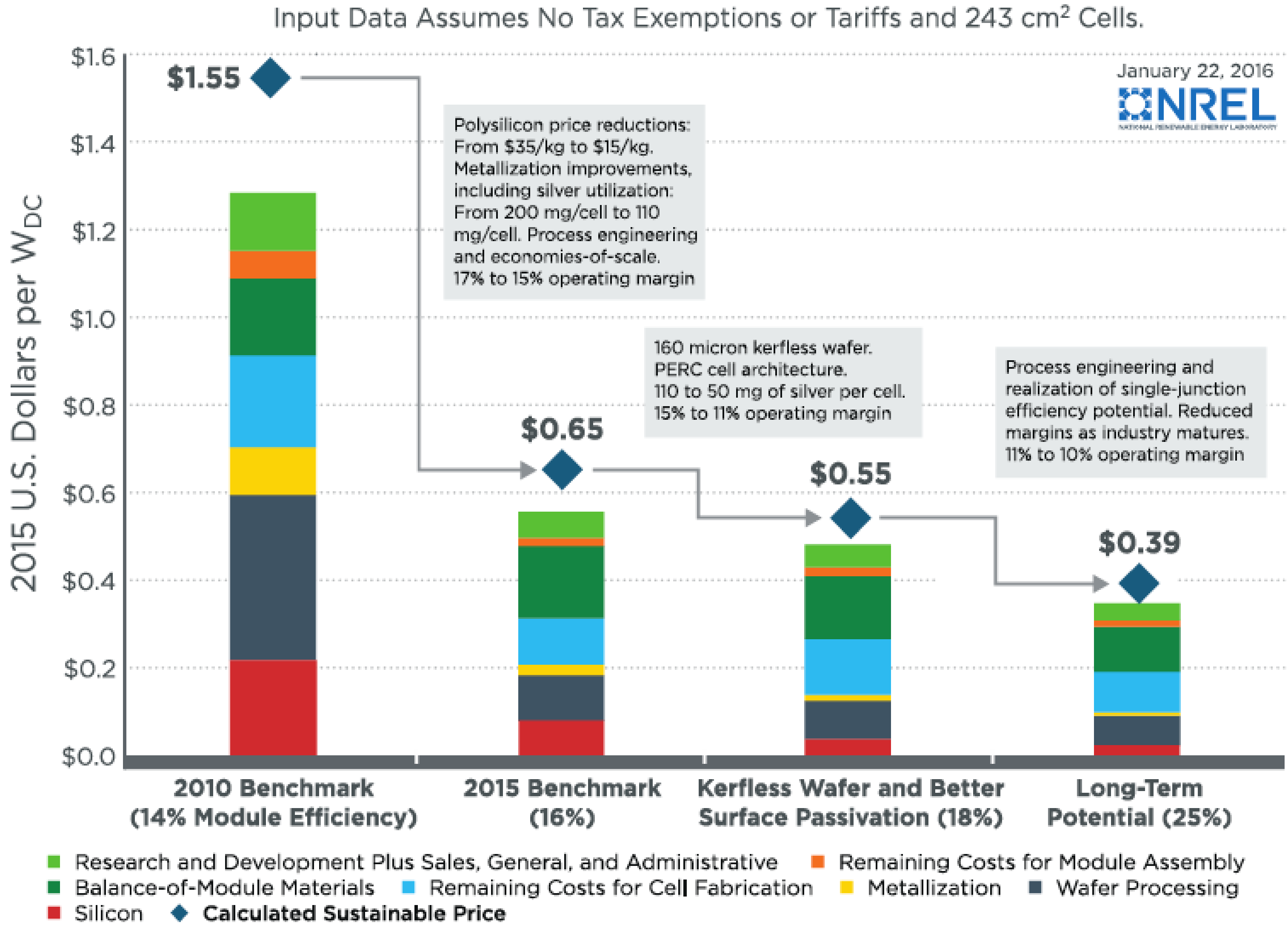


CdTe efficiency increased from 17% to 22% in six years!

Module and Cell Efficiencies for Commercial PV

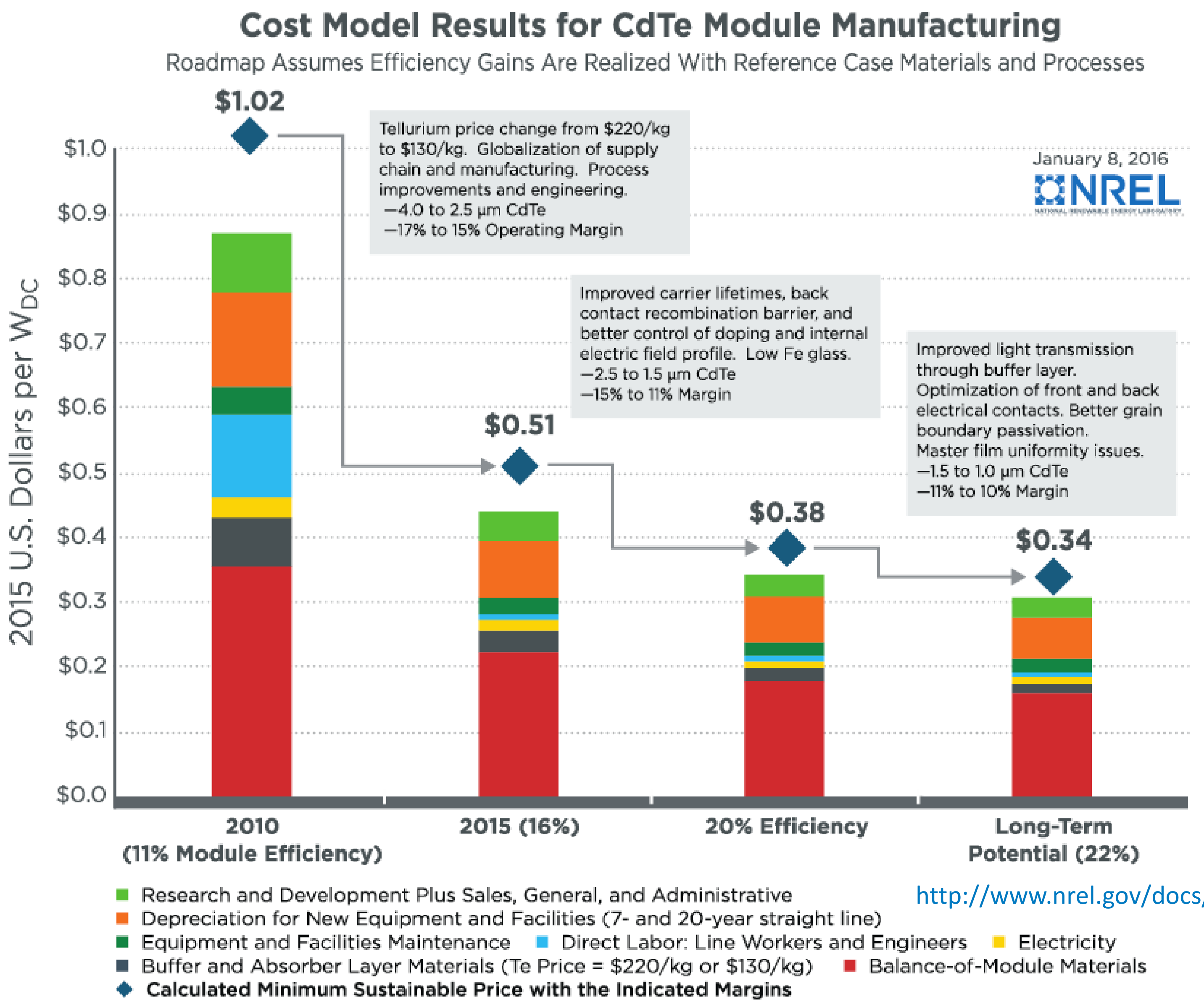


Silicon Module Prices



http://www.nrel.gov/docs/fy16osti/65872.pdf

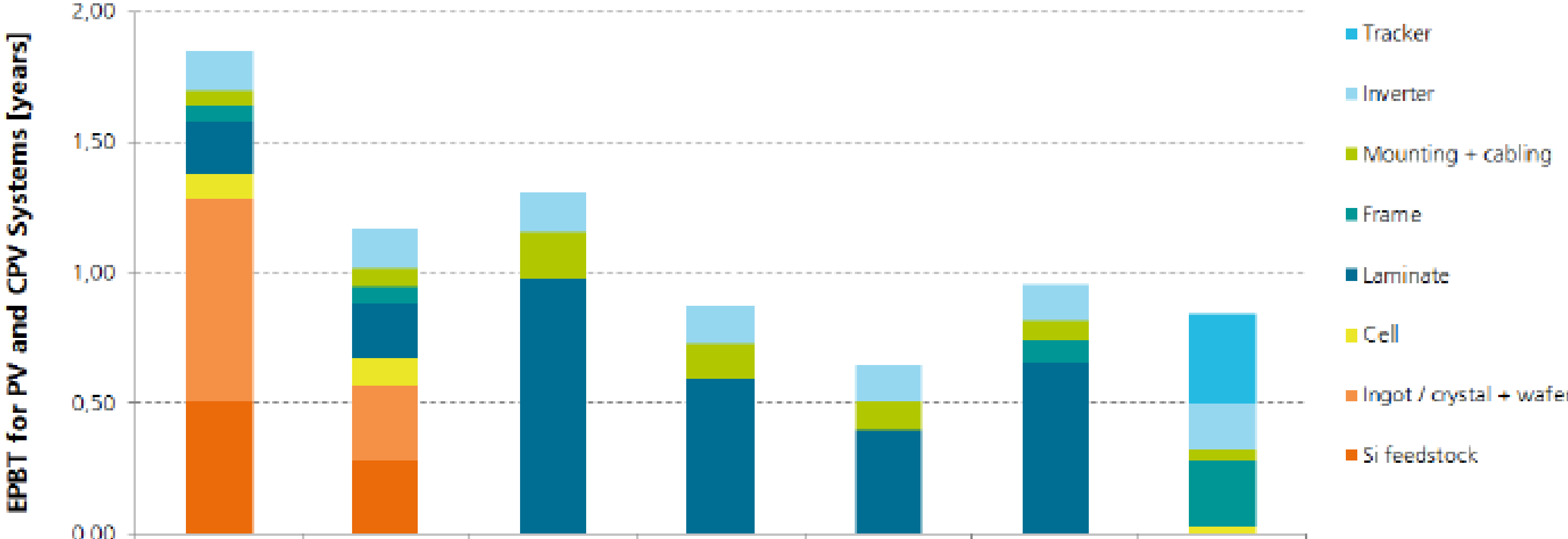
CdTe Module Costs



http://www.nrel.gov/docs/fy16osti/65872.pdf

Energy Pay-Back Time for PV and CPV Systems
Different Technologies located in Catania, Sicily, Italy

Global Irrad.: 1925 kWh/m²/yr, Direct Normal Irrad.: 1794 kWh/m²/yr



Technology	Mono-Si	Multi-Si	a-Si	µm-Si	CdTe	CIGS	CPV
Module composition	Glass-EVA-backsheet	Glass-EVA-backsheet	Glass-PVB-glass	Glass-EVA-glass	Glass-EVA-glass	Glass-EVA or PVB-glass	Flatcon CX-75 CPV-System
Status	2011	2011	2008-2011	2013 estimate	2010-2111	2011	2011
Efficiency	14,8%	14,1%	7,0%	10,0%	11,9%	11,7%	24,1%
Scale of production	~300 MWp	~300 MWp	33-45MWp	120MWp	963MWp	20-66MWp	-

Data: M.J. de Wild-Scholten 2013; CPV data: "Environmental Sustainability of Concentrator PV Systems: Preliminary LCA Results of the Apollon Project" 5th World Conference on PV Energy Conversion. Valencia, Spain, 6-10 September 2010. Graph: PSE AG 2014

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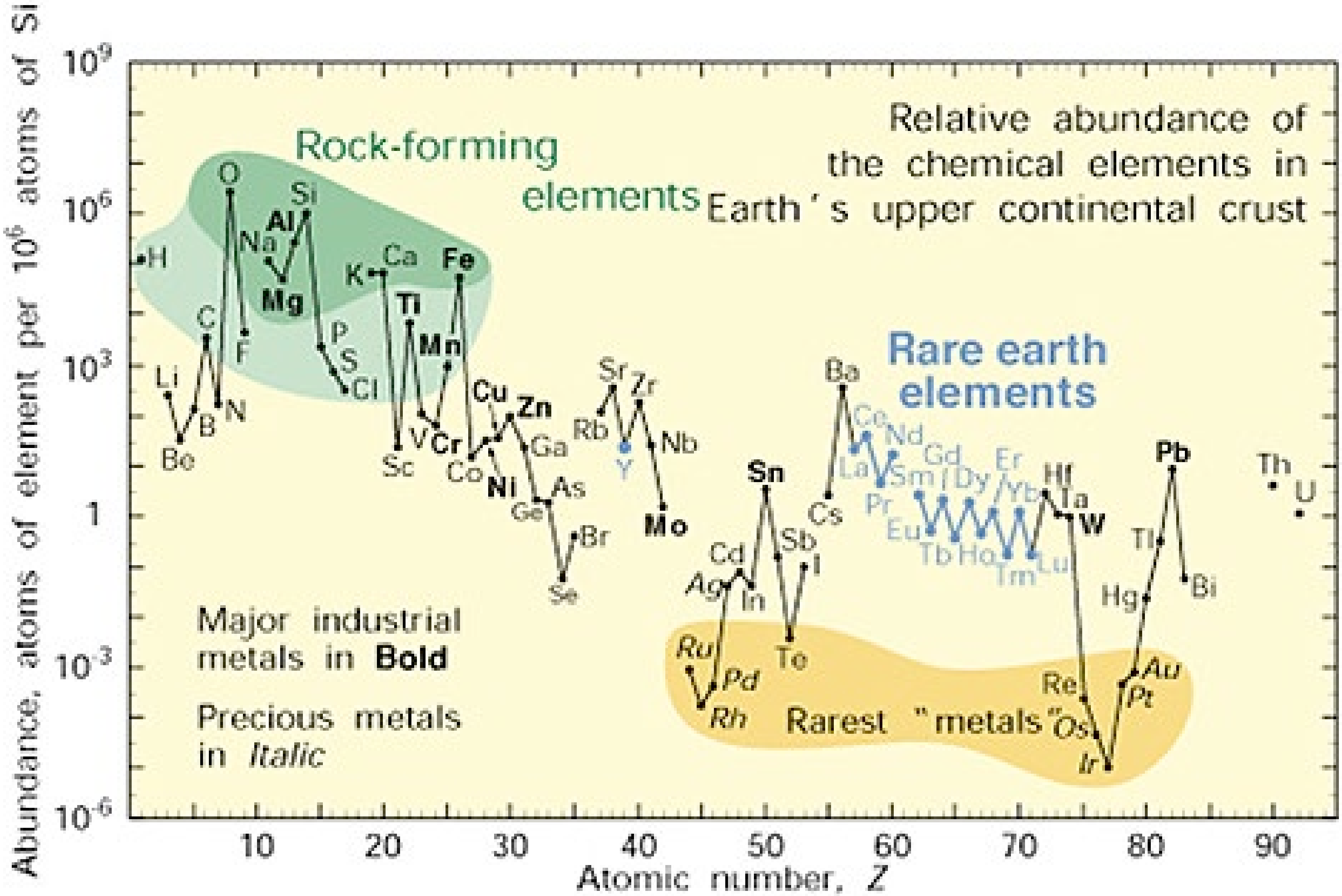
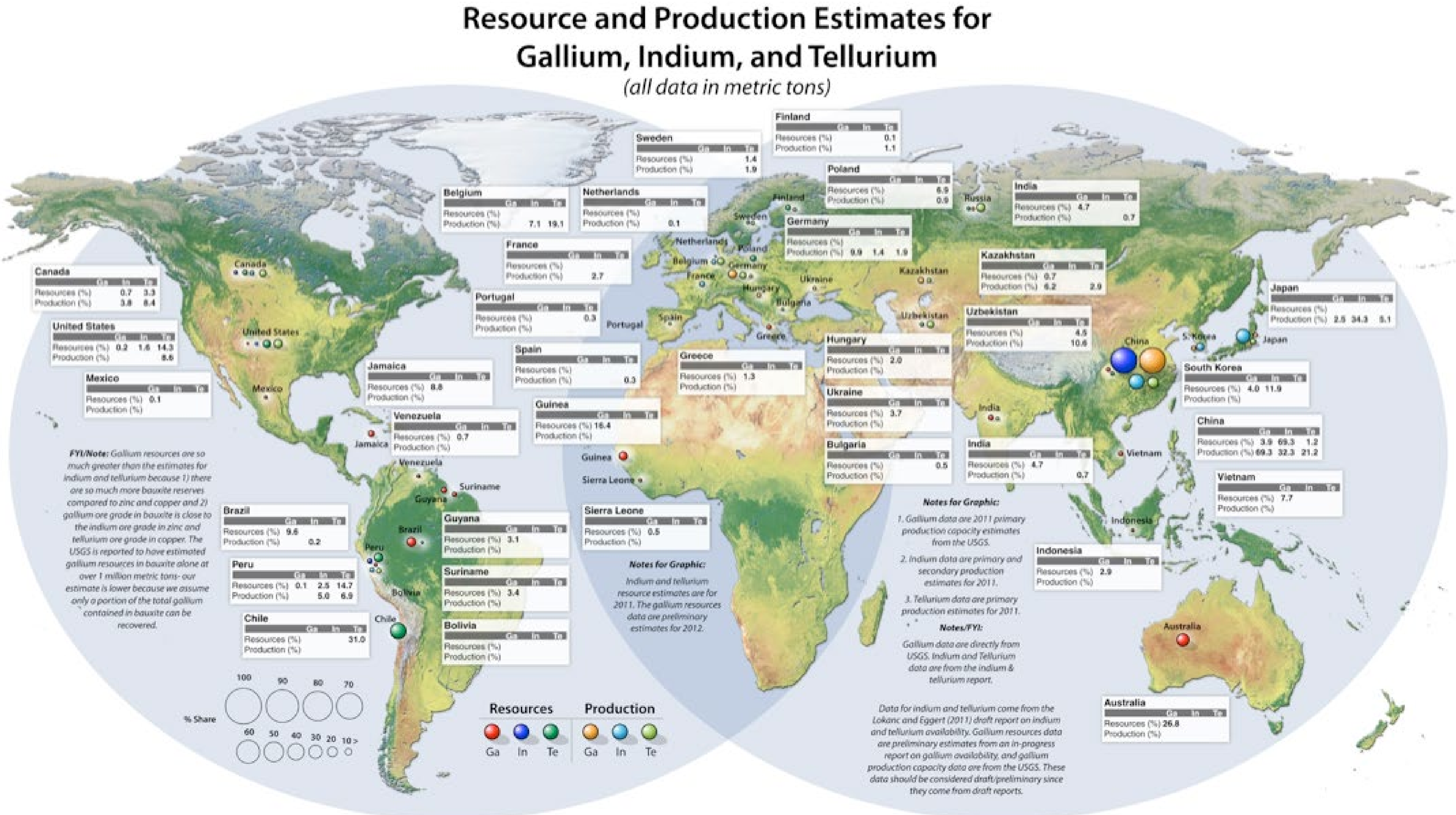
There Isn't Enough Te on Earth!!



Wikipedia, RSC, etc.

2012 PV Materials Resource Availability and Production



Source of Figure: NREL and Colorado School of Mines

Note that the percentages for each element do not add up to 100%.

This is because only the top 8 – 20 countries in resources and production are shown for each element.

They Will Find More if the Price is Right

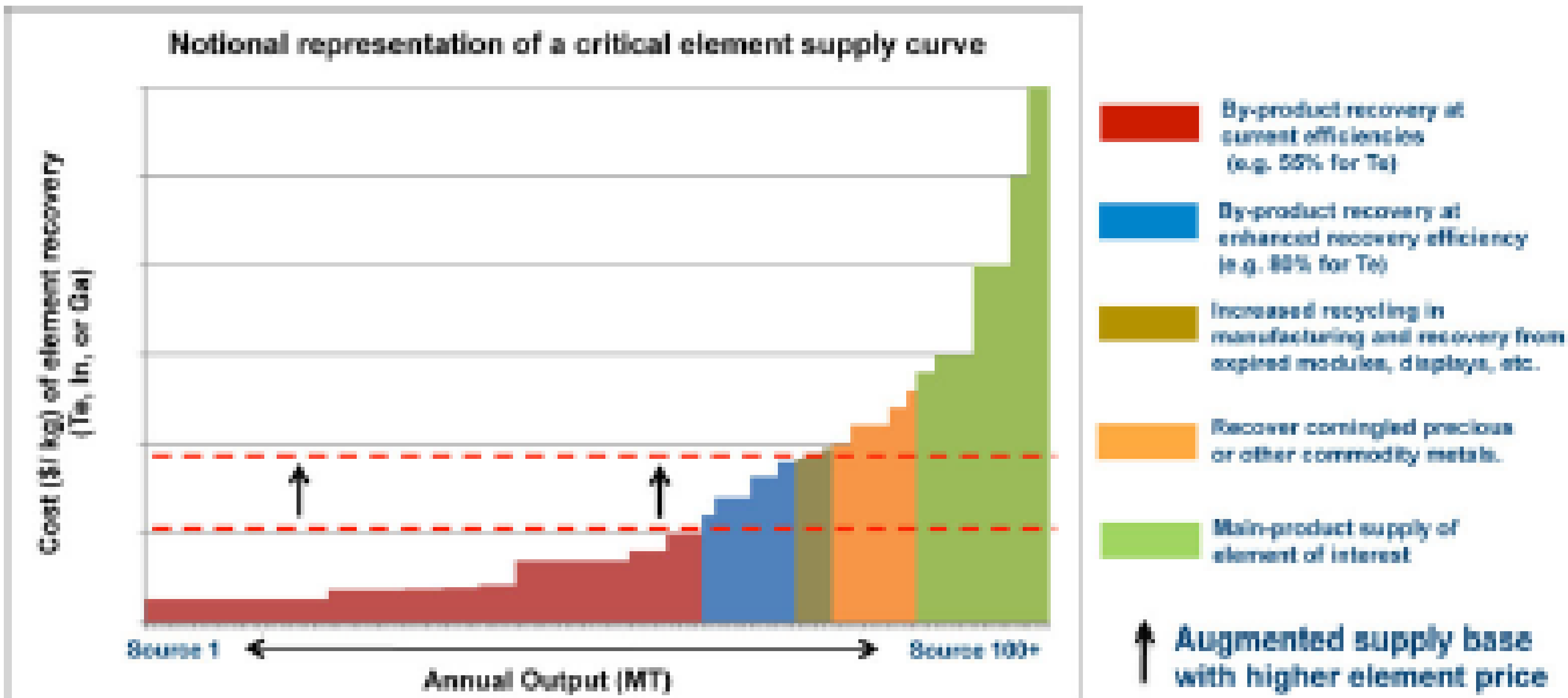
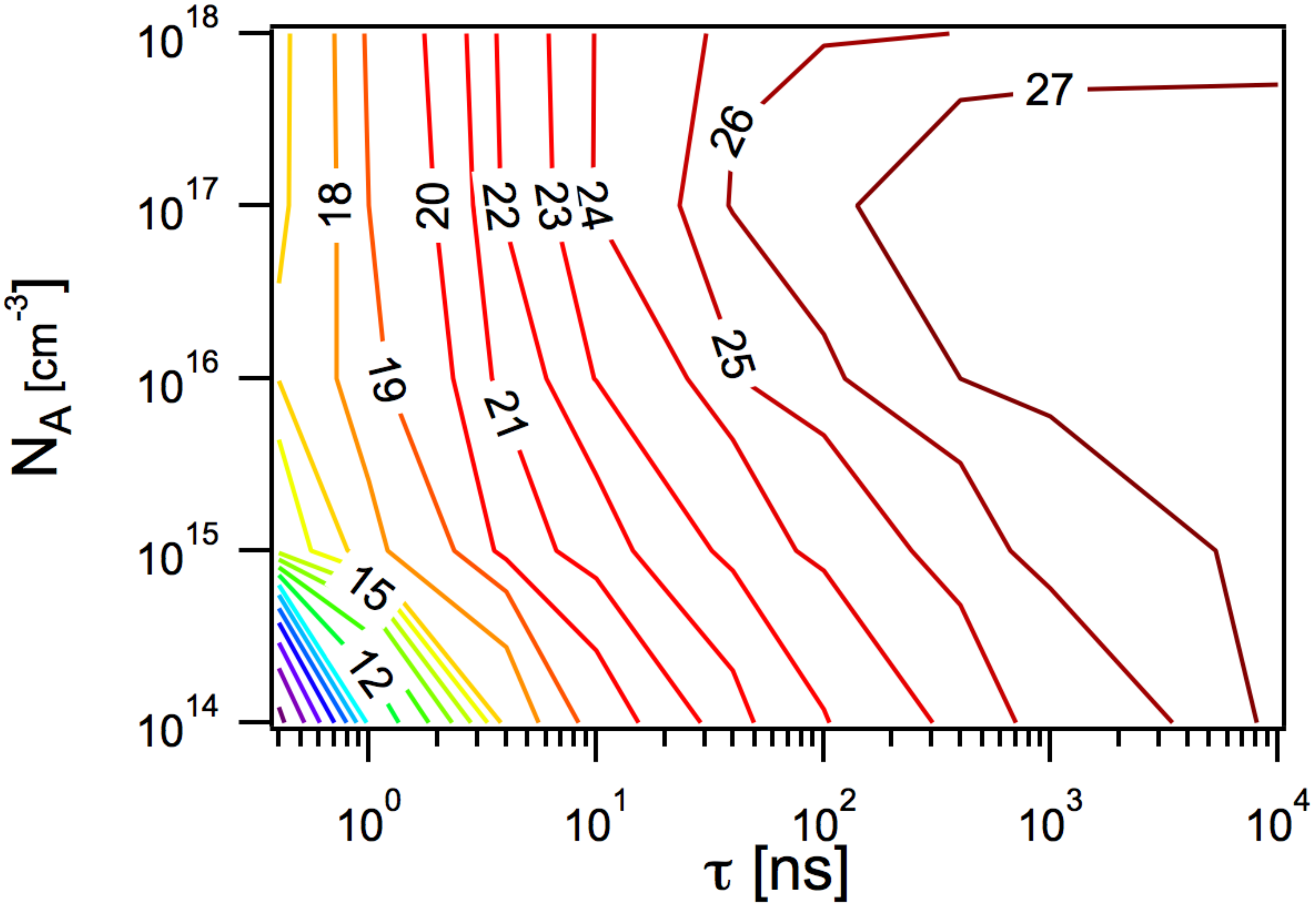


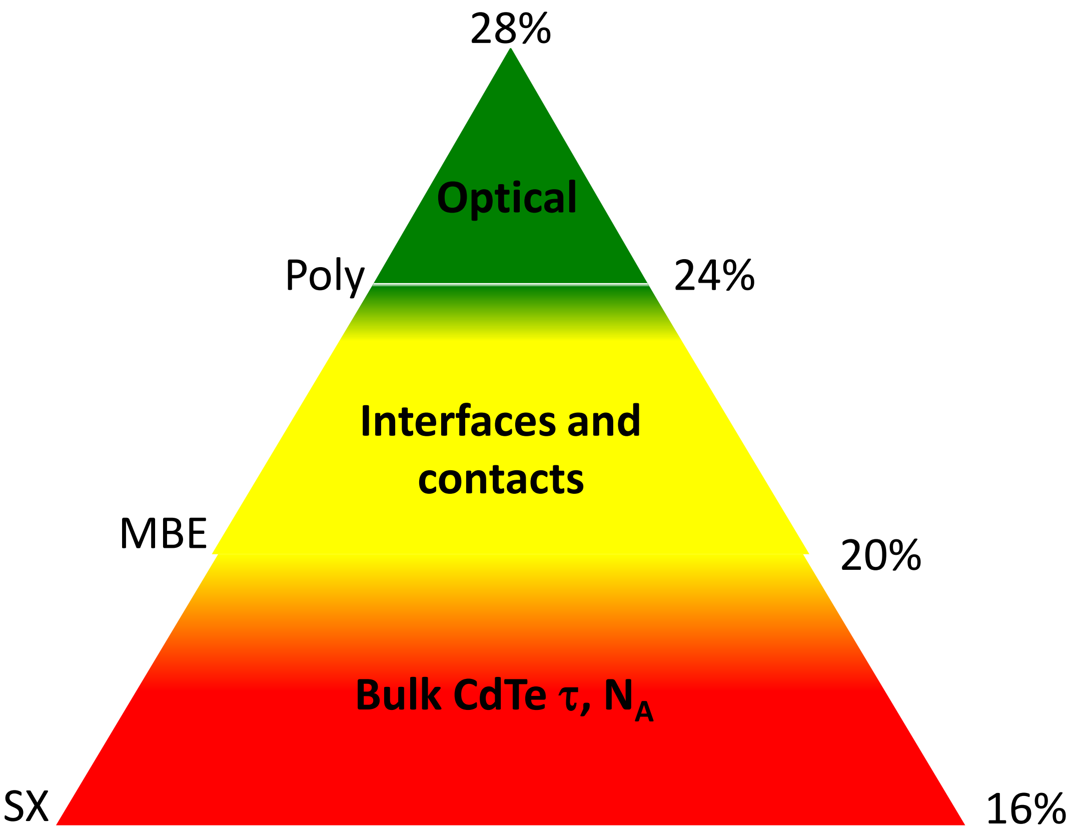
Fig. 1. Notional illustration of a cumulative availability curve for the critical elements of interest. The concept of this curve was adapted from [30], which was a similar analysis carried out for conventional and unconventional petroleum resources. The horizontal lines and arrow represent an increase in the supply base that could potentially be realized, if the higher range of recovery costs was still tolerable to thin-film PV manufacturers.

How Did We Get Here?

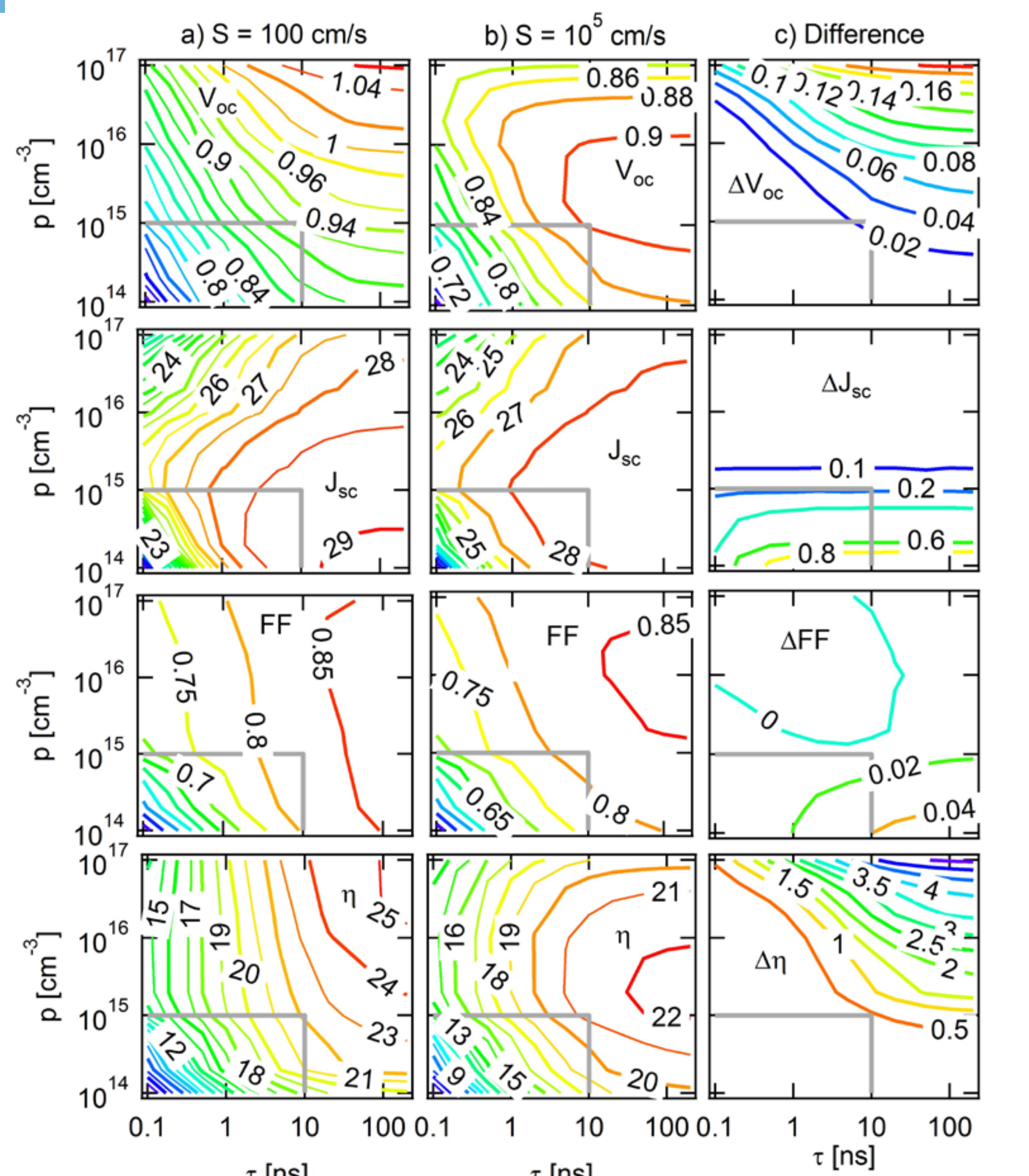


Why Interfaces?

- Interfaces are the next big problem in CdTe - they become more important as the bulk improves



What Happens When We Add Interface Recombination?

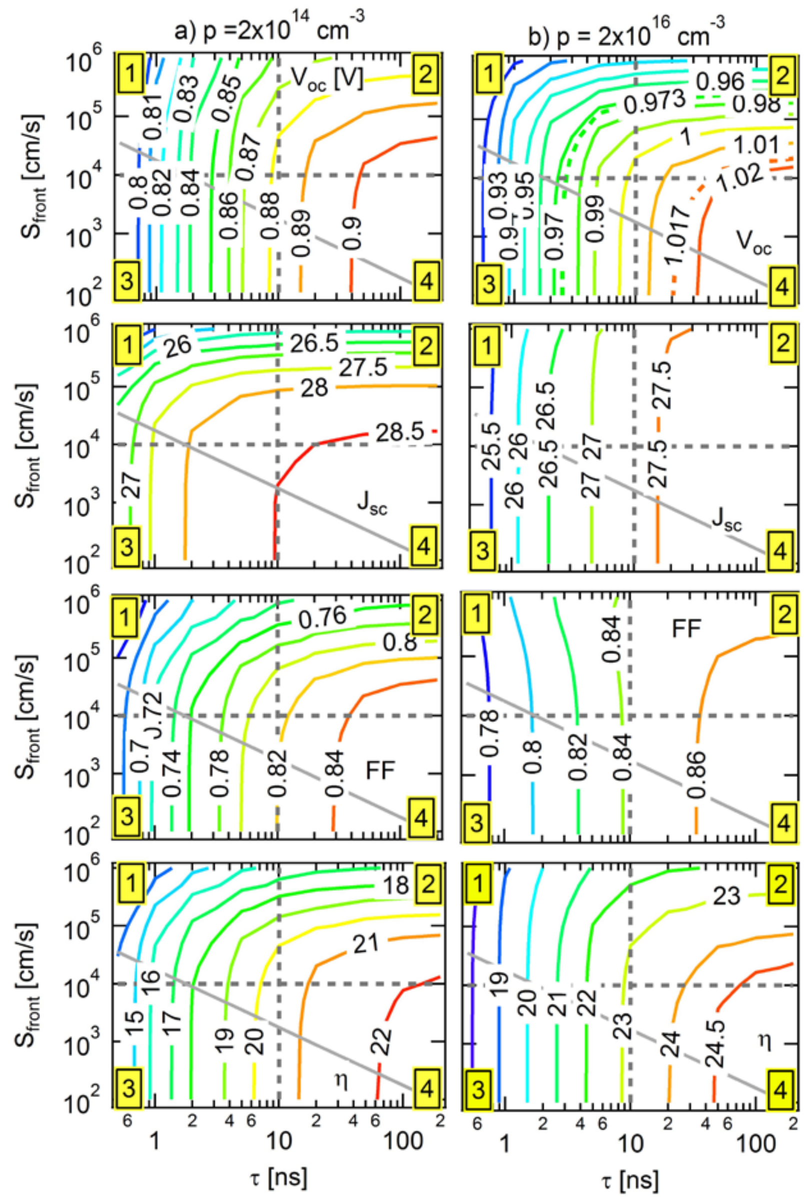


Interface recombination is not critical when t and p are low

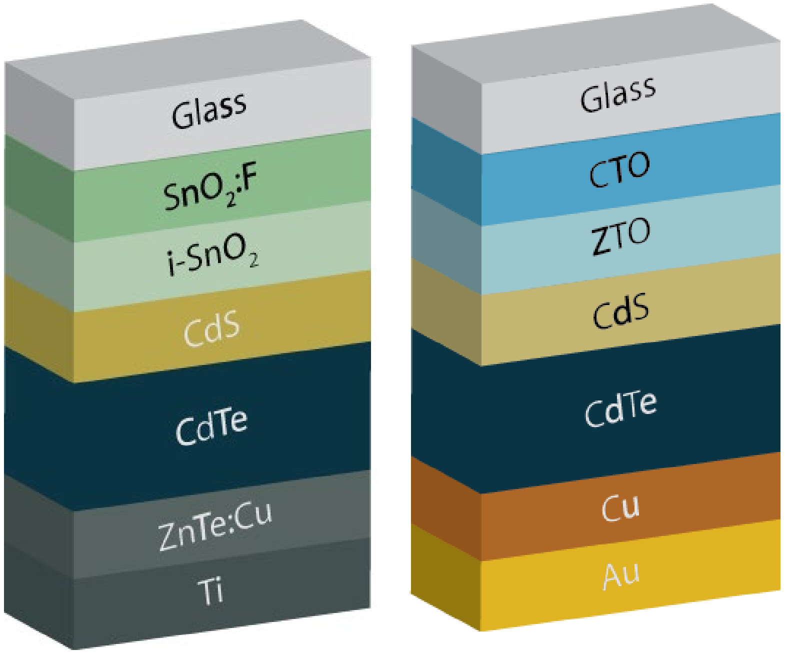
Interfaces Limit Performance with Long Bulk Lifetime

- Electronically thin vs. electronically thick
- $L = \sqrt{\mu \cdot \tau}$
- Longer diffusion lengths mean more carriers “see” the back interface
- S_{int} is often the reason we don’t get the expected V_{oc}.

$T_s = T_b$



Device Processing



14-16 %　　14-16%

TCO options: MOCVD SnO_2:F/SnO_2, sputtered CTO/ZTO, ITO
CdS: Chemical bath, sputtered CdS:O
CdTe: CSS 550 °C – 620 °C
$CdCl_2$: CSS~400 °C
Back Contact:
- Sputtered ZnTe:Cu/Ti (~320 °C)
- Evaporated Cu/Au + heat treatment
- Evaporated ZnTe:Cu/Au + heat treatment

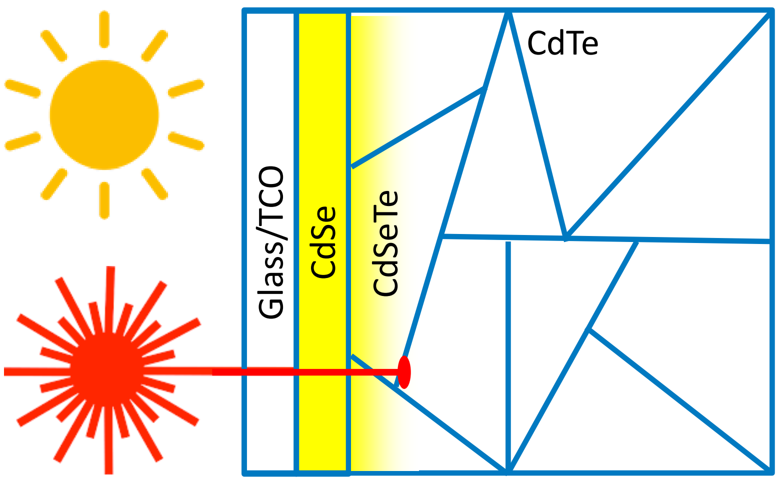
38 mm x 38 mm pieces of flexible glass
JV - Photolithographic isolation or apertures

- Four front contact stacks and three back contacts yield good performance
- Processing temperatures > 600 °C and thermal cycling during fabrication

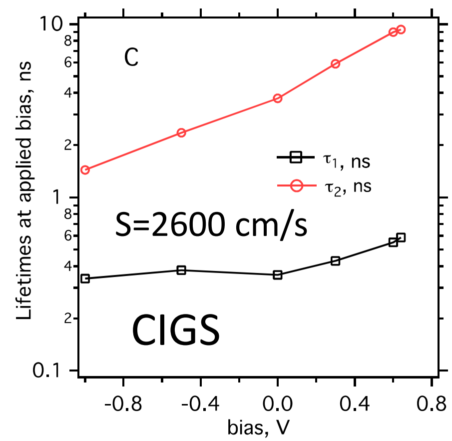
Electrical Measurements
JVTI - Interface recombination analysis

Numerical interface recombination analysis in thin film devices: (electrical JVTI) Li et al, Sol.Mat. 124, 143 (2014)
(optical) Kuciauskas et al, JAP 117, 185102 (2015)

Optical approach:



If interface lifetimes <1ns and PL emission is from near-interface, interface properties with “spike” band alignment can be analyzed from:



$$\frac{1}{\tau_1} = \frac{1}{\tau_R} + \frac{1}{\tau_{th}} + \frac{1}{\tau_S} + \frac{1}{\tau_D},$$

$$\frac{1}{\tau_{th}} = \frac{1}{L_w}\sqrt{\frac{k_B T}{2\pi m}}\exp\left(-\frac{\Delta E}{k_B T}\right),$$

$$\frac{1}{\tau_S} = \alpha S.$$

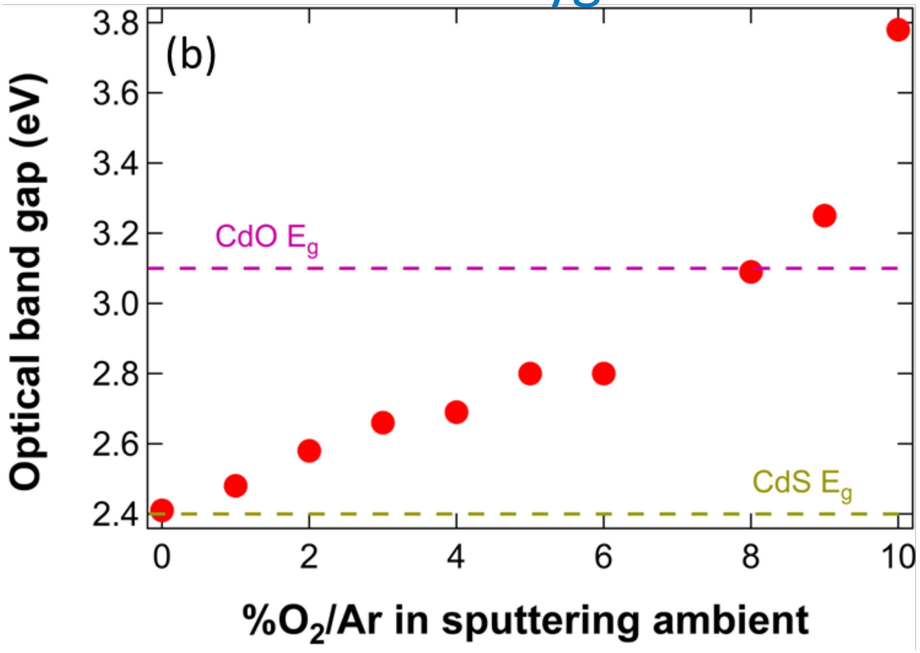
$$\frac{1}{\tau_D} = \frac{\pi^2 D}{4x_n^2},$$

If interface lifetimes are >1ns, carriers drift/diffuse from the interface. Optical methods can be also applied to such graded absorbers where Eg indicates depth. In non-Eg graded samples, TCAD needs to used to model interface recombination effects on TRPL (CL, EBIC, …) data

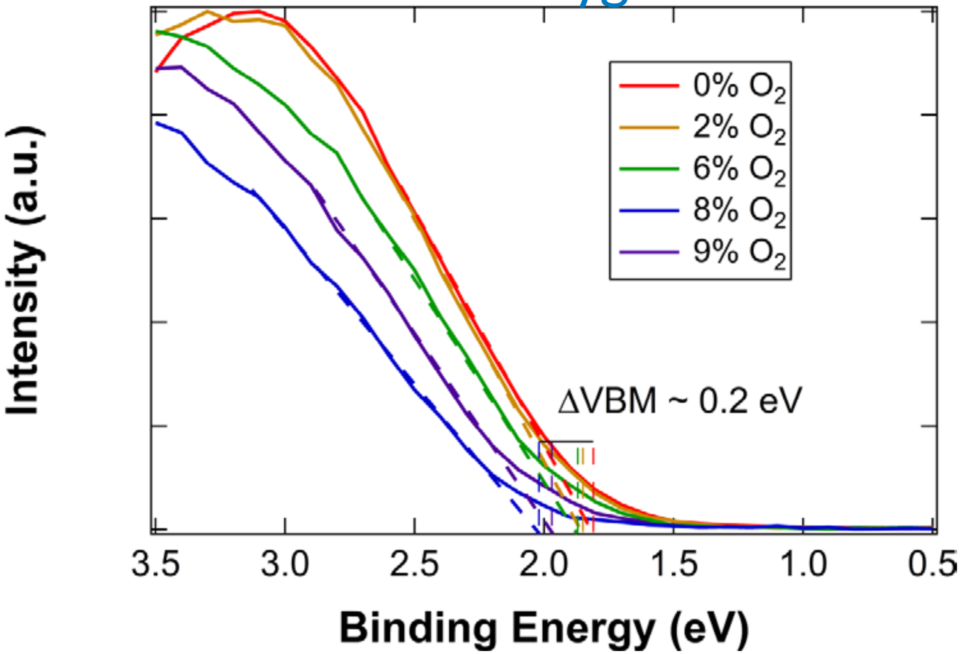
This analysis requires good devices and knowledge of band alignment, Eg-grading, etc. Therefore, standard – and much simpler – approach is to use double heterostructures

Example of a Student Project

CdS:O – Optical bandgap shifts with oxygen content



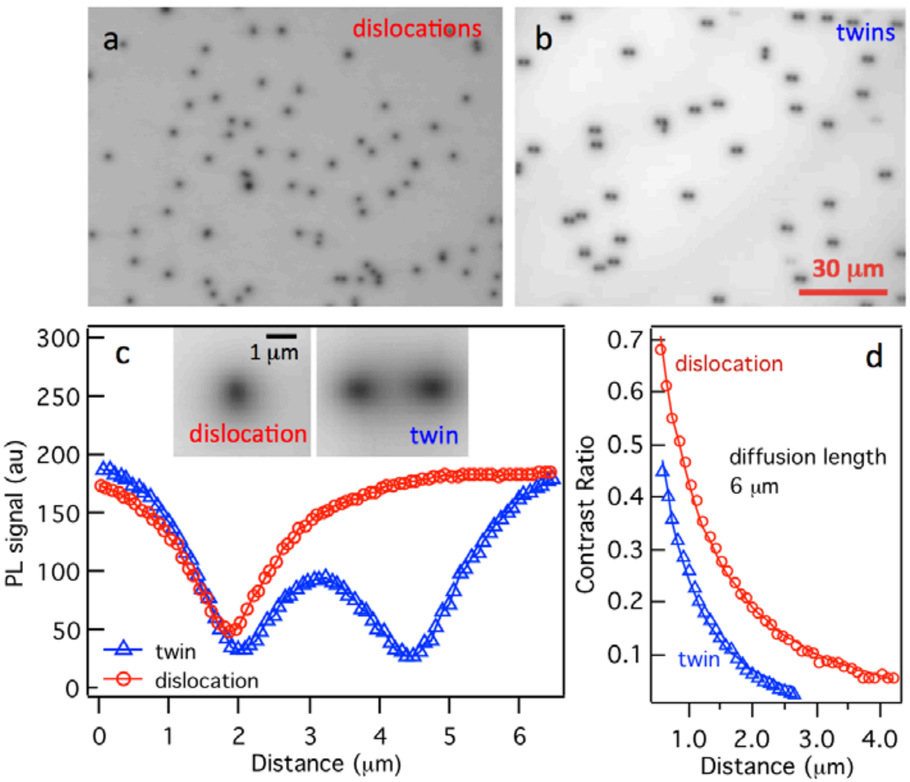
CdS:O – Valence band maximum shifts with oxygen content



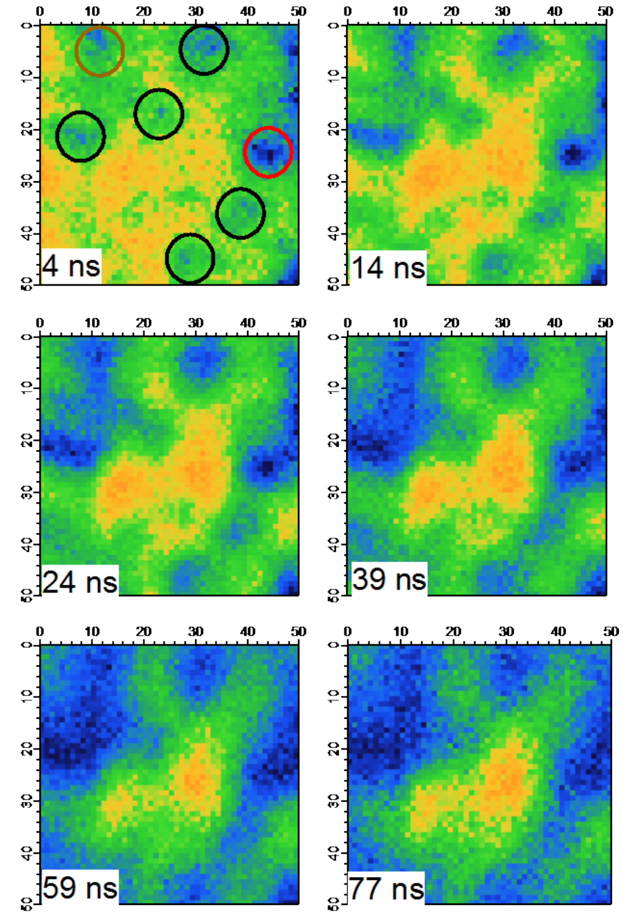
- CdS growth and materials characterization, device fabrication and characterization
- Surface analysis, band offset measurements, correlation to device performance and process-property relationships

Defect Mapping and Lifetime Mapping

Recombination at extended defects limits carrier lifetimes when dd is ≥10^6 cm^2



Zaunbrecher, Kuciauskas, Swartz, Dippo, Edirisooriya, Ogedengbe, Sohal, Hancock, LeBlanc, Jayathilaka, Barnes, Myers; Impact of Extended Defects on Recombination in CdTe Heterostructures Grown by MBE; APL, revision submitted



Also SuNLaMP 30306

Kuciauskas, Wernsing, Jensen, Barnes, Myers, Bartels; Analysis of Recombination in CdTe heterostructures with time-resolved 2PE microscopy; IEEE JPV, in press

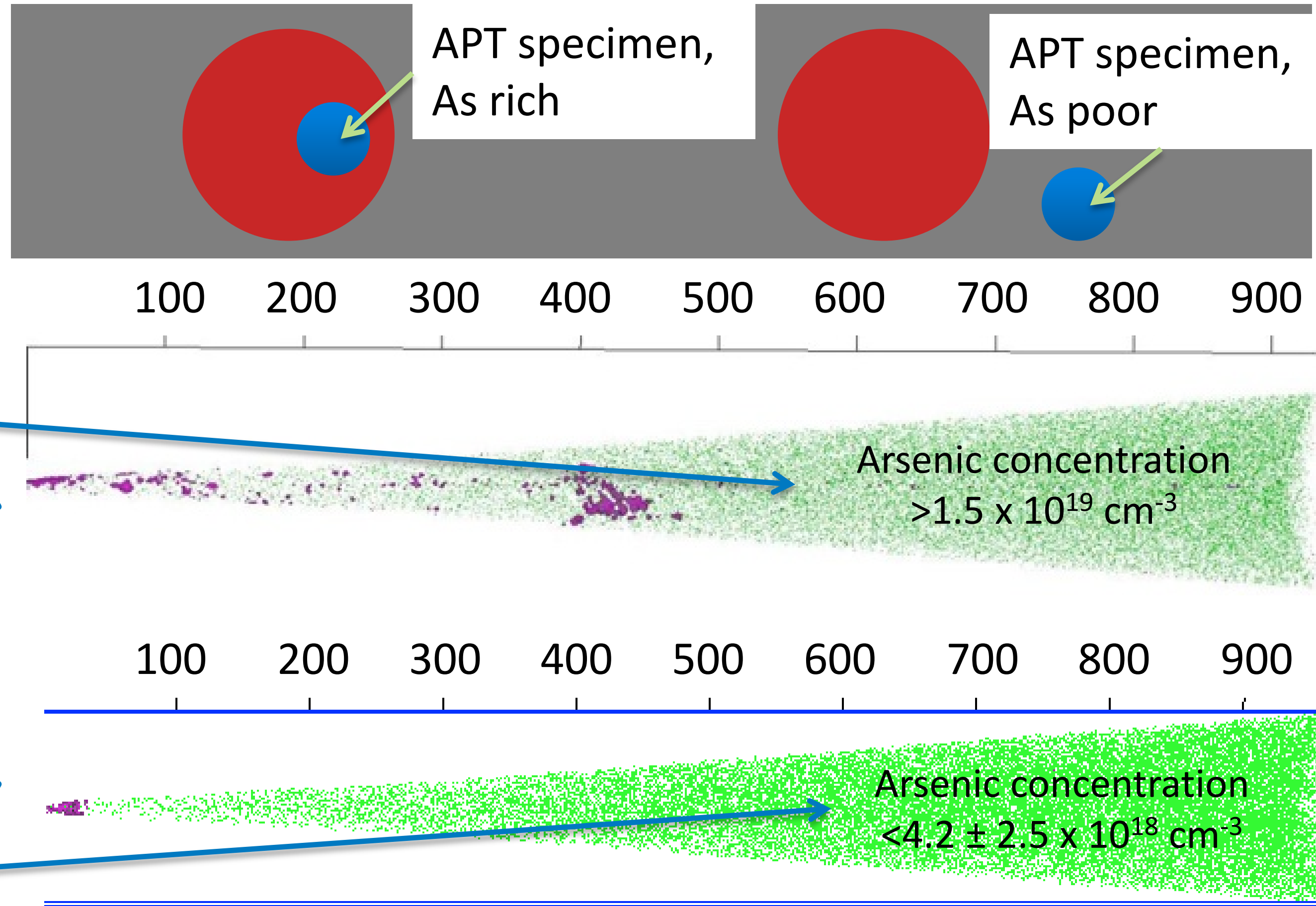
Atom Probe with Colorado School of Mines

Clusters on the nano-scale

As concentration higher than expected

Separated by 6 µm in growth plane

As concentration lower than expected



Opportunities for Students and Postdocs

- Work in a commercial technology that needs additional fundamental knowledge to continue advancing
- Range of projects from foundational to highly applied
- Highly Collaborative, publishable, innovative
- Measurements, synthesis, device integration, solid state theory, device modeling
- At least 6 months if you come to NREL
  - Shorter term projects possible if we send material to universities for unique measurements
- Can send samples out for unique characterization or analysis techniques

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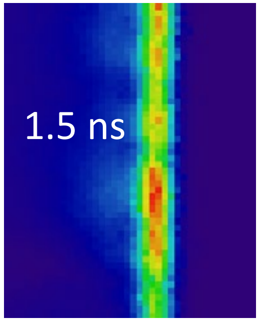
Two Photon TRPL Mapping

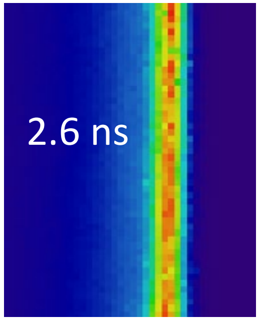
MBE728: As-doped

Carrier lifetimes 1.5-4.4 ns, depending on annealing conditions

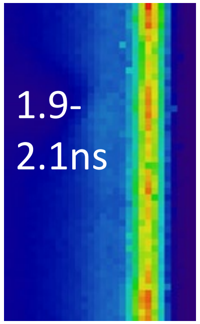
550C/1min
AN4 on Si (F2F)



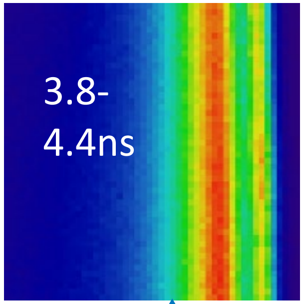
450C/20min
AN10 (F2F)

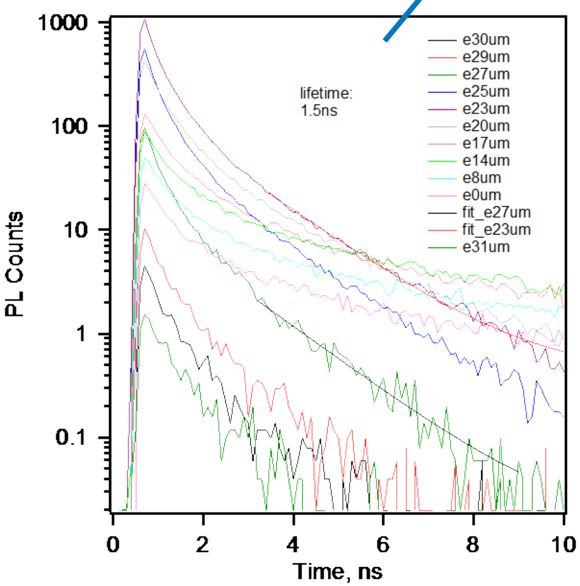


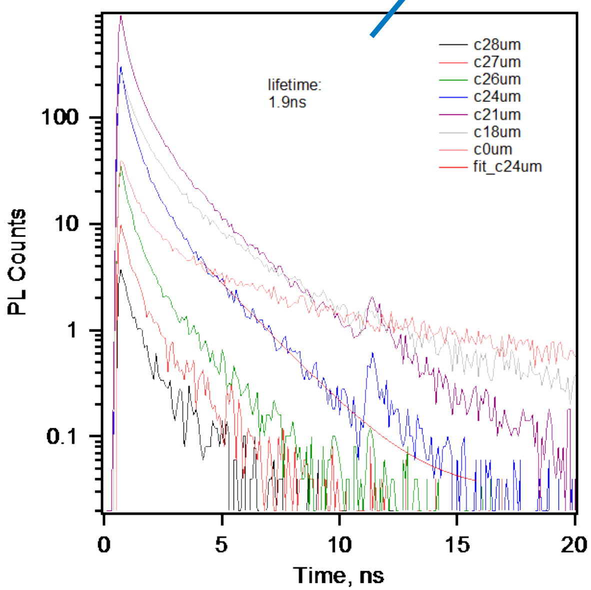
control

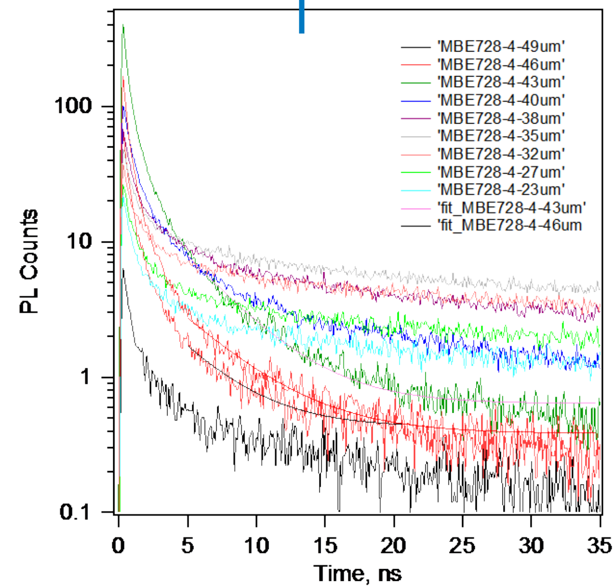


ampoule

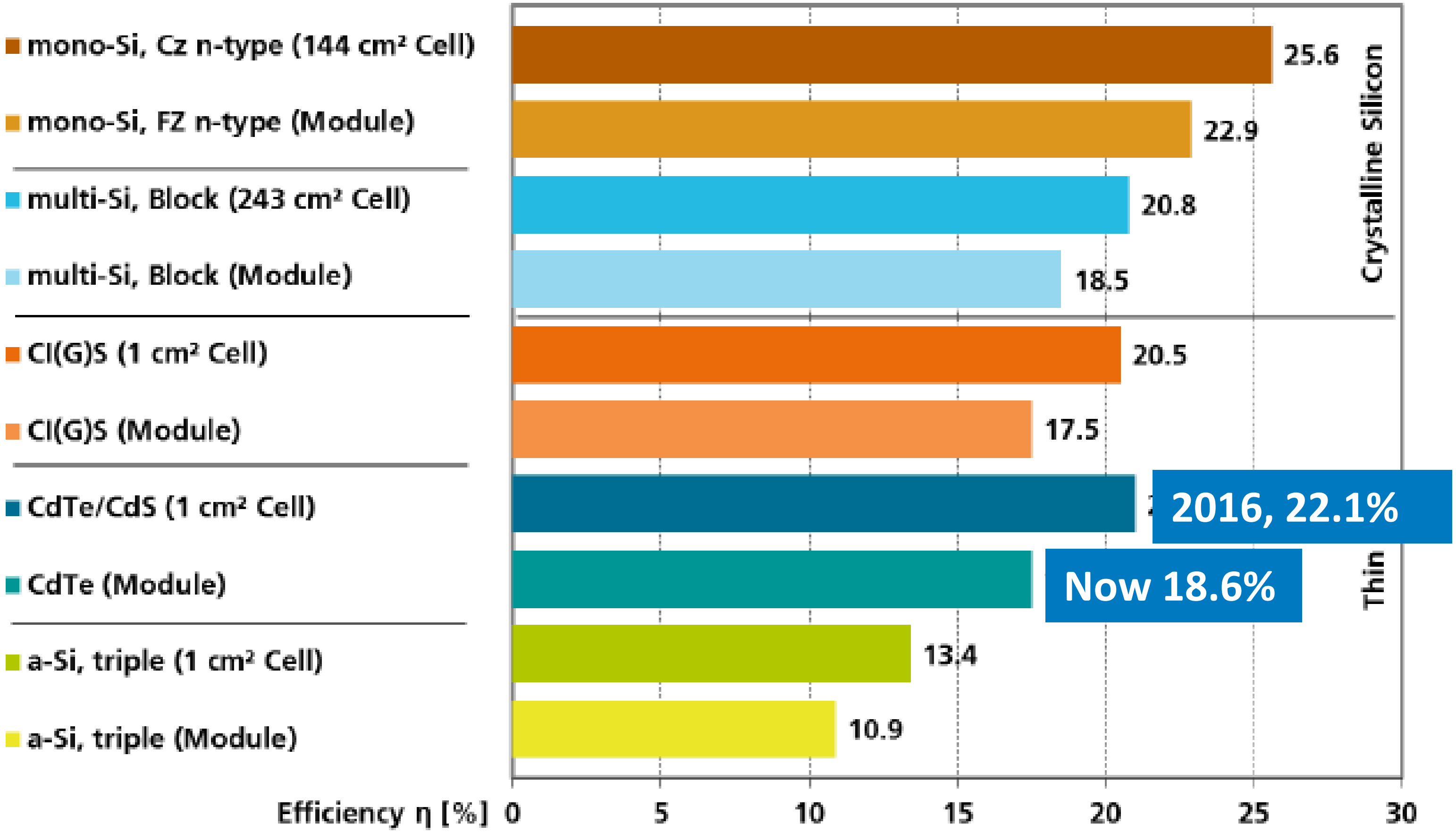








Efficiency Comparison of Technologies:
Best Lab Cells vs. Best Lab Modules



Data: Green et al.: Solar Cell Efficiency Tables,(Version 45), Progress in PV: Research and Applications 2015. Graph: PSE AG 2015

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