NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Research Challenges for CIGS and CdTe

Presented by I. Repins

Thanks to NREL's polycrystalline thin film group and characterization group .

This work was supported by the U.S. Department of Energy under Contract No. DOE-AC36-08GO28308 with the National Renewable Energy Laboratory.

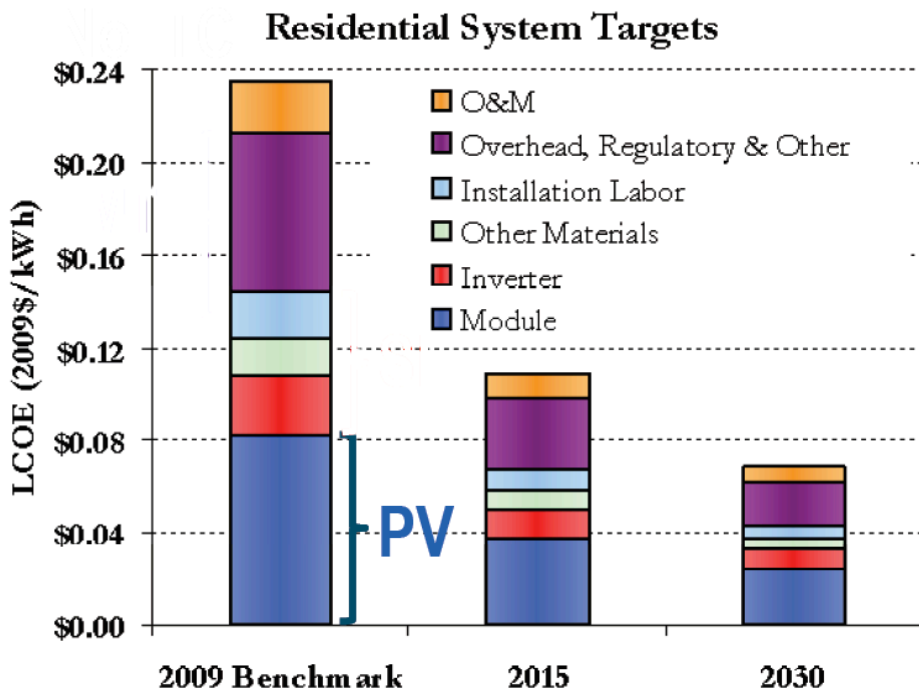
Outline

- Landscape for PV Research
- Needs for CIGS
- Needs for CdTe
- Wider-scope needs

Landscape

Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
  - First Solar CdTe $0.84 / Watt (self-reported cost Q4, 2009)
  - Trina Solar x-Si $1.24 / Watt (self-reported cost Q4, 2009)
  - Modules are only 30-50% of project cost.

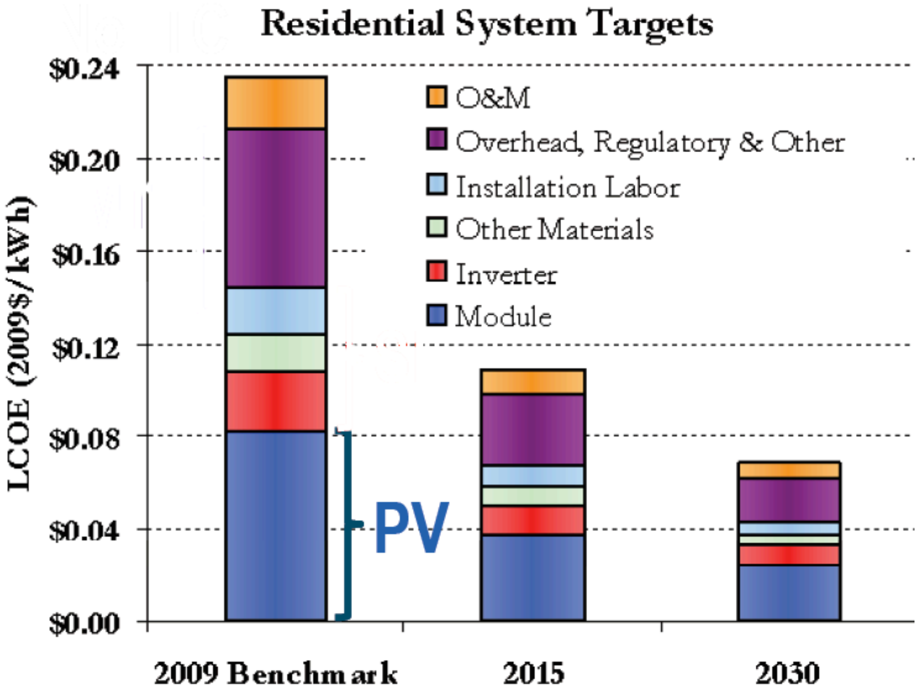


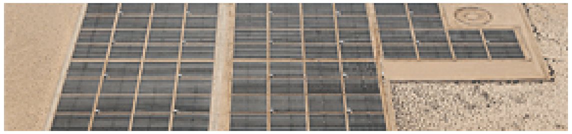
From "Solar Program Overview", Minh Le, DOE, 2010.

Landscape

Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
  - First Solar CdTe $0.84 / Watt (self-reported cost Q4, 2009)
  - Trina Solar x-Si $1.24 / Watt (self-reported cost Q4, 2009)
  - Modules are only 30-50% of project cost.
  - In some cases, PV is at grid parity now. (Eaglesham, 2009 SPIE)





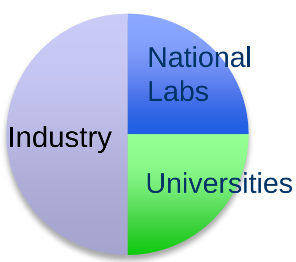
From “Solar Program Overview”, Minh Le, DOE, 2010.

Landscape

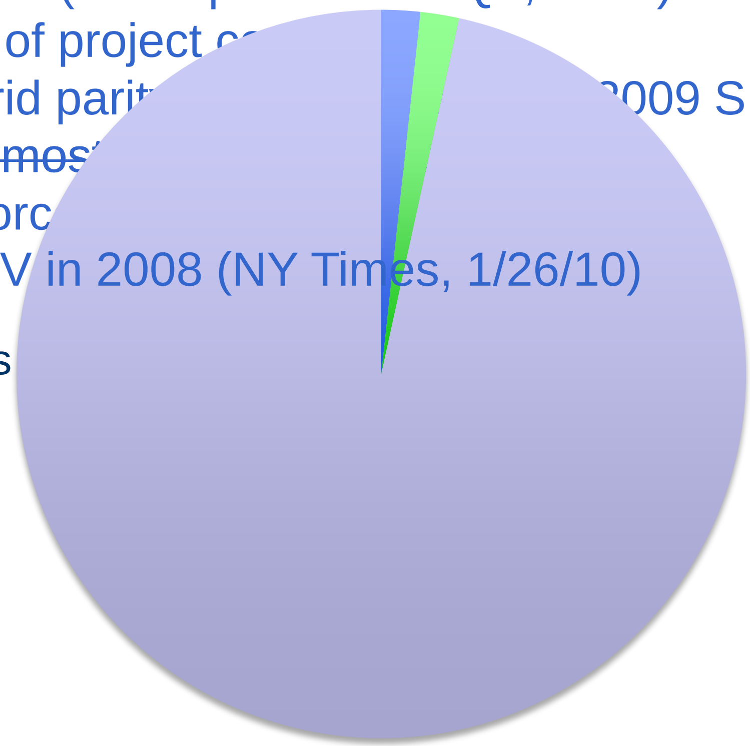
Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
  - First Solar CdTe $0.84 / Watt (self-reported cost Q4, 2009)
  - Trina Solar x-Si $1.24 / Watt (self-reported cost Q4, 2009)
  - Modules are only 30-50% of project c
  - In some cases, PV is at grid parit 2009 SPIE)
- ~~Thin Film polycrystalline PV is mos~~
  - Growth in industrial workforc
  - $2 billion VC funding for PV in 2008 (NY Times, 1/26/10)

U.S. Employees



2000



2010

Landscape

Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
    - First Solar CdTe $0.84 / Watt (Q4, 2009)
    - Trina Solar x-Si $1.24 / Watt (Q4, 2009)
    - Modules are only 30-50% of project cost.
    - In some cases, PV is at grid parity now. (Eaglesham, 2009 SPIE)
- ~~Thin Film polycrystalline PV is mostly a research project~~.
    - Growth in industrial workforce
    - $2 billion VC funding for PV in 2008 (NY Times, 1/26/10)
- ~~We know how to make good semiconductors. Good PV manufacturing will look like a chip fab.~~


Wet CIGS processing at Nanosolar

Landscape

Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
  - First Solar CdTe $0.84 / Watt (Q4, 2009)
  - Trina Solar x-Si $1.24 / Watt (Q4, 2009)
  - Modules are only 30-50% of project cost.
  - In some cases, PV is at grid parity now. (Eaglesham, 2009 SPIE)
- ~~Thin Film polycrystalline PV is mostly a research project~~.
  - Growth in industrial workforce
  - $2 billion VC funding for PV in 2008 (NY Times, 1/26/10)
- ~~We know how to make good semiconductors. Good PV manufacturing will look like a chip fab.~~
- ~~Thin film polycrystalline manufacturers must eliminate Cd to be viable.~~

Landscape

Timeless truths that have changed in the last 10 years

- ~~PV is *really* expensive~~
  - First Solar CdTe $0.84 / Watt (cost Q4, 2009)
  - Trina Solar x-Si $1.24 / Watt* (cost Q4, 2009)
  - Modules are only 30-50% of project cost.
  - In some cases, PV is at grid parity now. (Eaglesham, 2009 SPIE)
- ~~Thin Film polycrystalline PV is mostly a research project~~.
  - Growth in industrial workforce
  - $2 billion VC funding for PV in 2008 (NY Times, 1/26/10)
- ~~We know how to make good semiconductors. Good PV manufacturing will look like a chip fab.~~
- ~~Thin film polycrystalline manufacturers must eliminate Cd to be viable.~~
- ~~Thin film = low performance~~

Device type	Area (cm^2)	Efficiency (%)	Accredited measurement?	Origin	Date
CIGS/glass	0.5	20.1	Y	ZSW	4/10
Glass/CdTe	1.05	16.7	Y	NREL	9/1
CIGSS/glass	855	15.7	N	Solar Frontier	3/10
CIGSS/glass	3459	13.5	Y	Showa Shell	8/02
CIGS/steel	3900	13.2	Y	Global Solar	2/10
Glass/CdTe	6623	12.6	Y	First Solar	8/08
CIGS/glass	6716	13.9	N	Honda	12/07

Landscape

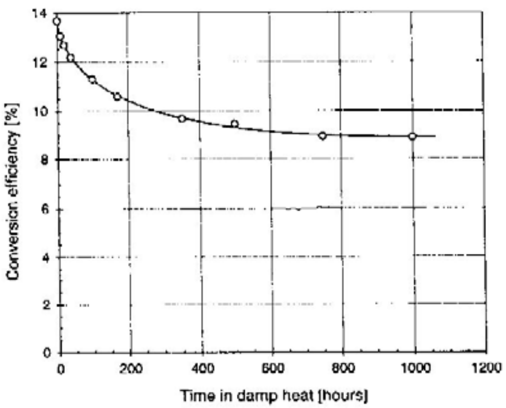
Implication for research needs:

- Definition for "low-cost" has changed
- Module efficiency is key, since it can reduce both module and non-module costs
- Research community should avoid duplicating effort with the massive industrial workforce.
- The best research problems are applicable to the widest variety of deposition techniques and device designs used in the industry.

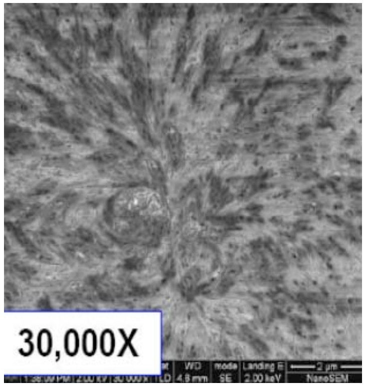
Outline

- Landscape for PV Research
- Needs for CIGS
- Needs for CdTe
- Wider-scope needs

CIGS: Moisture-resistance



Wennerberg et al, 2nd WCPVSEC, 1998.

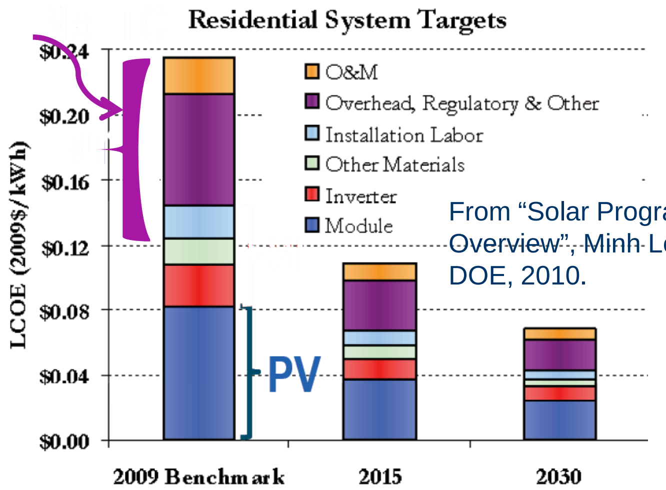


ZnO bilayer
480 hours DH

Pern et al, 2nd WCPVSEC, 1998.

- Why is this issue important if product works well enough with a glass-glass package?
  - Shipping, installation costs increase with weight
  - Flexible, building-integrated product may further reduce installation costs
  - Cost of additional glass contributes to module cost
- Need moisture hardening of device, and/or
- Low-cost, flexible, moisture-impermeable encapsulant (10^{-6} gm / m^2 / day)

CIGS: Efficiency



From "Solar Program Overview", Minh Le, DOE, 2010.

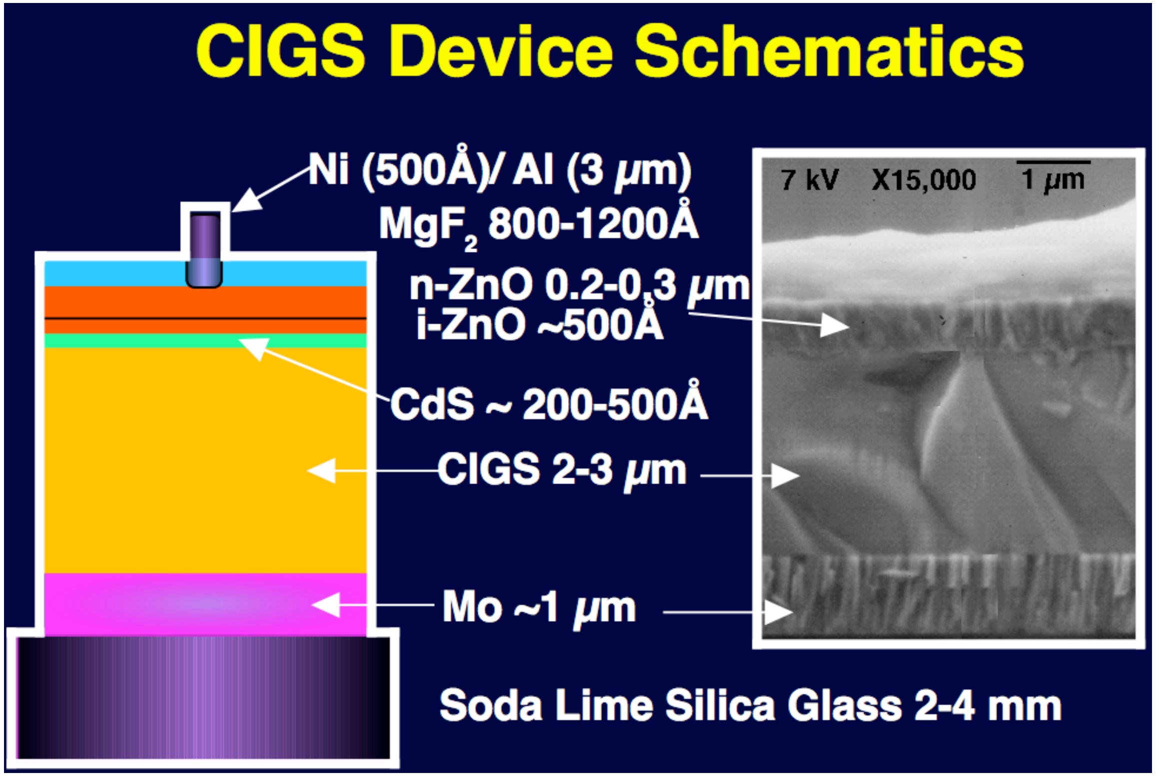
Device type	Area (cm^2)	Efficiency (%)	Accredited measurement?	Origin	Date
CIGS/glass	0.5	20.1	Y	ZSW	4/10
CIGSS/glass	855	15.7	N	Solar Frontier	3/10
CIGSS/glass	3459	13.5	Y	Showa Shell	8/02
CIGS/steel	3900	13.2	Y	Global Solar	2/10
CIGS/glass	6716	13.9	N	Honda	12/07

- Further improvements affect both module and non-module costs.
- Short-term: closing the gap between module and cell efficiencies. Examples:
  - Metrology
  - Comparative analysis
- 20.1% is not the end of the road. Examples:
  - 2.9 mW/cm^2 to gain by increasing band gap without decreasing lifetime.
  - 1.8 mW/cm^2 to gain by replacing CdS with less absorptive layer

CIGS: Fundamental understanding

- Improve fundamental understanding of how the important properties and processing of each layer relate to device performance.

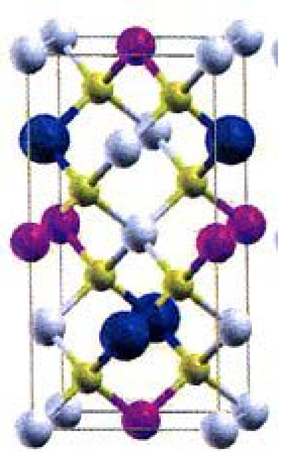
- Needed for transfer of champion results to manufacturing, quick optimization of new processes, high yields, and device improvement.



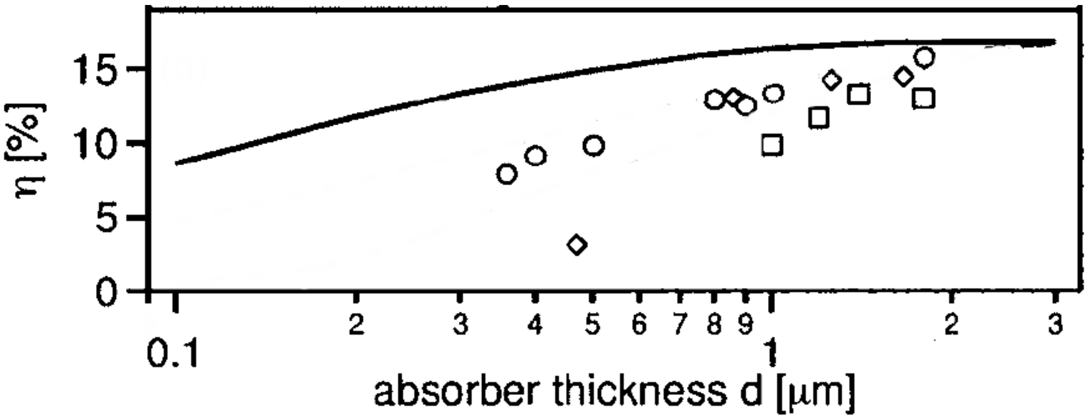
- For example
  - What mechanisms control lifetime and carrier density in CIGS?
  - How should we routinely measure Na? What is the sensitivity of 20% devices to variations in Na profile?
  - Can we define the role of bath-deposited CdS to a point where we can replace it with other processes and materials?

CIGS: Reduced sensitivity to indium price

- Currently, In in absorber adds ~ $0.03/W to module (In $700/kg, 50% utilization, 2 μm CIGS, 30% Ga ratio, 12% efficiency)
- Concern is possible increase In price with high-volume (many GW/yr) CIGS manufacturing and growth in LCD industry
- Investigation of earth-abundant materials (such as CZTS)
- Reduction of absorber thickness



Chen et al, *APL* **94**, 2009

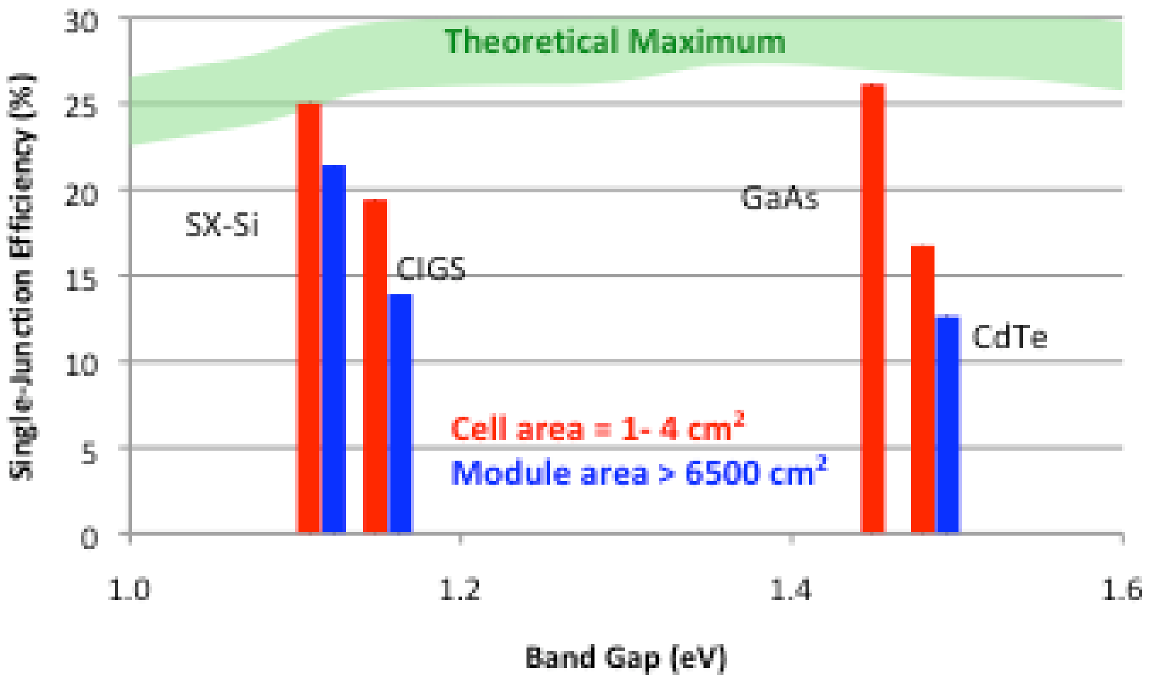


Gloeckler et al, *JAP* **98**, 2005

Outline

- Landscape for PV Research
- Needs for CIGS
- Needs for CdTe
- Wider-scope needs

CdTe: Demonstrated efficiency

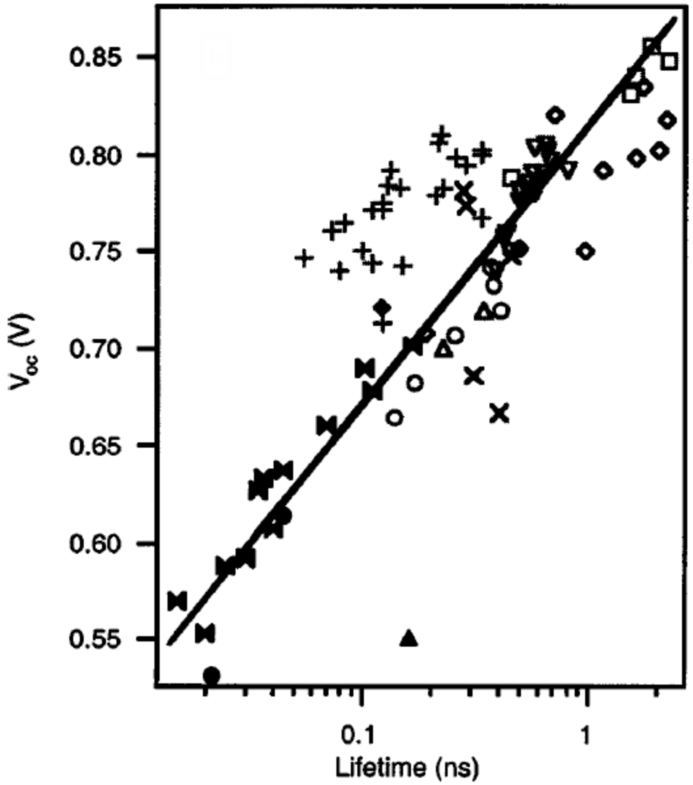


CdTe has the most potential for improvement based on difference between theoretical limit and demonstrated cells or modules.

CdTe: Minority Carrier Lifetime

Record cell type	Approximate E_g (eV)	J_{sc} (mA/cm^2)	Ff (%)	V_{oc} (V)	Efficiency (%)	E_g/q - Voc (V)
SX-Si	1.11	42.7	82.8	0.706	25.0	0.404
CIGS	1.15	35.7	81.0	0.692	20.0	0.458
GaAs	1.43	29.6	84.6	1.045	26.1	0.385
CdTe	1.48	26.1	75.5	0.845	16.7	0.635

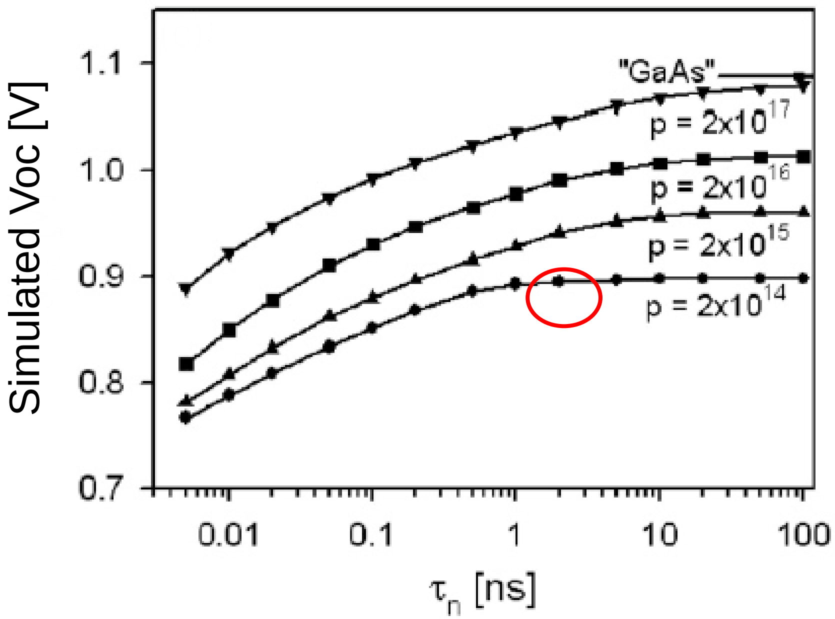
- Comparing cell technologies
  - J_{sc} losses are minimal and well-quantified.
  - Largest loss is in V_{oc}.
- Voc is a strong function of minority carrier lifetime.
- Longest lifetimes in PX CdTe ~ 3 nS. Best CIGS devices: lifetime > 100 nS.
- Either increase lifetime, or utilize *p-i-n* structure that minimizes recombination with several nS lifetime.



Metzger et al, JAP **94 (**5), 2003.

CdTe: Carrier Density

- Free carrier densities are low, ~10^{14} cm^{-3}. (Compare to 10^{16} cm^{-3} in CIGS)
- Strong contribution to Voc loss.
- Increased carrier density should also facilitate back contact formation.
- However, it may necessitate re-examination of CdS/CdTe interface and associated recombination.

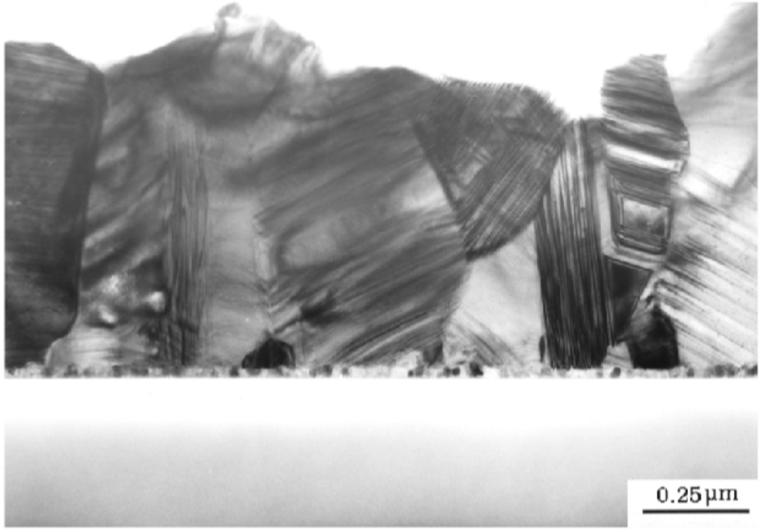


Sites et al, *Thin Solid Films* **515**, 2007

CdTe: Understand defects and grain boundaries

- For epitaxial-grown CdZnTe, free carrier densities of ~10^{16} cm^{-3} and lifetimes of ~ 1 μs have been demonstrated (Carmody et al, *Appl. Phys. Lett.* **96,** 153502, 2010**)**

- What about the PX film processing or structure limits lifetimes to < 3 nS and free carrier density to ~10^{14} cm^{-3}?

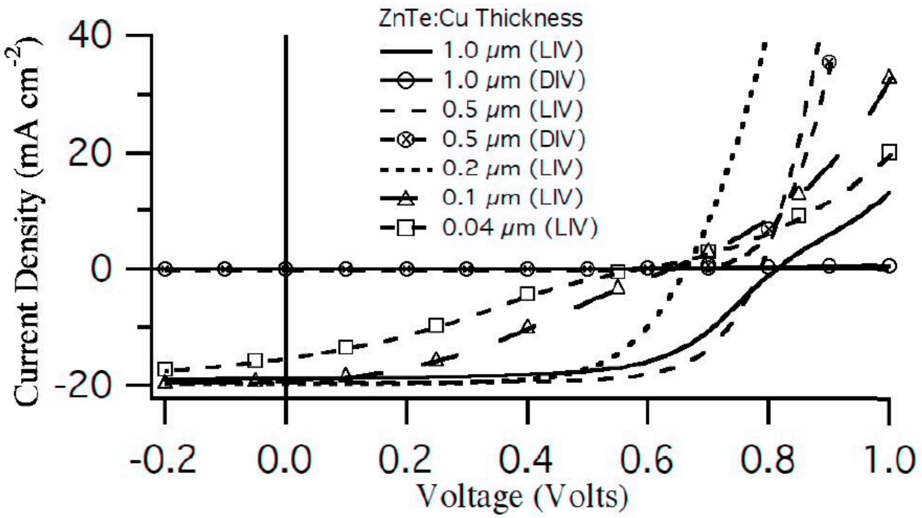


TEM cross section view of a CdTe solar cell

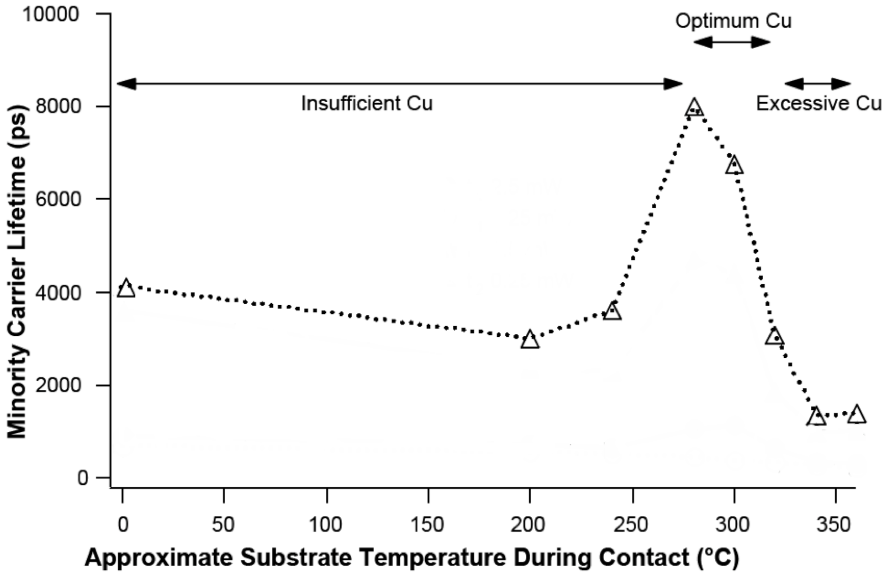
- Note: Examinations of defects, carrier density, and lifetime may be convenient entry points for new research groups. Full device fabrication capabilities not necessarily required.

CdTe: More robust back contact

- Back contact is functional.
- Processing window is narrow.
- Absorber and back contact properties are coupled.
- May be some fill factor loss associated with back contact.



Gessert et al, IEEE PVSC, 2008



Outline

- Landscape for PV Research
- Needs for CIGS
- Needs for CdTe
- Wider-scope needs

Wider-Scope Needs

In 10-20 year time-frame, some enabling factors for low-cost PV may be related to things other than the module:

- Innovations to attack non-module side of costs. Examples of some current efforts:
  - Dow shingle rolls PV installation cost with standard roof installation.
  - Reduced BOS costs through lighter weight, larger panels, vertical integration.

- Grid management (>20% local penetration by PV)
- Tapping into transportation fuel usage (27% of U.S. energy consumption)

Summary: Highest impact research needs for TF PX devices

1. Be aware of the current landscape: decreased costs, large industrial workforce, wide variety of processing techniques, higher performance.

2. CIGS: moisture resistance, efficiency improvements (module and cell), better understanding of relationship between film and device properties, decreased sensitivity to In cost

3. CdTe: improved efficiency, longer lifetimes, higher carrier density, better understanding of defects and grain boundaries, more robust back contact.

4. Issues of a wider scope than just module development may be key enablers in 10-20 years.