Thin Film Photovoltaics

April 9, 2013

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Principles and Varieties of Solar Energy (PHYS 4400)

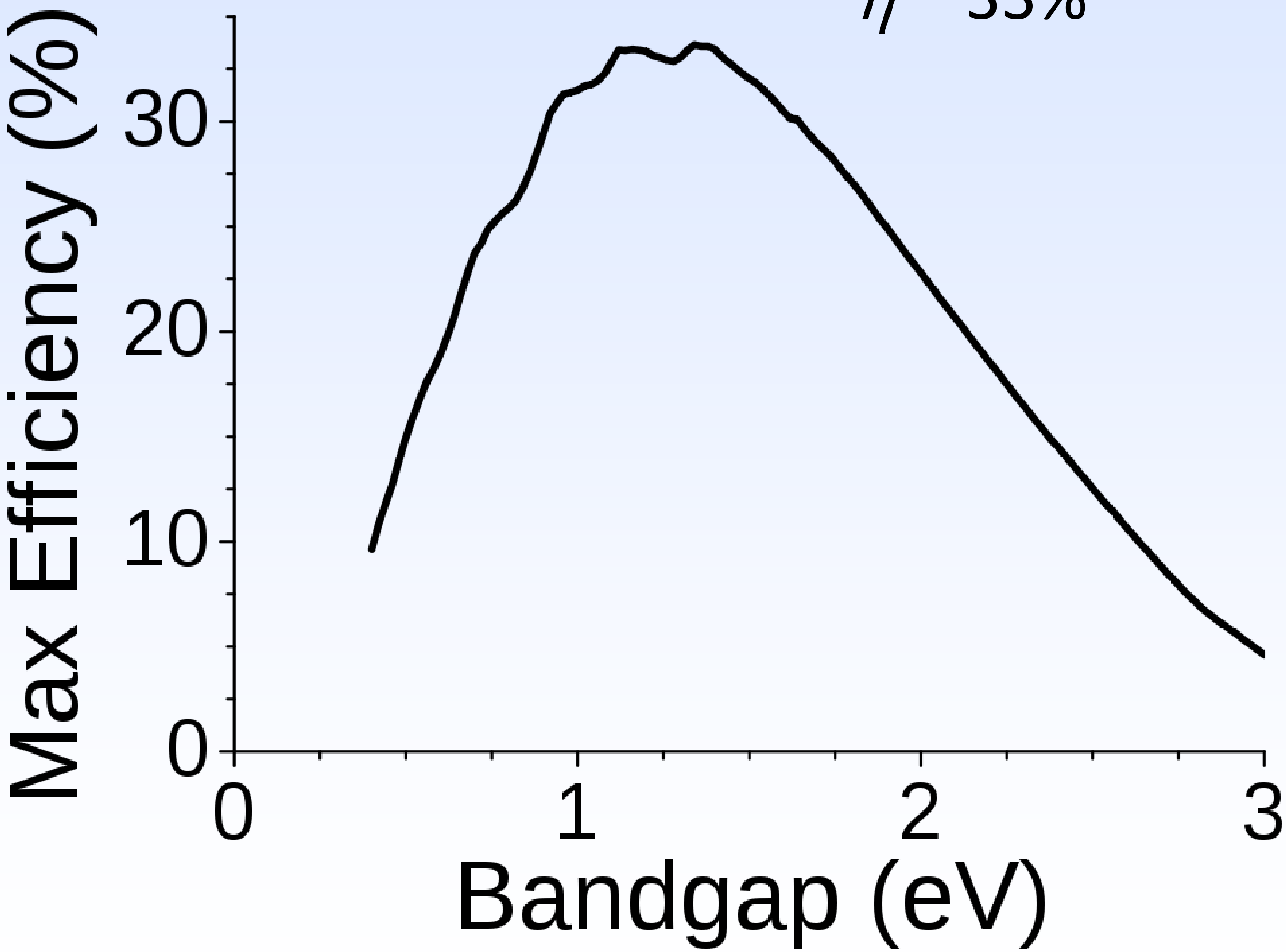
Requirements/conditions for constructing a valuable solar cell

A partial list…

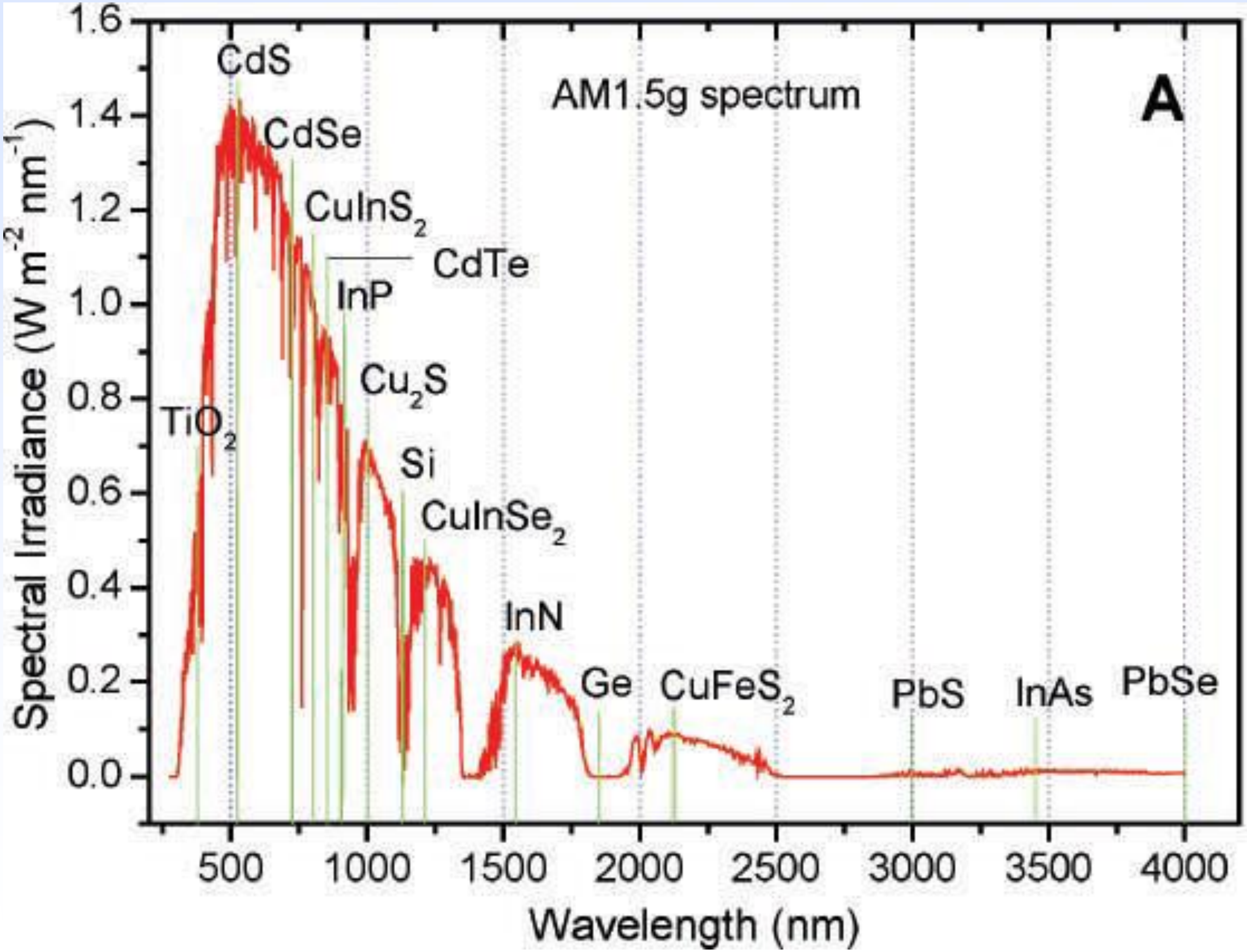
- Efficiently absorb a large fraction of irradiance to optimize photogeneration of carriers
- Achieve charge separation, directing electrons and holes to different contacts (e.g., use doped materials for p-n junction)
- Demonstrate strongly-rectifying (diode) behavior
- Avoid excessive electron-hole recombination within the solar cell (maximize photocurrent)
- Maintain as much of the electric potential as possible (avoid resistive losses, and optimize energy band offsets)
- Resist/avoid degradation by air and water (seal the modules) – i.e. achieve stability
- Do all of these things (a) with high yield, (b) inexpensively, and (c) produce at mass scale
- What else?

Getting everything right…

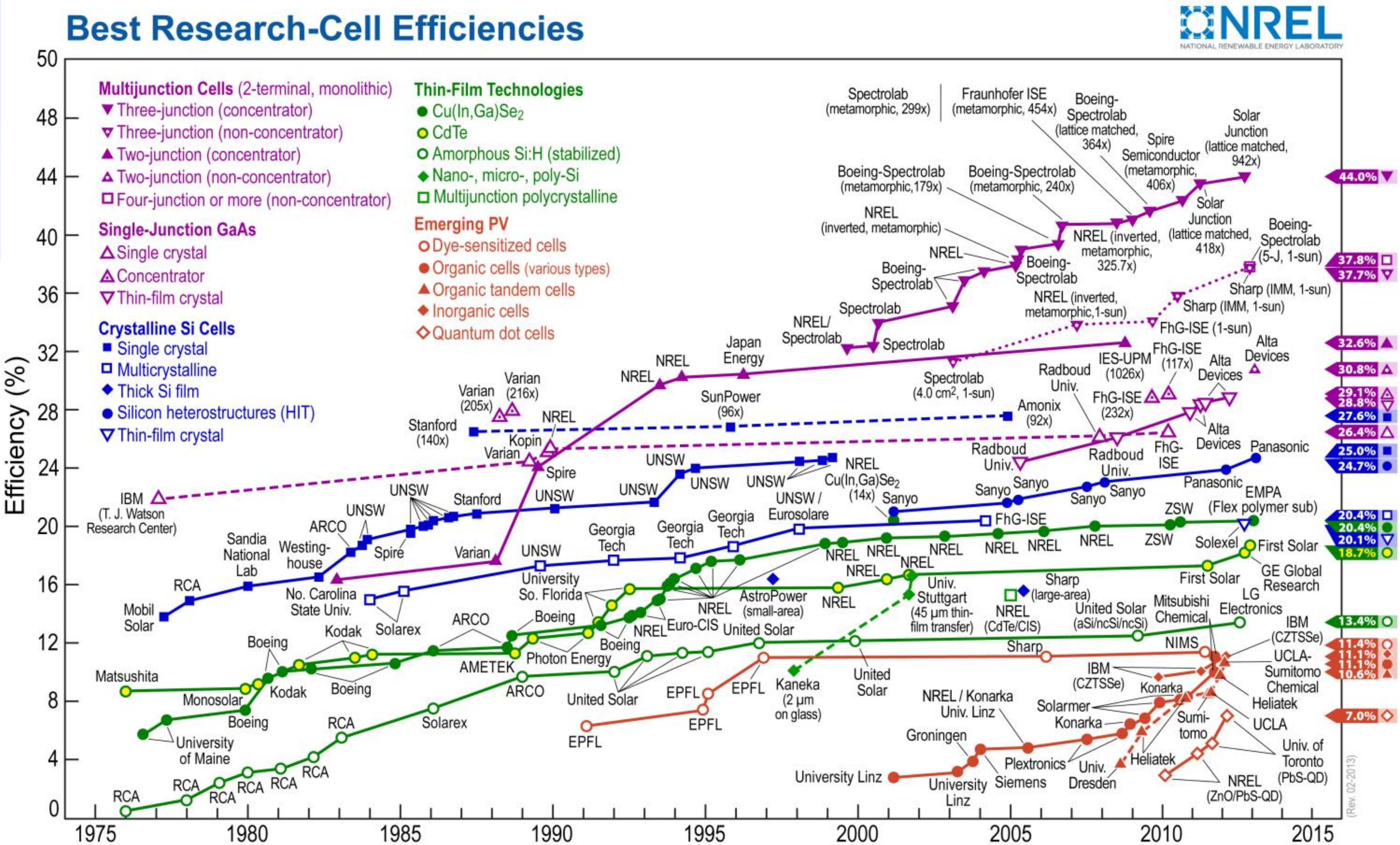
$\eta \sim 33\%$



Semiconductor bandgaps relative to the solar spectrum



Record Cell Efficiencies (March 2013)



Attained vs. attainable efficiencies

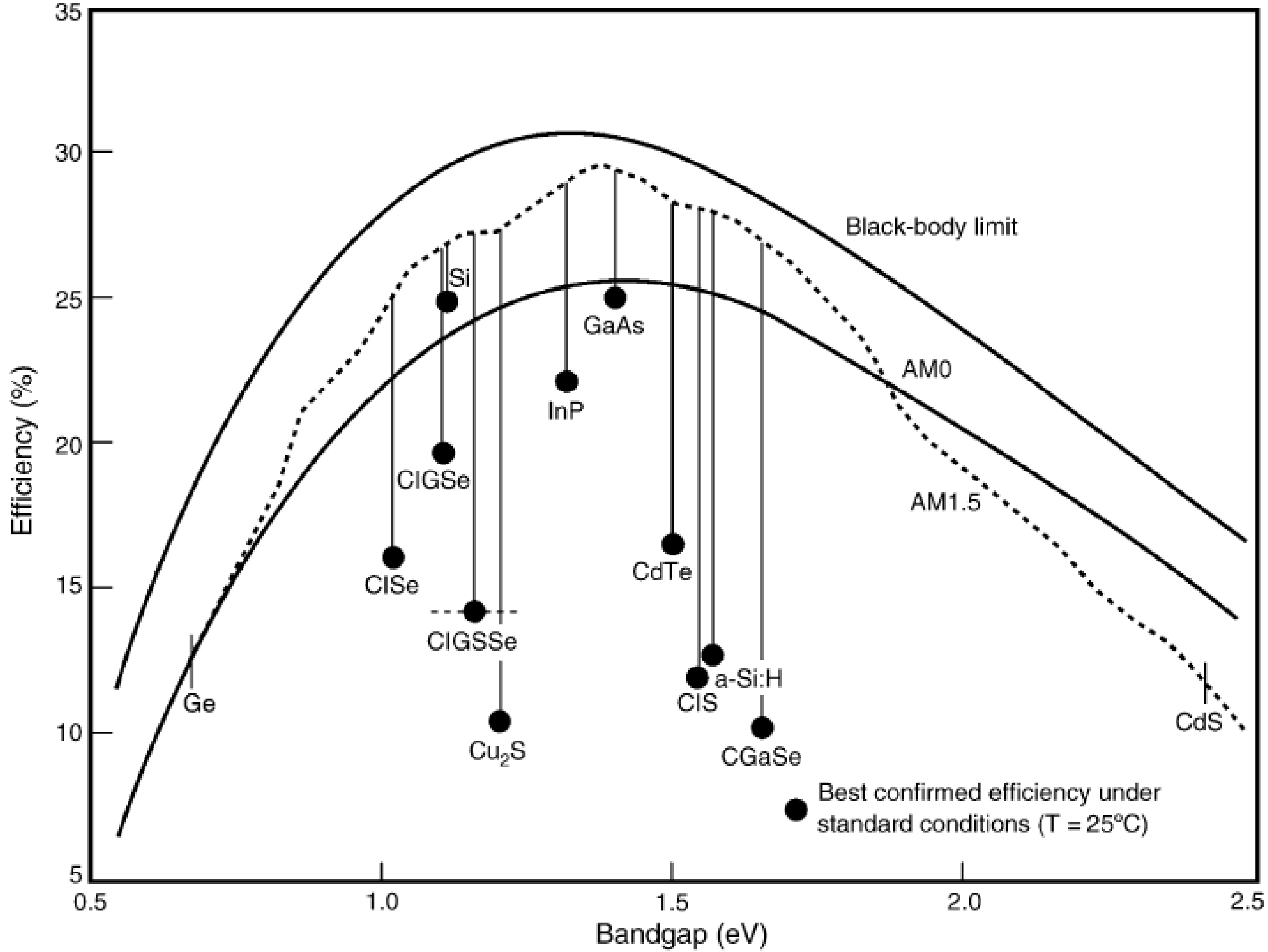


Fig. 3. Performance gaps between best device efficiencies in the laboratory and attainable efficiencies for several solar cell technologies.

L.L. Kazmerski / Journal of Electron Spectroscopy and Related Phenomena 150 (2006) 105–135

A look at the TF PV market

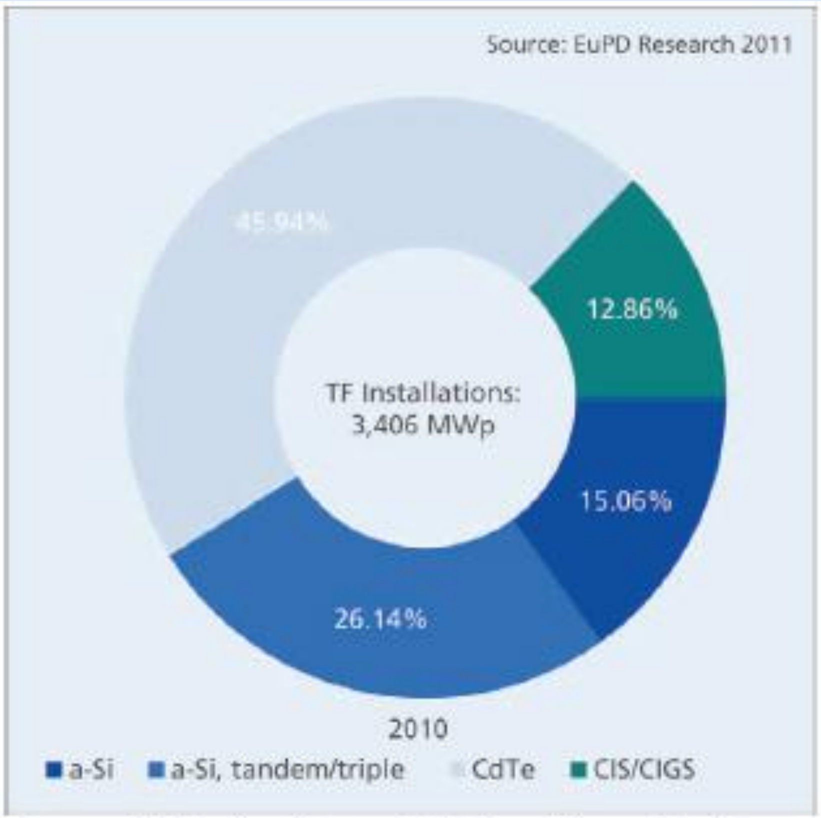


Figure 1. Market shares PV thin-film technologies 2011 (Source: EuPD Research)

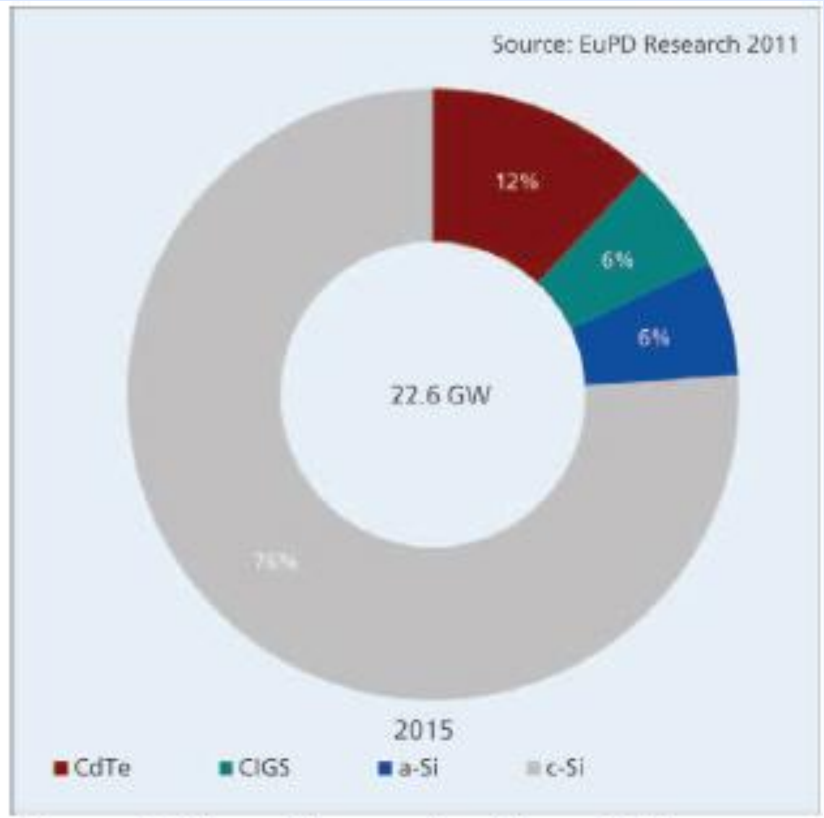
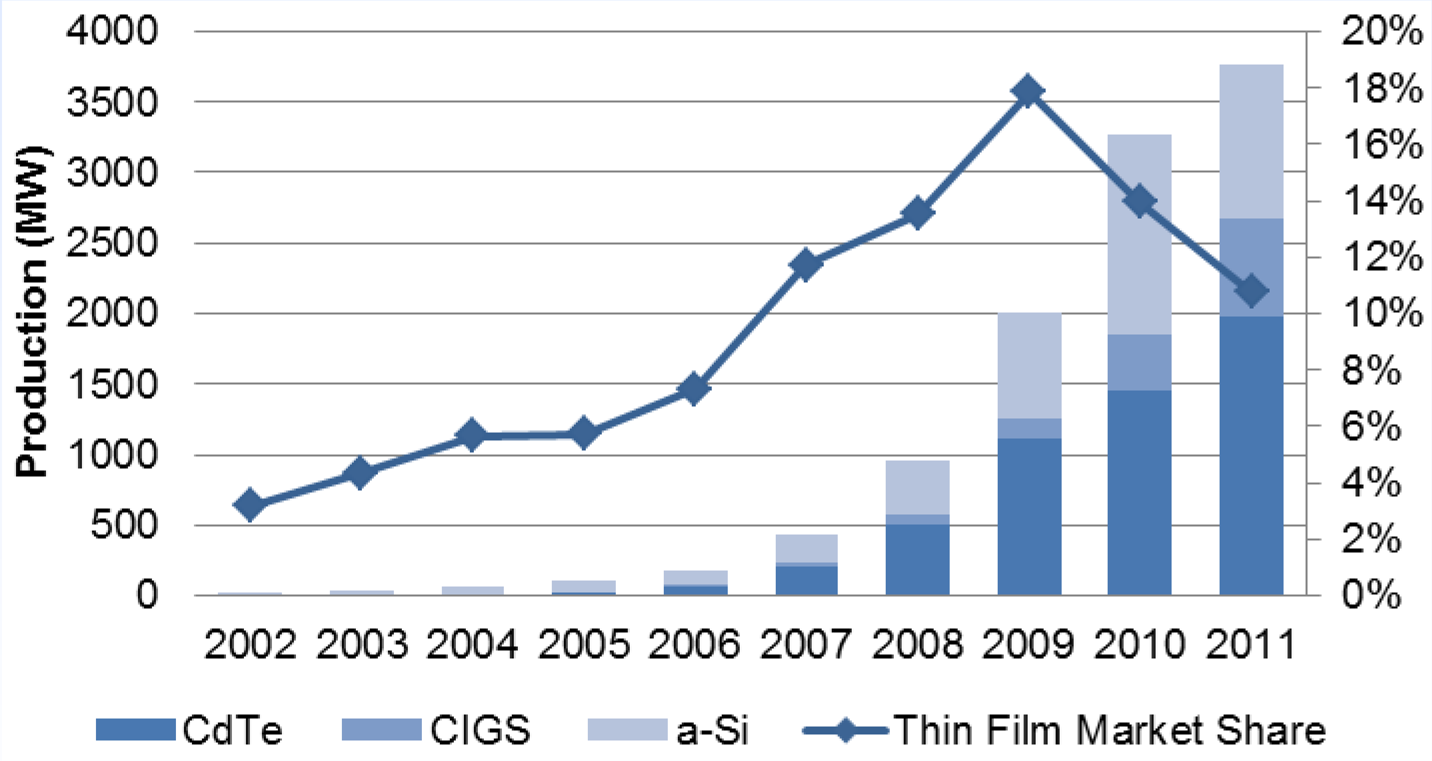


Figure 2. Photovoltaic market shares 2015 (Source: EuPD Research)

Commercial Thin Film Photovoltaics (2011)



http://www.greentechmedia.com/articles/read/thin-film-manufacturing-prospects-in-the-sub-dollar-per-watt-market

What is Thin Film PV?

A straight-up comparison of light absorption in three different semiconductor absorbers used for PV -- c-Si, CIGS, and CdTe:

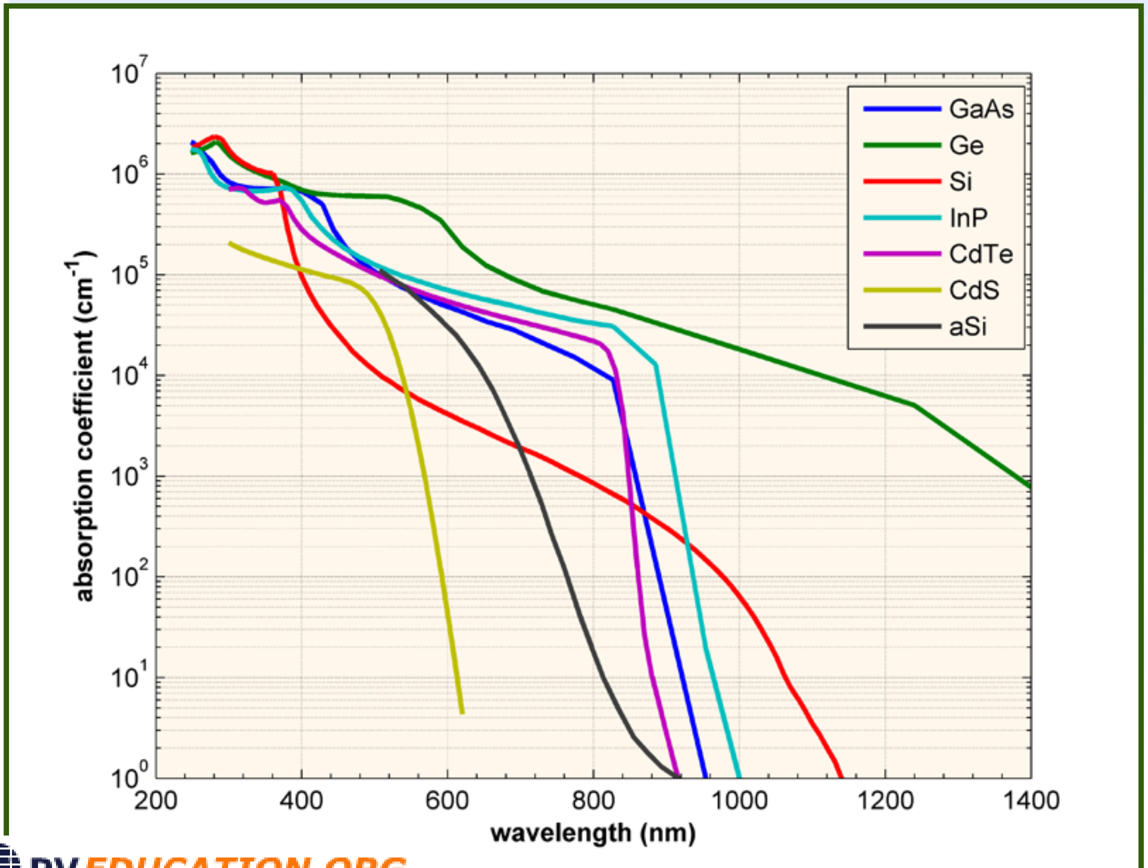
Material (t = 1 μm)	Band Gap Energy	Absorption coefficient, α(600 nm) in cm^{-1}	% of 600 nm light absorbed in 1 μm film
c-Si	1.12	2.5×10^3	22
CIGS	1.2	6×10^4	99.7
CdTe	1.5	6×10^4	99.7
a-Si	1.7	3×10^4	95

Short answer – thin film PV utilizes direct-bandgap materials with strong absorption coefficient throughout the visible spectrum, which absorb a large fraction of sunlight for thicknesses on the order of 1 μm.

Absorbing sunlight efficiently

What matters for absorption of sunlight to make a good solar cell?

High extinction coefficient, short absorption length, large **absorption coefficient**.



$$I = I_0 e^{-\alpha x}$$

$$I(\lambda) = I_0(\lambda) e^{-\alpha(\lambda)x}$$

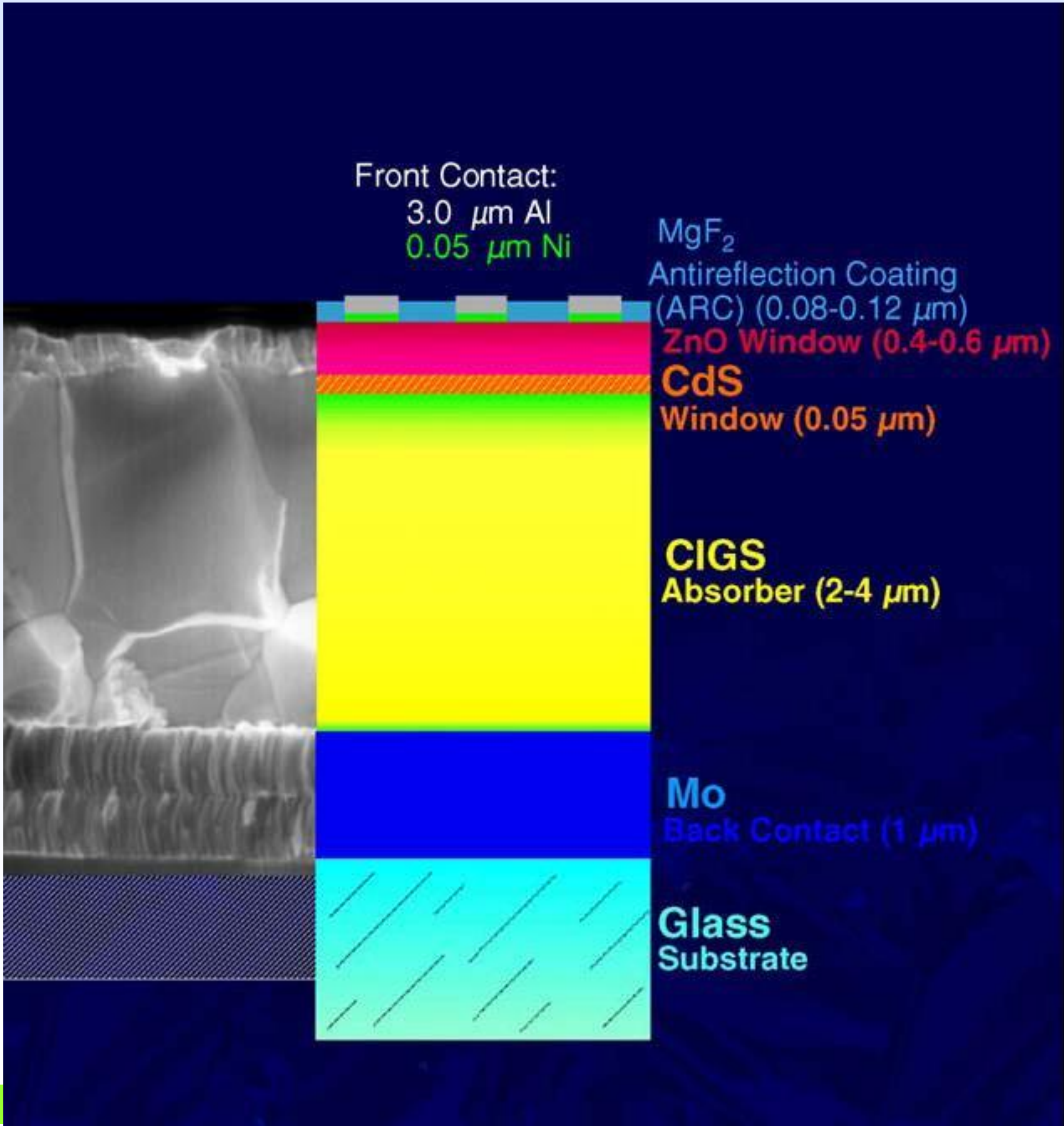
Bandgap

Low **reflection** loss (can't convert reflected photons).

How do we measure the parameters in **bold**?

CIGS = $CuInGaSe_2$

Quaternary material;
Substrate configuration;



http://upload.wikimedia.org/wikipedia
/commons/d/d7/CIGSdevice.JPG

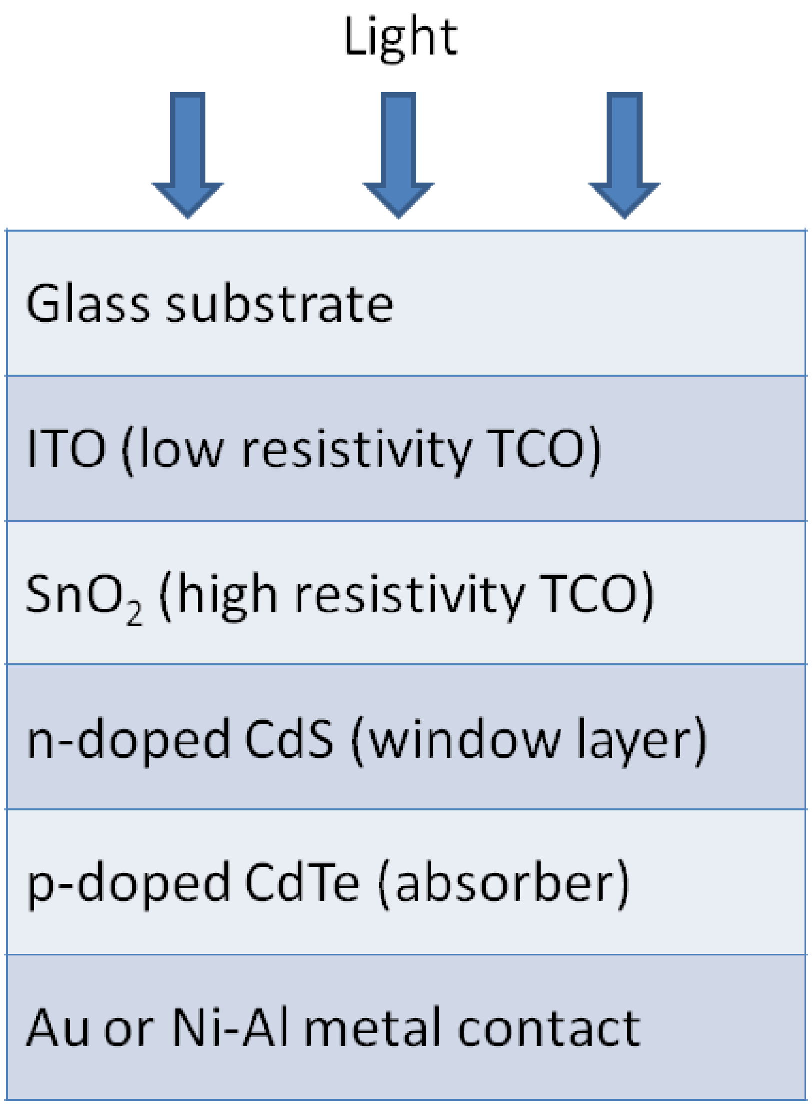
Attained vs. attainable **open circuit photovoltage**

Cell Type	E_g at RT (eV)	V_{OC}^{MAX} (V)	V_{OC} (V)	V_{OC} loss (V)	V_{OC}/V_{OC}^{MAX} (%)
SC-Si	1.12	0.84	0.71	0.13	85
GaAs	1.42	1.14	1.02	0.12	90
InP	1.28	1.00	0.88	0.12	88
CdTe	1.45	1.17	0.84	0.33	72
CIGS	1.14	0.86	0.72	0.14	84
a-Si	1.7	1.42	0.86	0.56	61
DSSC (black dye) (Red N719) (Red N3)	1.4 1.6 2.0	1.12 1.32 1.72	0.72 0.85 0.80	0.40 0.47 0.92	64 64 47
OPV	1.55	1.27	0.75	0.52	59

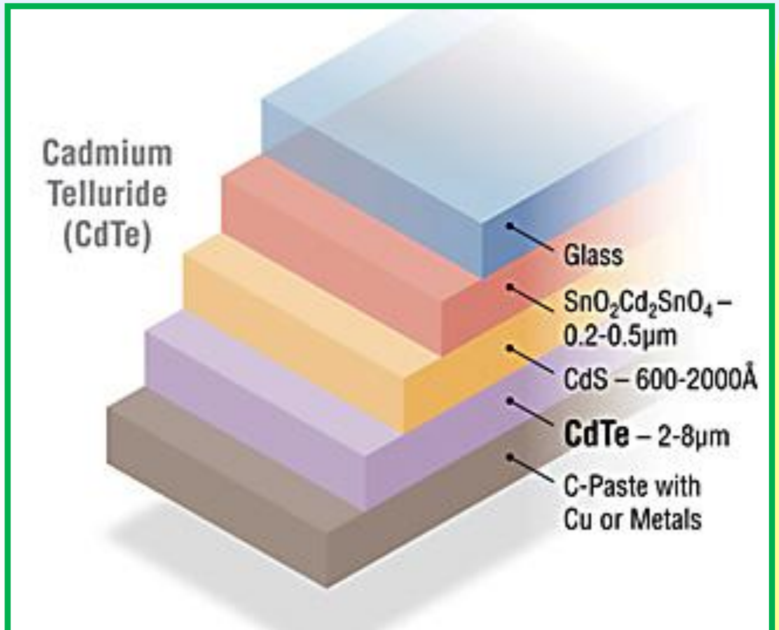
Attained vs. attainable **short-circuit photocurrent**

Cell Type	E_g at RT (eV)	J_{SC}^{MAX} (mA/cm^2)	J_{SC} (mA/cm^2)	J_{SC}/J_{SC}^{MAX} (%)
SC-Si	1.12	43.8	42.7	98
GaAs	1.42	32.0	28.5	89
InP	1.28	36.3	29.5	81
CdTe	1.45	30.8	25.9	84
CIGS	1.15	42	33.5	80
a-Si	1.7	22.4	17.5	78
DSSC (black dye) (Red N719) (Red N3)	 1.4 1.6 2.0	 33.3 25.5 14.4	 20.5 17.7 9.2	 62 70 64
OPV	1.55	26.9	14.7	55

Basic CdTe PV Device Architecture(s)



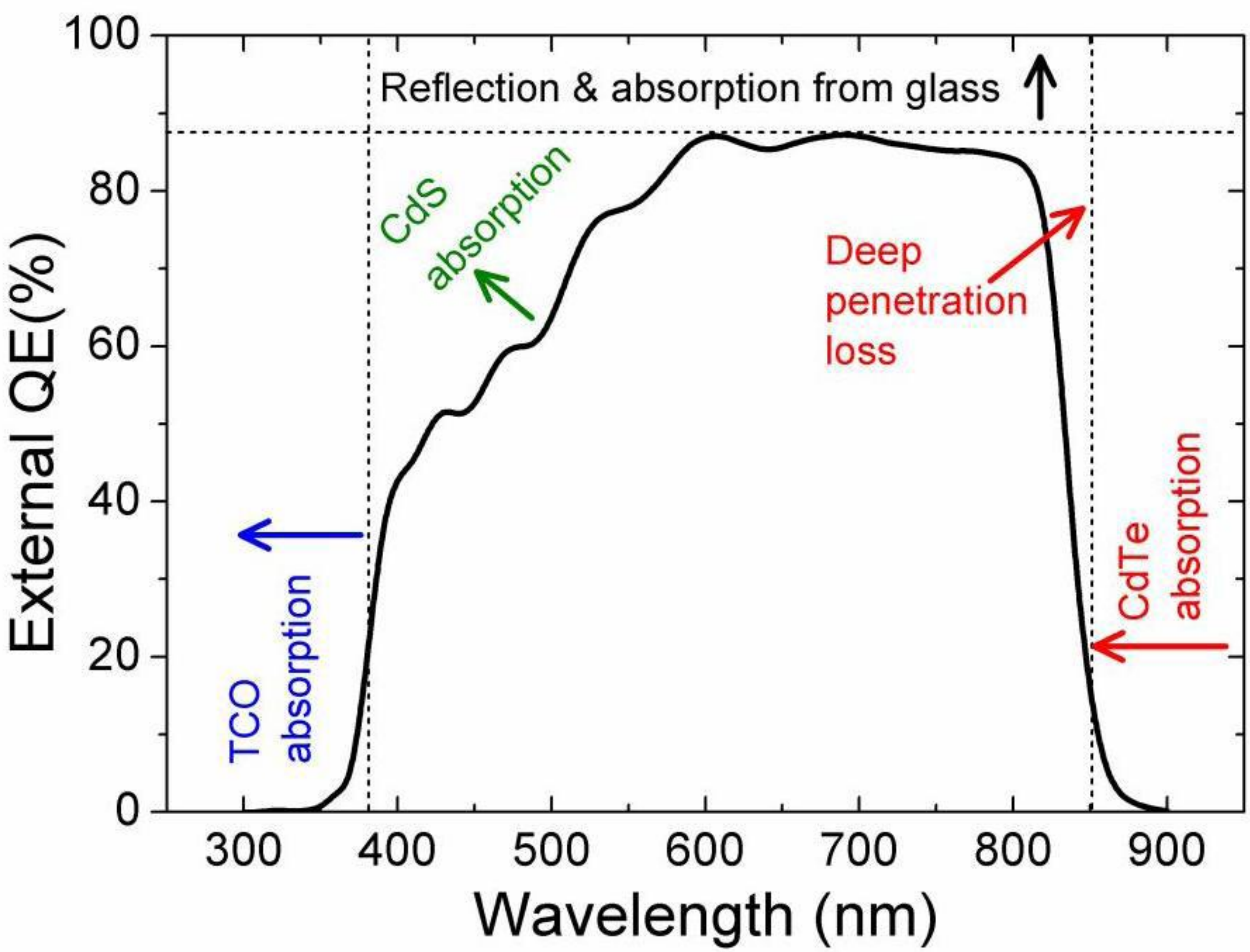
"superstrate"



http://en.wikipedia.org/wiki/File:Cadmium_telluride_thin_film_solar_cell.png

http://www.nrel.gov/pv/thinfilm.html

EQE for typical CdTe solar cell



Naba R. Paudel, University of Toledo Dissertation: "Stability issues in sputtered CdS/CdTe solar cells"

TCO materials for used w/ CdTe solar cells

Materials	Resistivity	Transmission	Stability
SnO_2:F	$(5\text{-}7)\times10^{-4}$ Ω-cm	~80%	excellent
SnO_2:In_2O_3	2.5×10^{-4} Ω-cm	~85%	good
In_2O_3:F	2.5×10^{-4} Ω-cm	~85%	good
In_2O_3:GeO_2	2×10^{-4} Ω-cm	~85%	good
Cd_2SnO_4	2×10^{-4} Ω-cm	>85%	fair
ZnO:Al_2O_3	$(4\text{-}6)\times10^{-4}$ Ω-cm	>85%	fair
ZnO:In	8×10^{-4} Ω-cm	~85%	good

Naba R. Paudel, University of Toledo Dissertation: "Stability issues in sputtered CdS/CdTe solar cells"

CdS and CdTe sputtering system

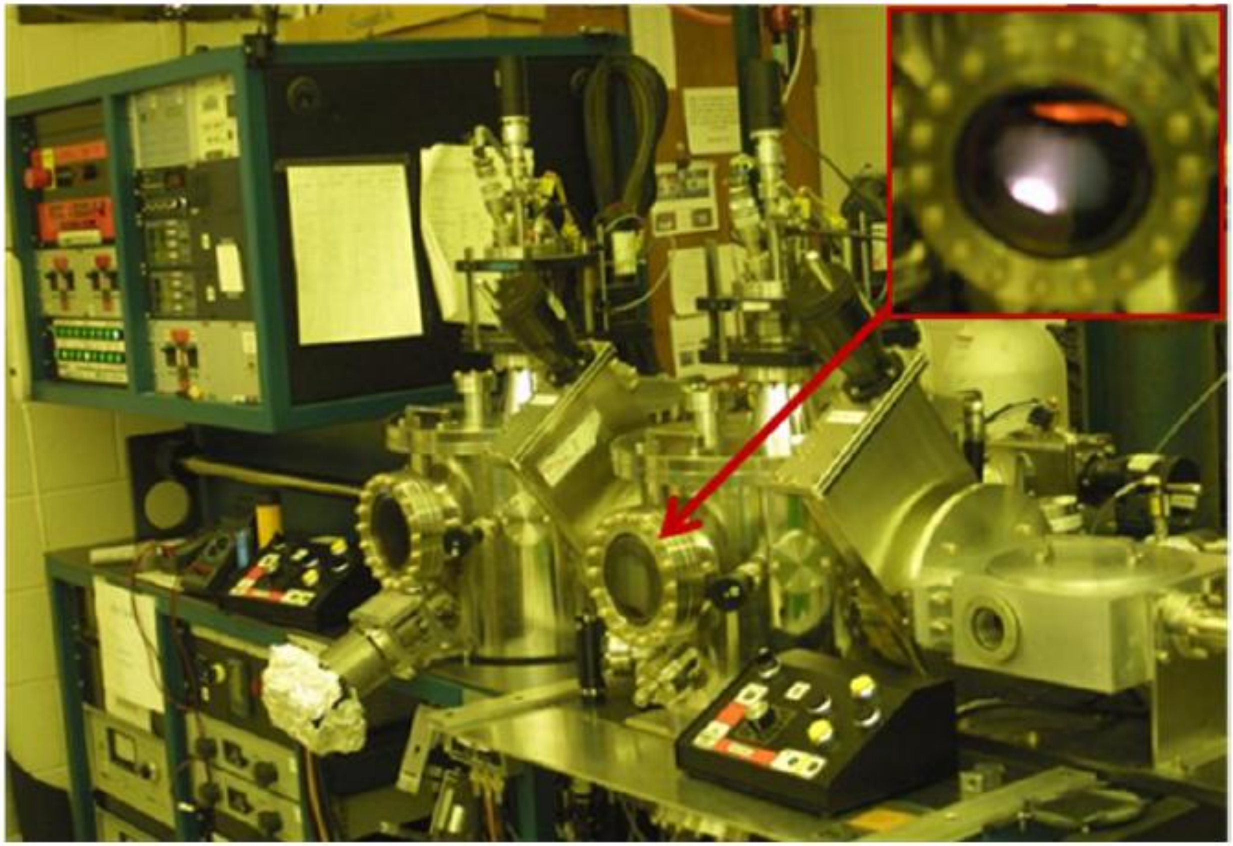


Figure 2-2. CdS/CdTe sputtering system designed by AJA International located at MH3023 in University of Toledo. [Inset shows CdTe plasma through the viewport of chamber B during sputter deposition. The CdTe deposition is going on the glass substrate which is face down and rotating continuously for uniform coating.]

Naba R. Paudel, University of Toledo Dissertation: “Stability issues in sputtered CdS/CdTe solar cells”

Sputtered CdS film

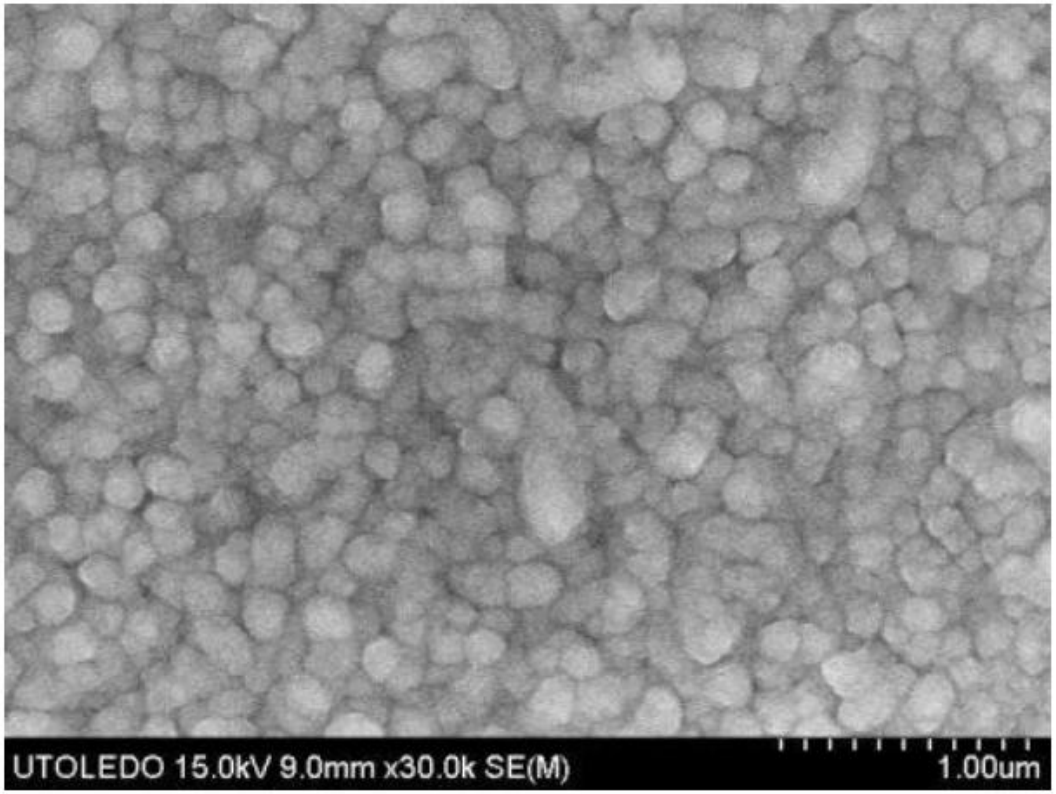


Figure 1-14. Secondary electron micrograph of as grown CdS film sputtered on SnO_2:F coated glass substrate.

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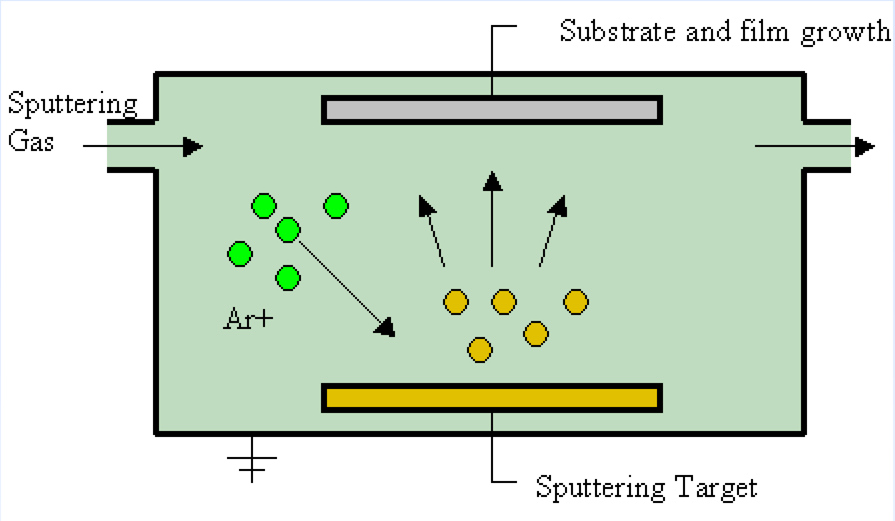
Sputter deposition

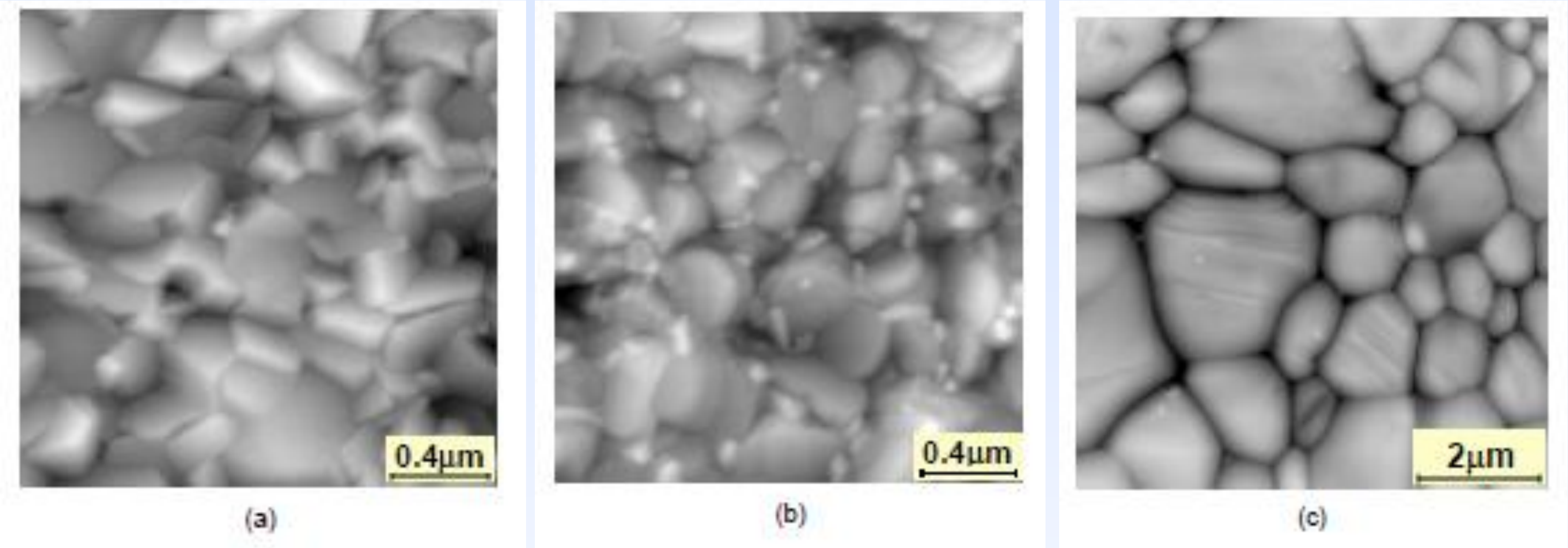


- Sputtered atoms have a wide range of energies;
- Ballistic atoms or ions can result in resputtering from thin film;
- Control of the atom energetic distribution can be accomplished through variation of chamber inert gas pressure (e.g., Ar);
- Note that CdTe sputters (and evaporates) congruently, i.e., as a CdTe molecule. This maintains very close 1:1 stoichiometry of the resulting film.

http://heraeus-targets.com/en/technology/_sputteringbasics/sputtering.aspx

http://en.wikipedia.org/wiki/Sputter_deposition

$CdCl_2$ treatment (recrystallization of CdTe)



PVD CdTe films: (a) untreated, (b) and (c) after CdCl2 heat treatment at 350° and 400°C, respectively.

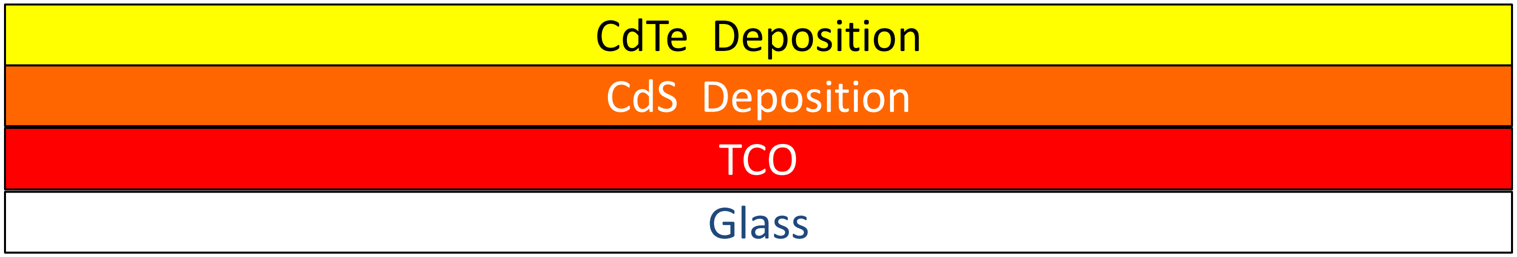
Studies of Recrystallization of CdTe Thin Films After CdCl Treatment
H.R. Moutinho, M.M. Al-Jassim, F.A. Abufoltuh, D.H. Levi, P.C. Dippo, R.G. Dhere, and L.L. Kazmerski
Presented at the 26th IEEE Photovoltaic Specialists Conference, September 29–October 3, 1997, Anaheim, California

<u>Effects of $CdCl_2$ treatment on as-deposited CdTe films</u>

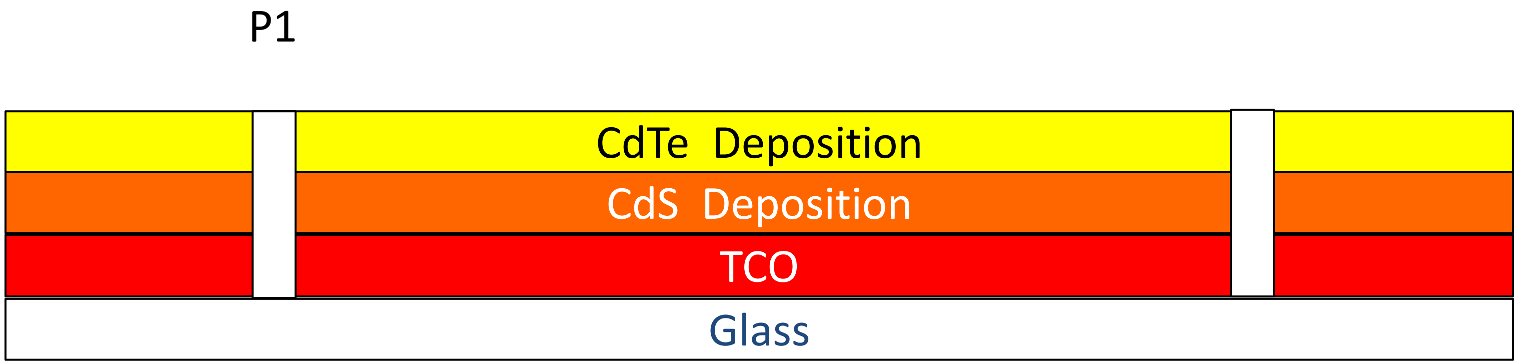
- Results in CdTe grain growth (especially w/ sputtered films and PVD-grown films, less so w/ CSS)
- Reduces lattice strain (also promotes grain growth)
- Increases minority carrier lifetime (~ x10), perhaps due to reduction in deep level defect densities within the bandgap.

CdTe module production and scribing steps

- Start with TCO Coated Glass

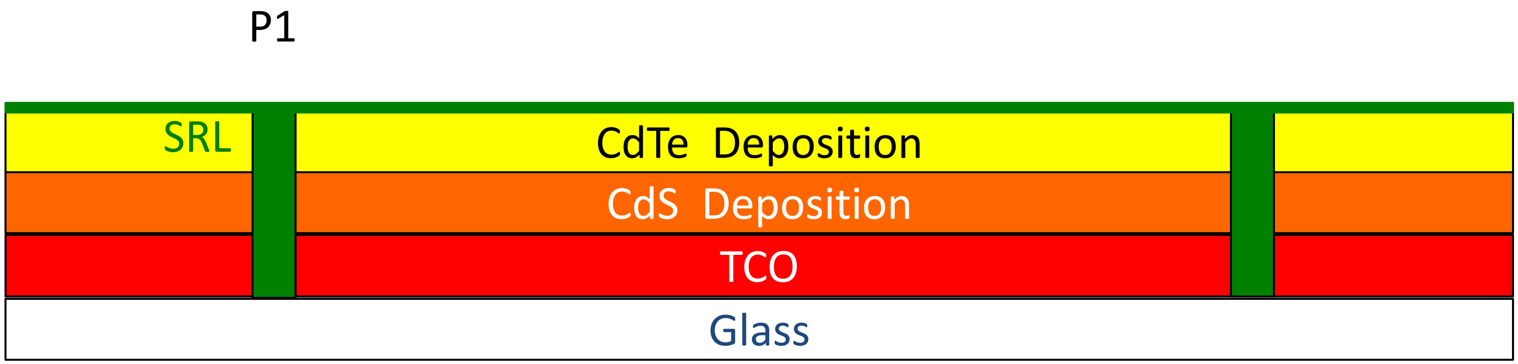


- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe

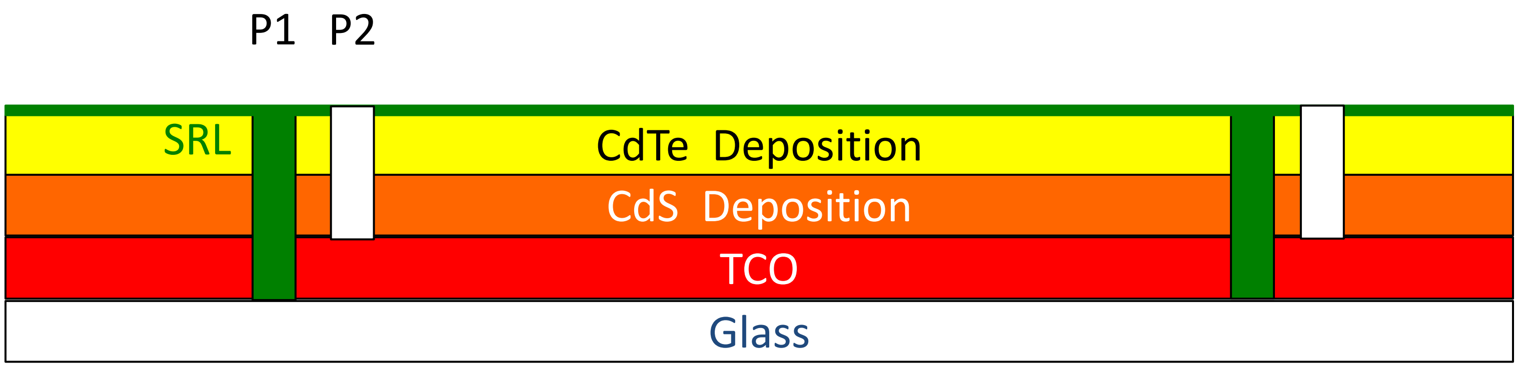


- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe
- Process 1 – P1 – 1064 nm Scribe through TCO/CdS/CdTe

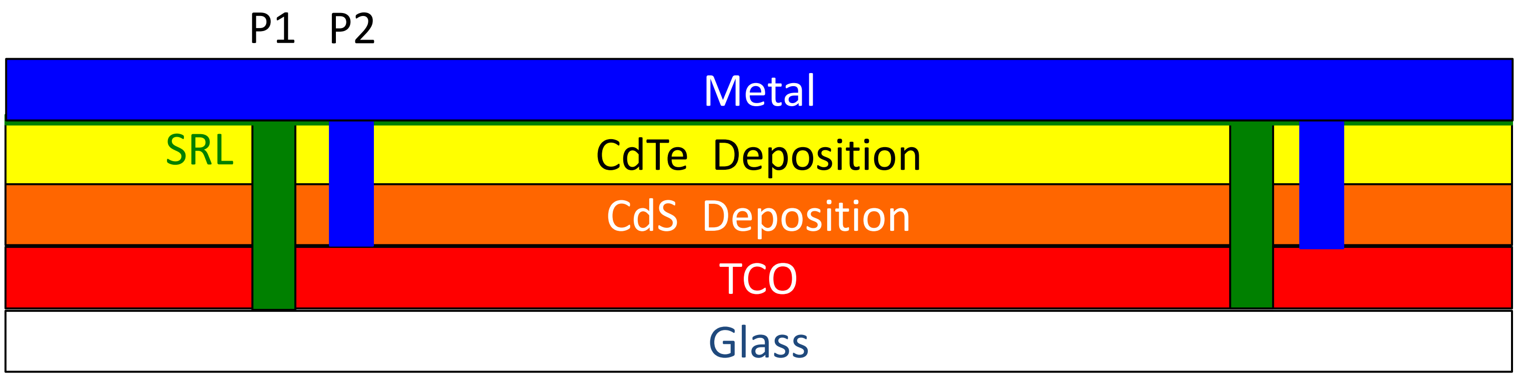
Note: All scribes from sunny side



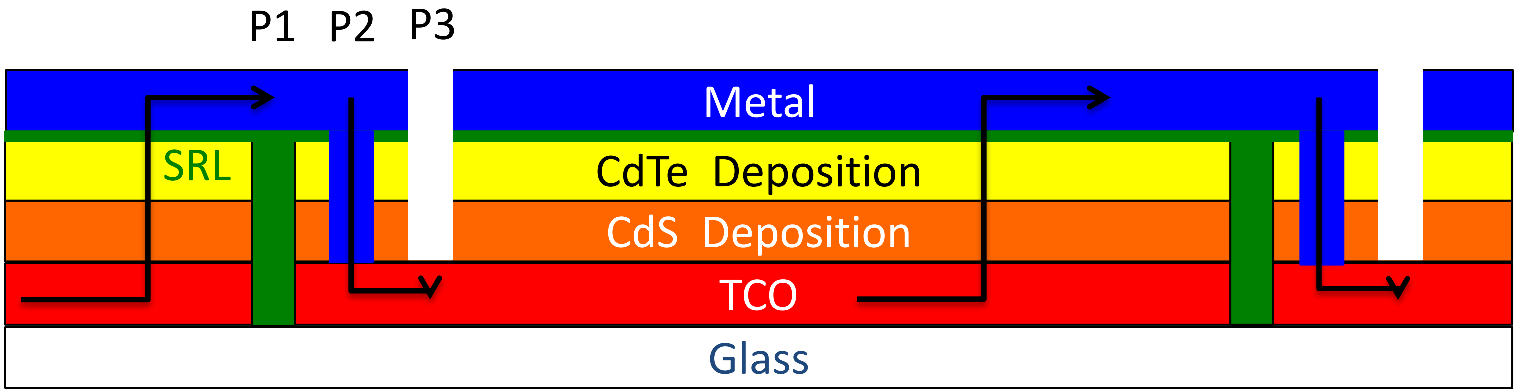
- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe
- Process 1 – P1 – 1064 nm Scribe through TCO/CdS/CdTe
- Process 2 – Shunt resistance layer



- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe
- Process 1 – P1 – 1064 nm Scribe through TCO/CdS/CdTe
- Process 2 – Shunt resistance layer
- Process 3 – P2 – 532 nm Scribe through CdS/CdTe



- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe
- Process 1 – P1 – 1064 nm Scribe through TCO/CdS/CdTe
- Process 2 - Shunt resistance layer
- Process 3 – P2 – 532 nm Scribe through CdS/CdTe
- Process 4 – Cu treatment
- Process 5 – Metallization



- Start with TCO Coated Glass
- Deposition 1 – CdS
- Deposition 2 – CdTe
- Process 1 – P1 – 1064 nm Scribe through CdTe/CdS/TCO
- Process 2 - Shunt resistance layer
- Process 3 – P2 – 532 nm Scribe through CdTe/CdS
- Process 4 – Cu treatment
- Process 5 – Metallization
- Process 6 – P3 – 532 nm Scribe through Metal/CdTe/CdS
- Process 7 – Post Metal Heat Treatment

CdTe news for today (April 9, 2013)

9:36AM First Solar sets CdTe module efficiency world record, launches Series 3 Black module: Co announced it set **a new world record** for cadmium-telluride (**CdTe**) photovoltaic (PV) **module conversion efficiency, achieving a record 16.1% total area module efficiency** in tests confirmed by the U.S. Department of Energy's National Renewable Energy Laboratory. The new record is **a substantial increase over the prior record of 14.4% efficiency**, which the co set in Jan 2012. Separately, First Solar also **set a record for CdTe open circuit voltage (VOC), reaching 903.2 millivolts (mV)** in NREL-certified testing. Co also launched a new evolution of its proven Series 3 thin-film PV module platform, the Series 3 Black.

http://finance.yahoo.com/marketupdate/inplay