

# Thin Film Photovoltaics

April 7, 2015

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The University of Toledo

Principles and Varieties of Solar Energy (PHYS 4400)



# Learning more about the J-V behavior of a solar cell

- Intrinsic Carrier Concentration
- Equilibrium Carrier Concentration
  - Surface Recombination
  - Tandem Solar Cells
  - Characteristic Resistance
- Effect of Parasitic Resistances
  - Series Resistance
  - Shunt Resistance
- Impact of Both Series and Shunt Resistance
  - Effect of Temperature
  - Effect of Light Intensity
    - Ideality factor
- Thin Film PV



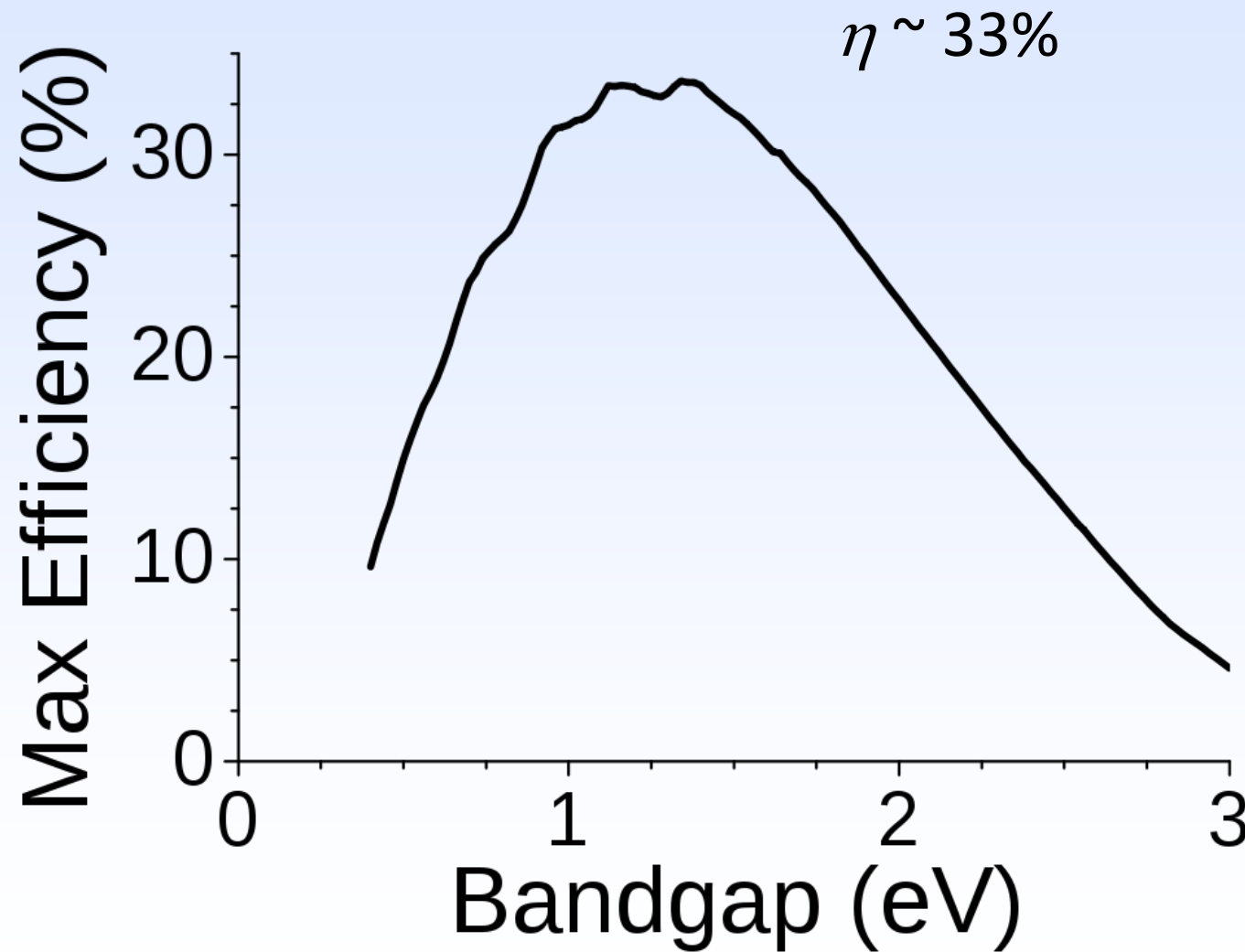
# Requirements/conditions for constructing a valuable solar cell

## **A partial list...**

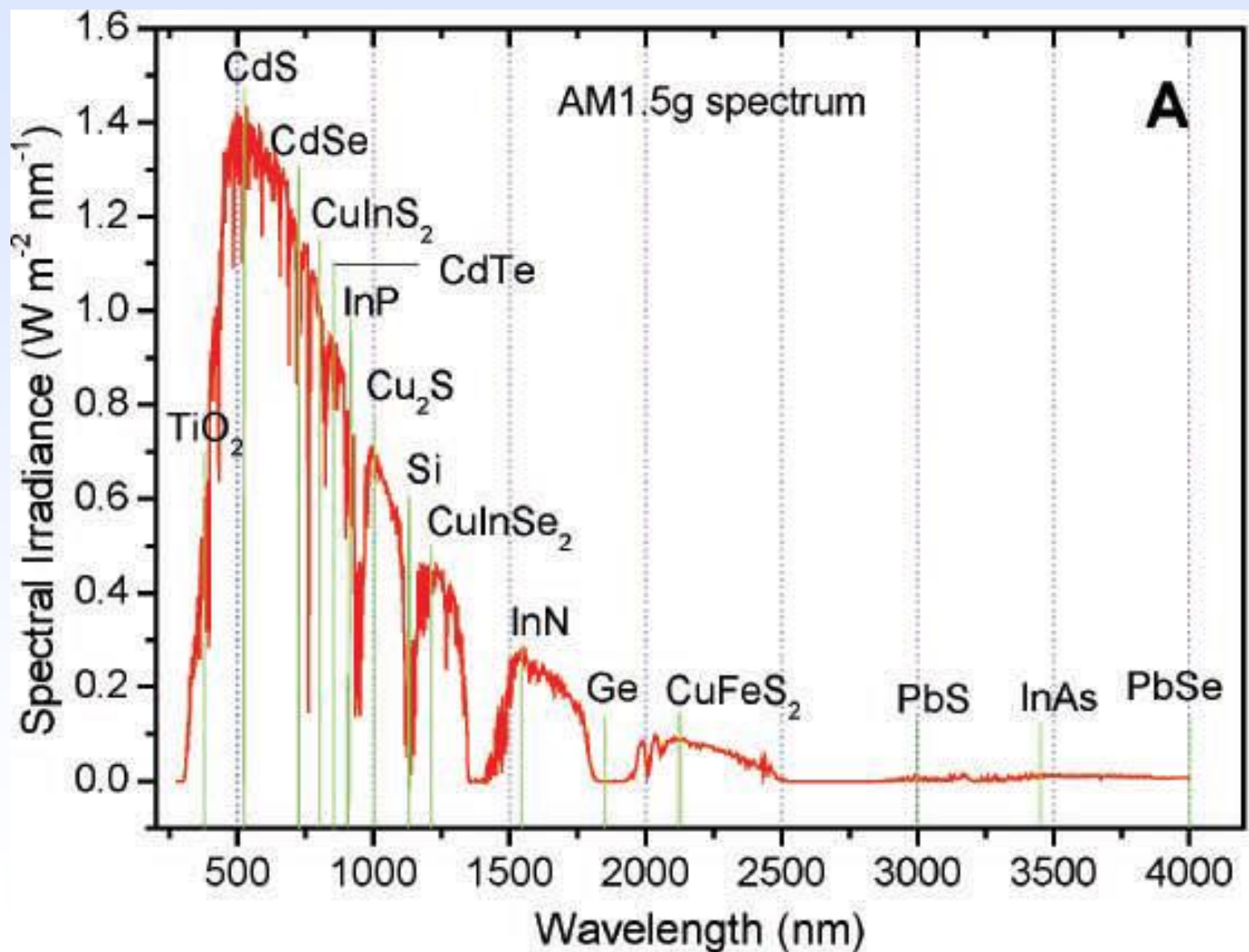
- Efficiently absorb a large fraction of irradiance to optimize photogeneration of carriers
- Achieve charge separation, directing electrons and holes to different contacts (e.g., use doped materials for p-n junction)
- Demonstrate strongly-rectifying (diode) behavior
- Avoid excessive electron-hole 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...

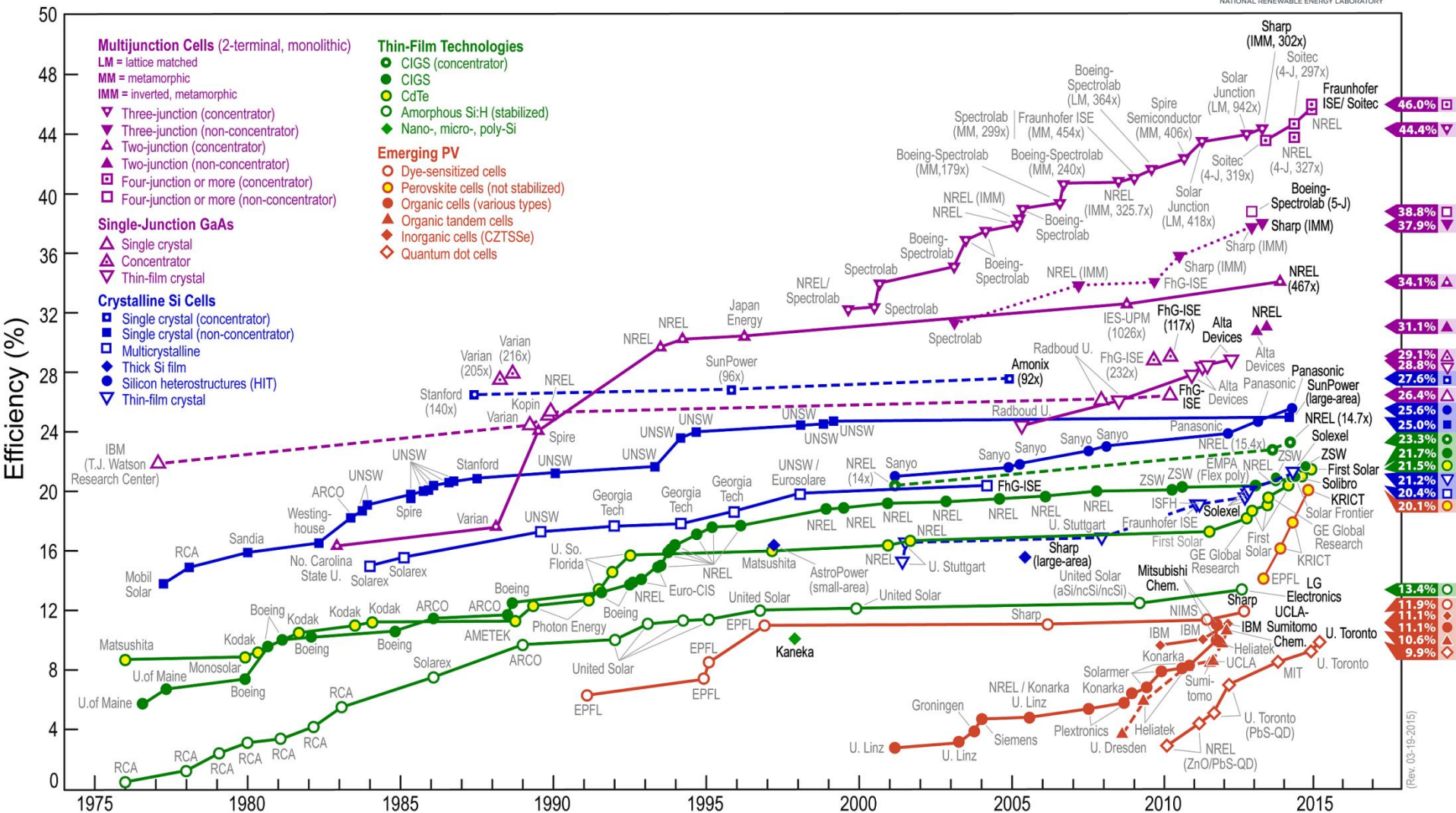


# Semiconductor bandgaps relative to the solar spectrum



# Record Cell Efficiencies (March 2014/2015)

## Best Research-Cell Efficiencies



# Attained vs. attainable efficiencies

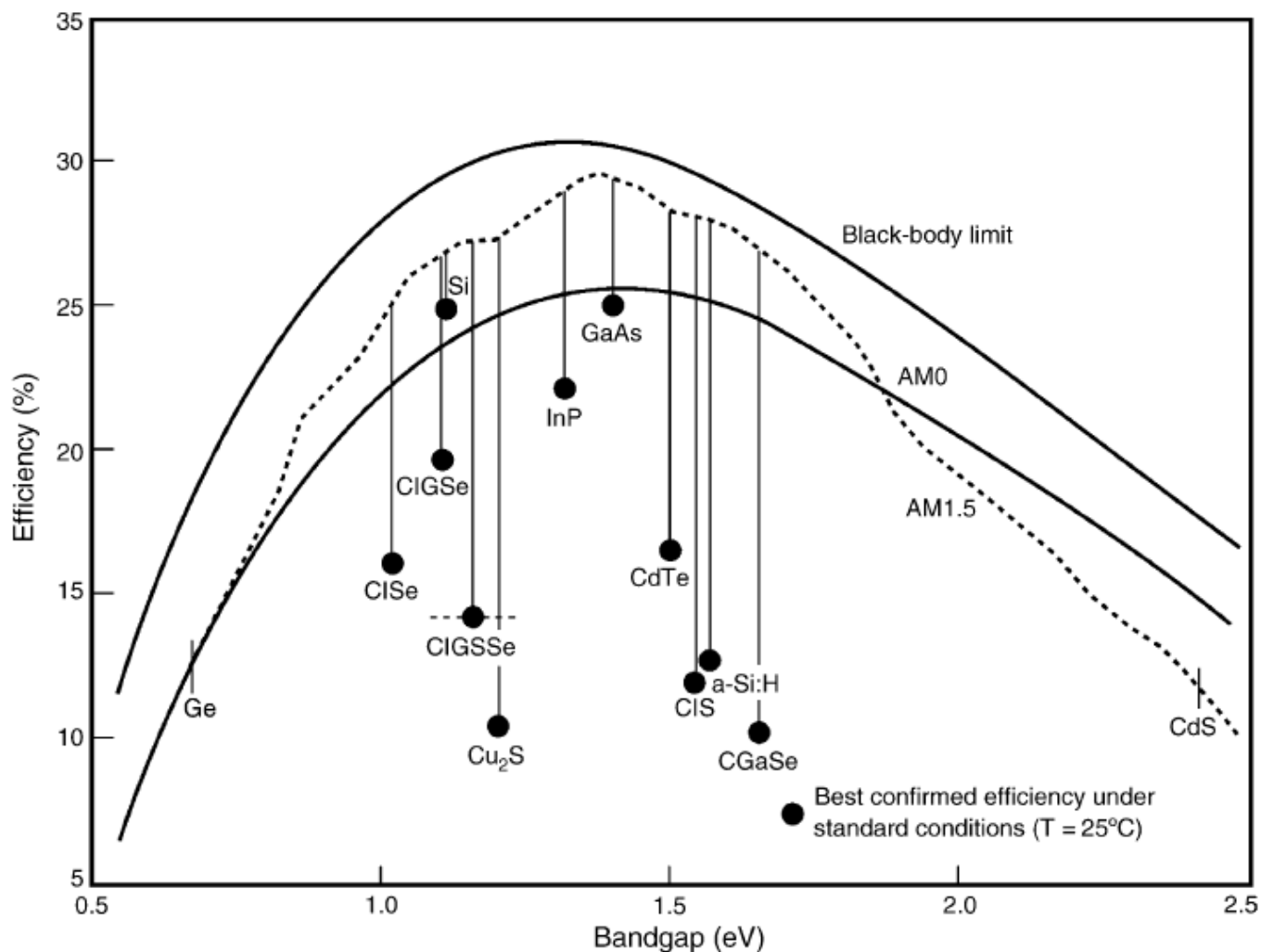
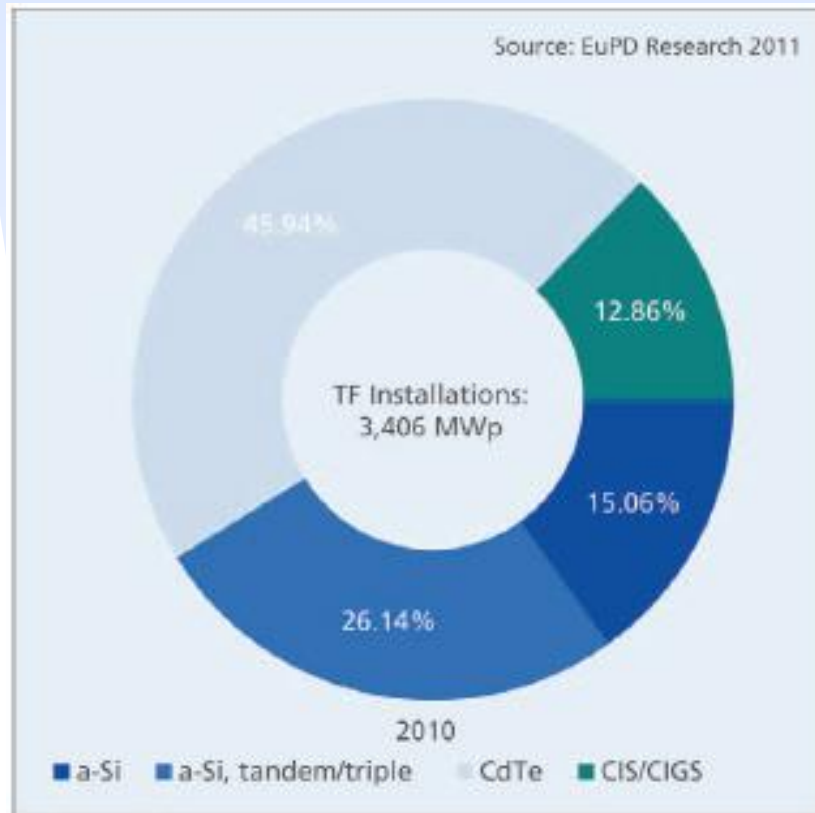


Fig. 3. Performance gaps between best device efficiencies in the laboratory and attainable efficiencies for several solar cell technologies.

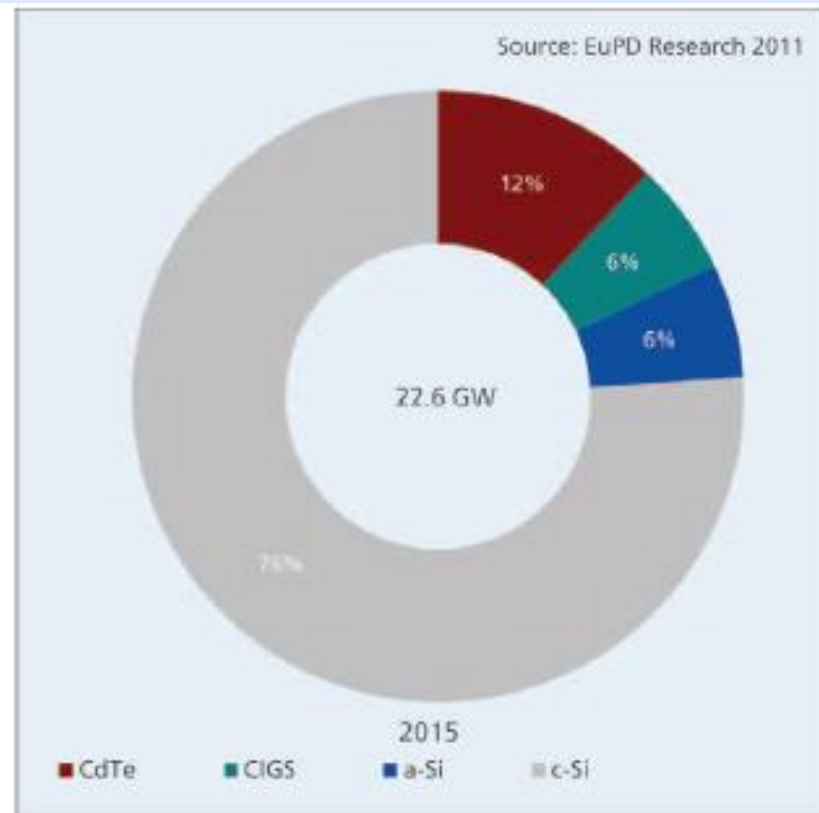




# A look at the TF PV market



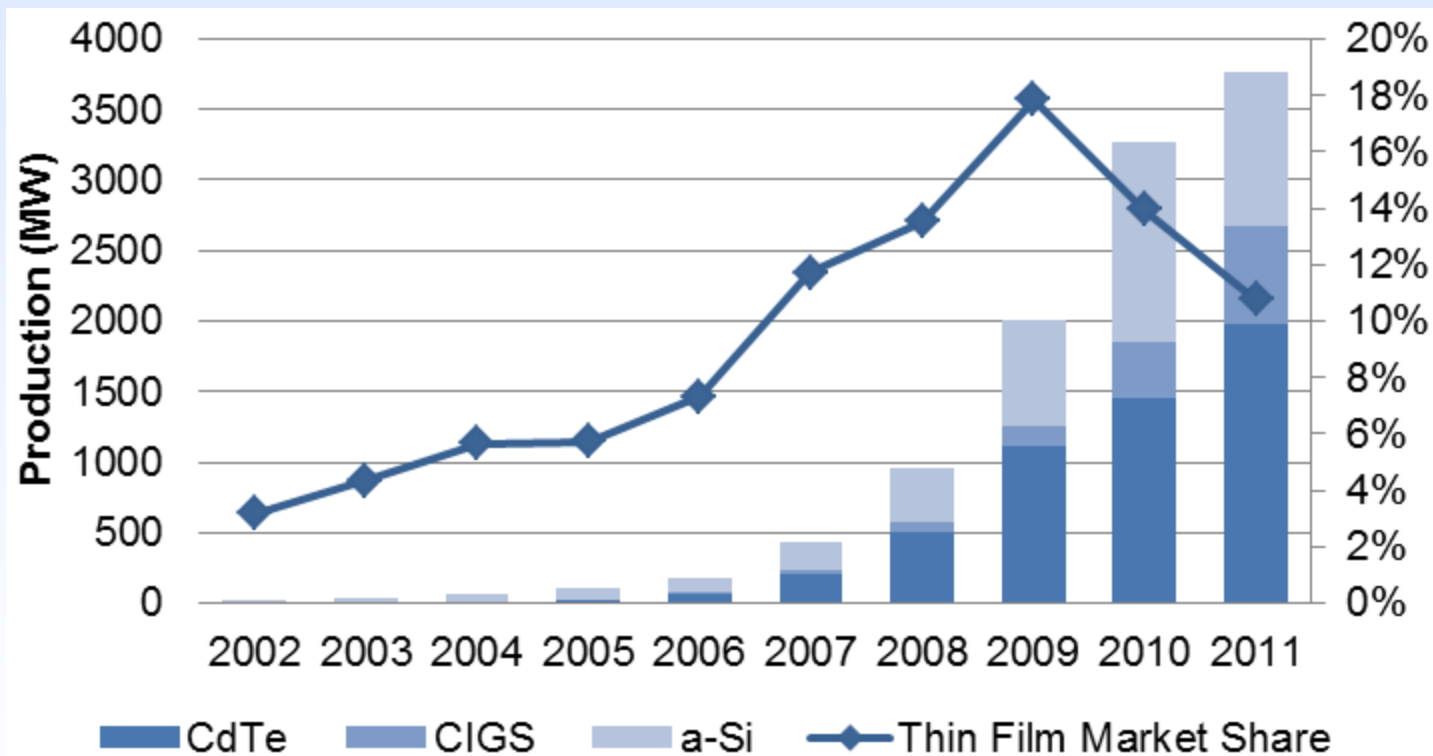
*Figure 1. Market shares PV thin-film technologies 2011* (Source: EuPD Research)



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



# Commercial Thin Film Photovoltaics (2011)



# 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 $\mu\text{m}$ )	Band Gap Energy	Absorption coefficient, $\alpha(600 \text{ nm})$ in $\text{cm}^{-1}$	% of 600 nm light absorbed in 1 $\mu\text{m}$ film
c-Si	1.12	$2.5 \times 10^3$	22
CIGS	1.2	$6 \times 10^4$	99.7
CdTe	1.5	$6 \times 10^4$	99.7
a-Si	1.7	$3 \times 10^4$	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  $\mu\text{m}$ .



# Absorbing sunlight efficiently

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

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

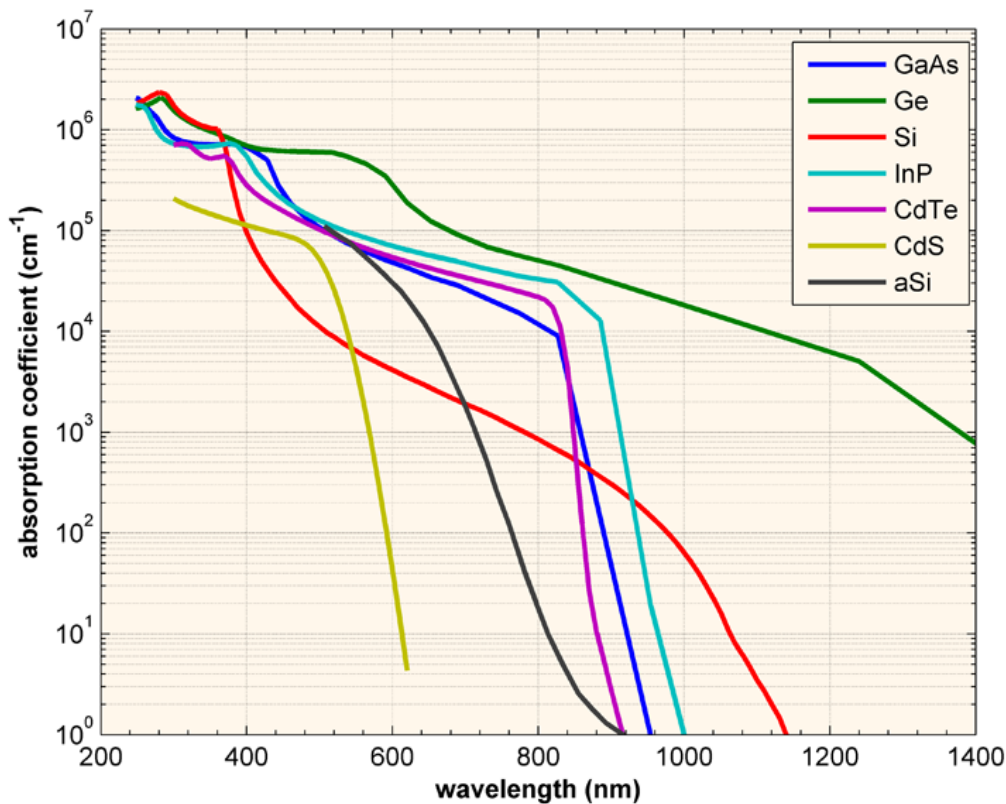
$$I = I_0 e^{-\alpha x}$$

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

## Bandgap

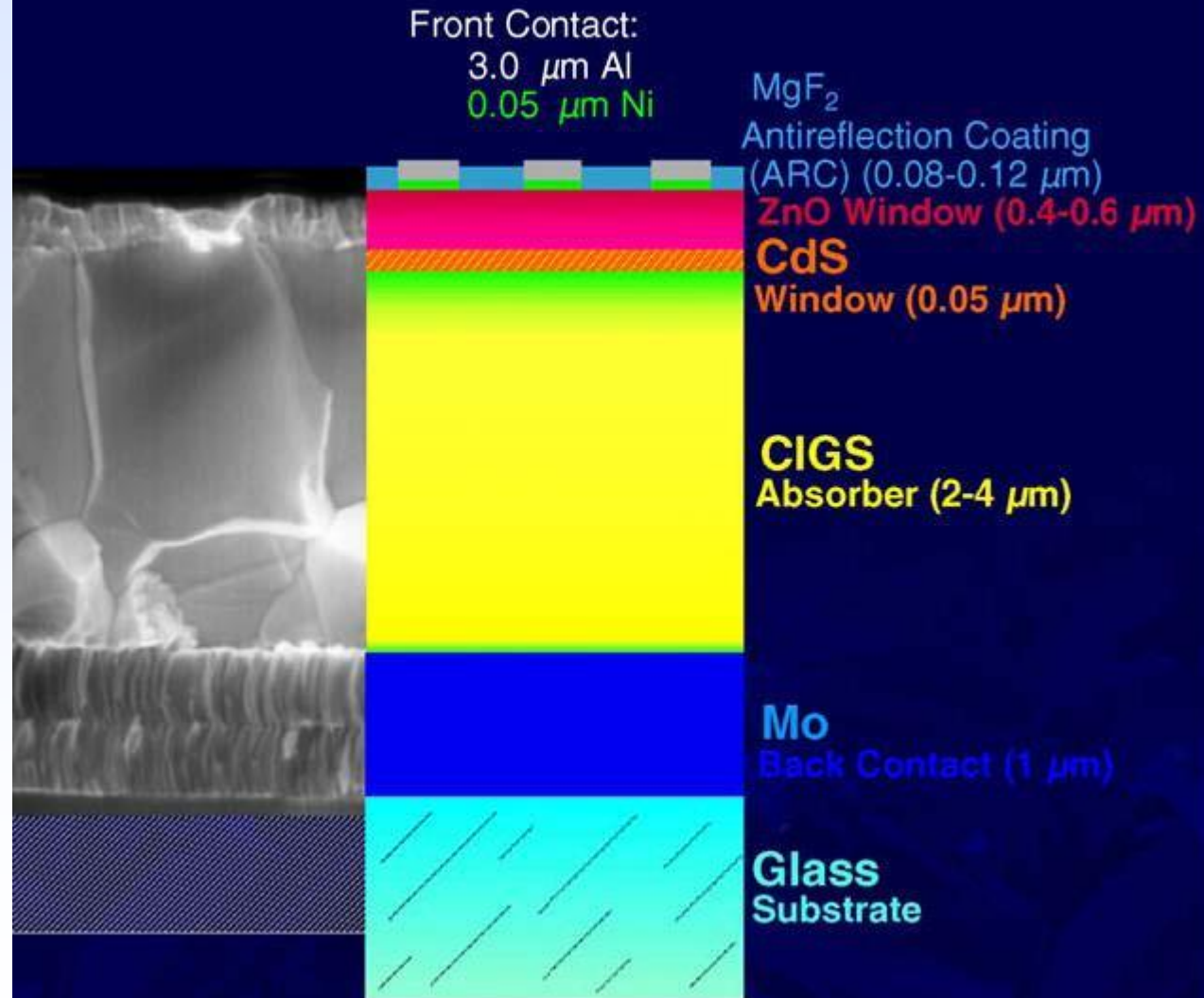
Low **reflection** loss (can't convert reflected photons).

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





Quaternary material;  
Substrate configuration;



# 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
$\alpha$ -Si	1.7	1.42	0.86	0.56	61
DSSC (black dye) (Red N719) (Red N3)	1.4	1.12	0.72	0.40	64
	1.6	1.32	0.85	0.47	64
	2.0	1.72	0.80	0.92	47
OPV	1.55	1.27	0.75	0.52	59



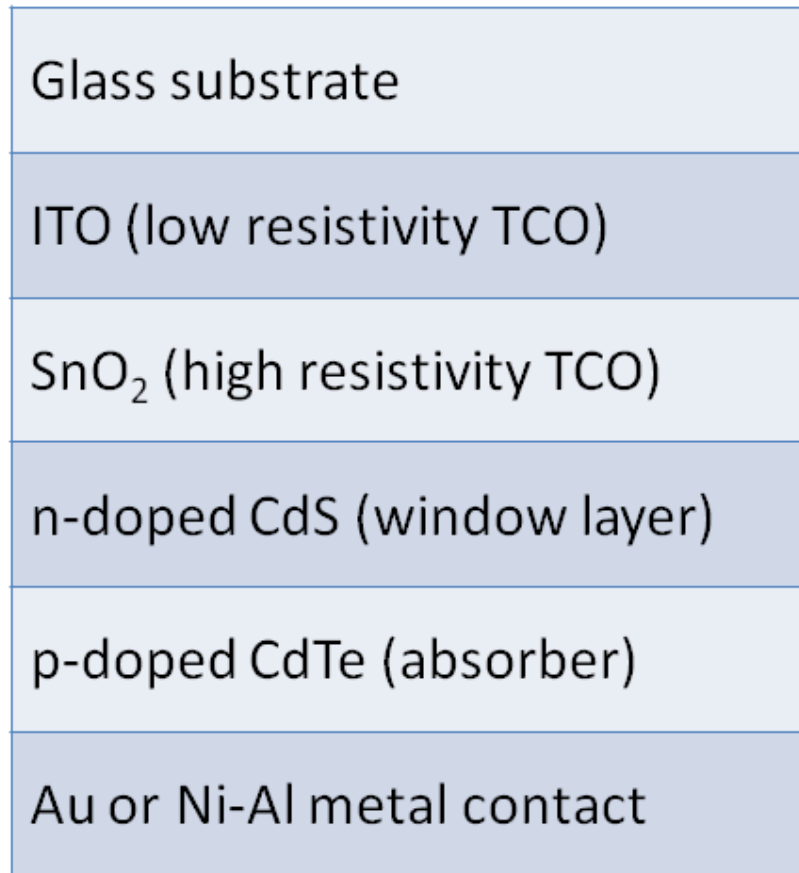
# Attained vs. attainable **short-circuit photocurrent**

Cell Type	$E_g$ at RT (eV)	$J_{sc}^{MAX}$ (mA/cm <sup>2</sup> )	$J_{sc}$ (mA/cm <sup>2</sup> )	$J_{sc}/J_{sc}^{MAX}$ (%)
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
$\alpha$ -Si	1.7	22.4	17.5	78
DSSC (black dye)	1.4	33.3	20.5	62
(Red N719)	1.6	25.5	17.7	70
(Red N3)	2.0	14.4	9.2	64
OPV	1.55	26.9	14.7	55

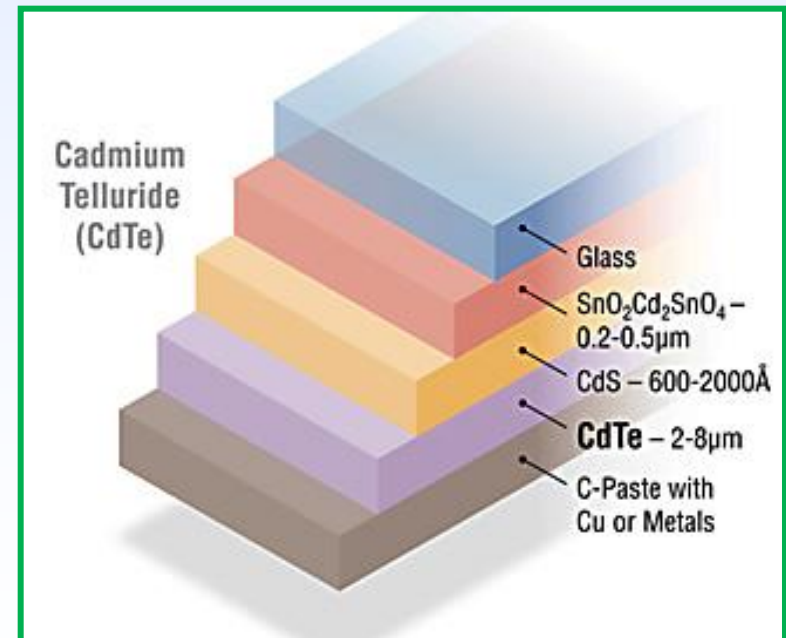


# Basic CdTe PV Device Architecture(s)

Light

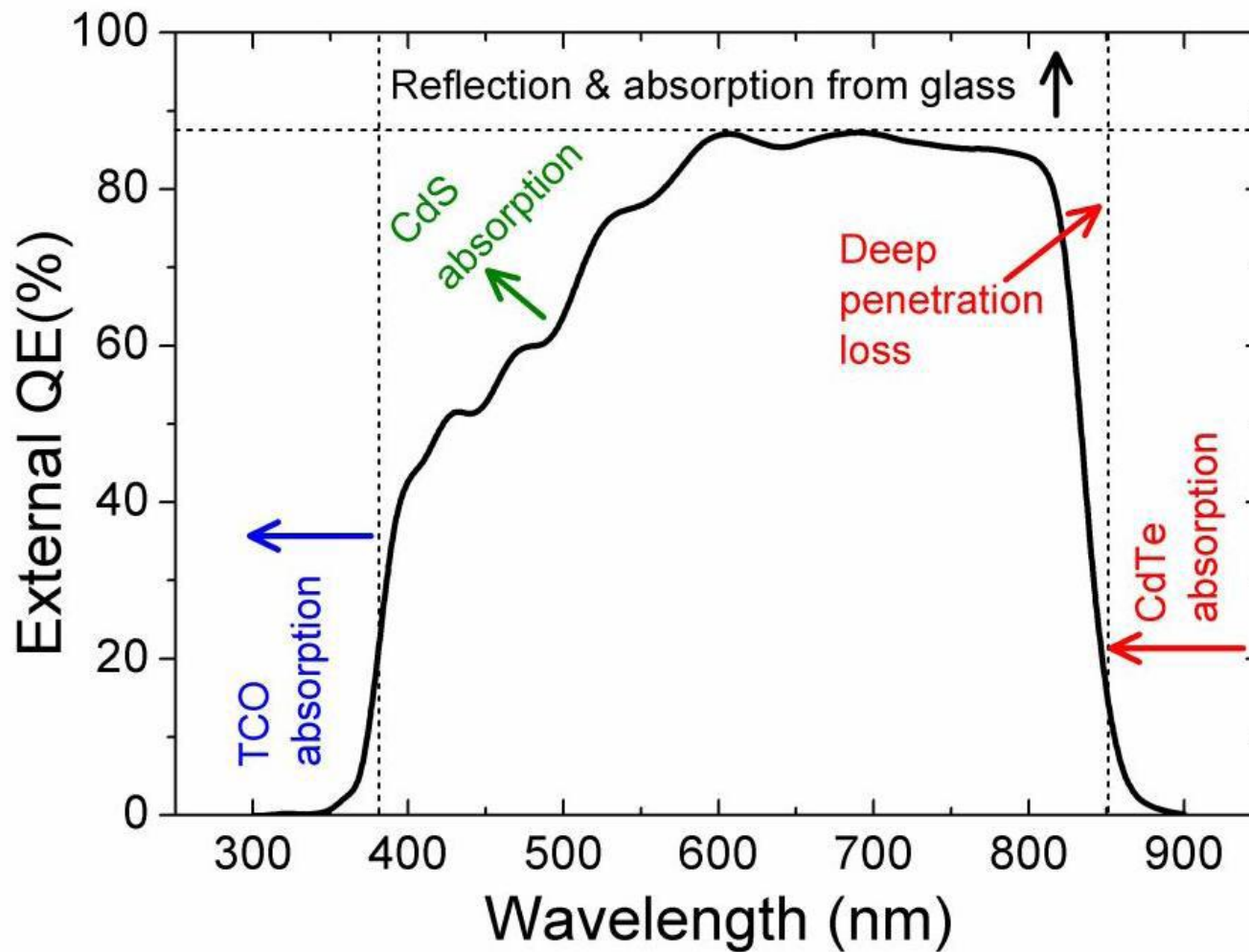


“superstrate”





# EQE for typical CdTe solar cell

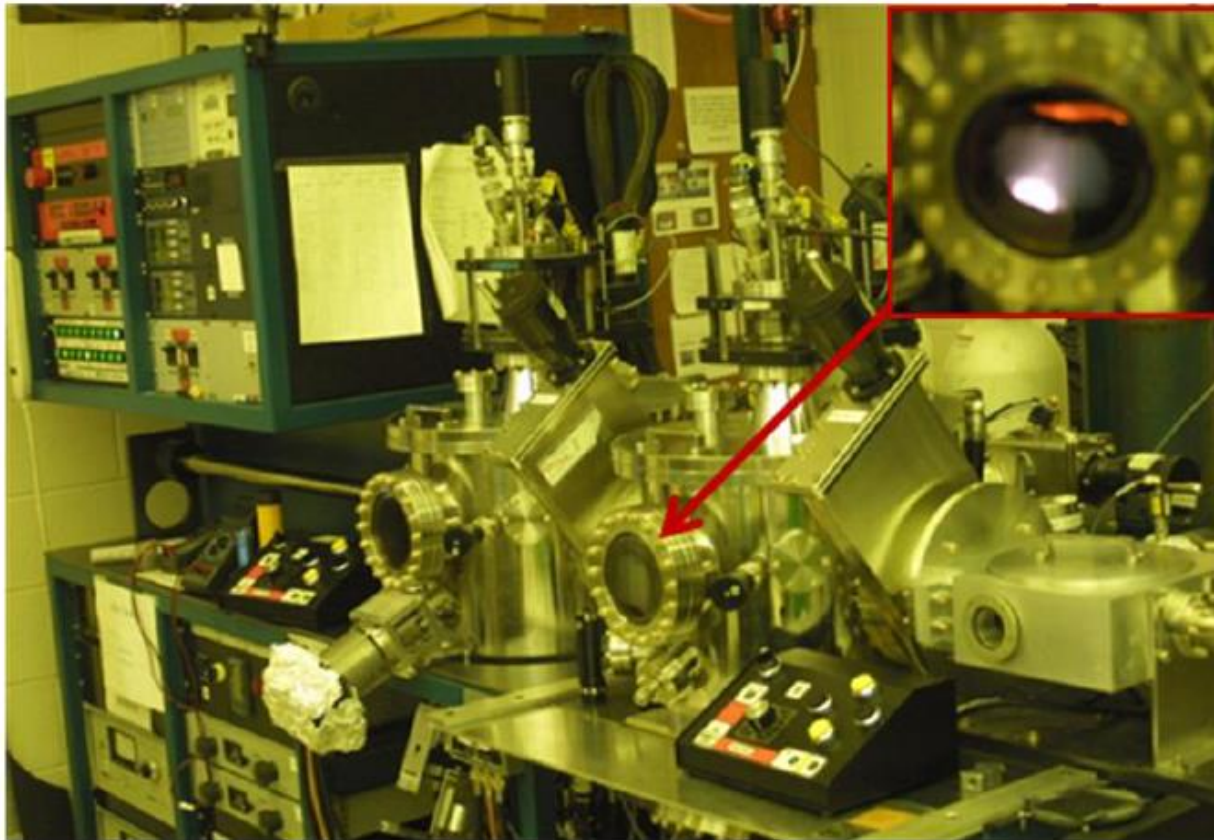


# TCO materials for used w/ CdTe solar cells

Materials	Resistivity	Transmission	Stability
$\text{SnO}_2:\text{F}$	$(5-7) \times 10^{-4} \Omega\text{-cm}$	$\sim 80\%$	excellent
$\text{SnO}_2:\text{In}_2\text{O}_3$	$2.5 \times 10^{-4} \Omega\text{-cm}$	$\sim 85\%$	good
$\text{In}_2\text{O}_3:\text{F}$	$2.5 \times 10^{-4} \Omega\text{-cm}$	$\sim 85\%$	good
$\text{In}_2\text{O}_3:\text{GeO}_2$	$2 \times 10^{-4} \Omega\text{-cm}$	$\sim 85\%$	good
$\text{Cd}_2\text{SnO}_4$	$2 \times 10^{-4} \Omega\text{-cm}$	$> 85\%$	fair
$\text{ZnO}:\text{Al}_2\text{O}_3$	$(4-6) \times 10^{-4} \Omega\text{-cm}$	$> 85\%$	fair
$\text{ZnO}:\text{In}$	$8 \times 10^{-4} \Omega\text{-cm}$	$\sim 85\%$	good



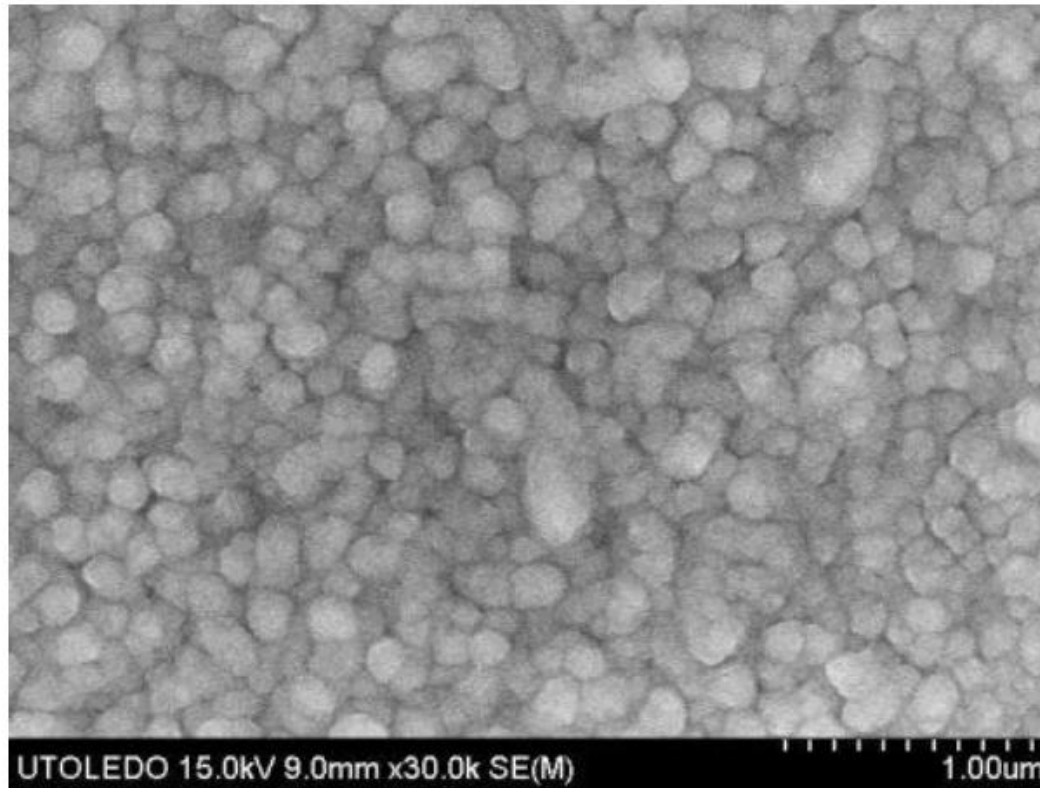
# CdS and CdTe sputtering system



**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.]



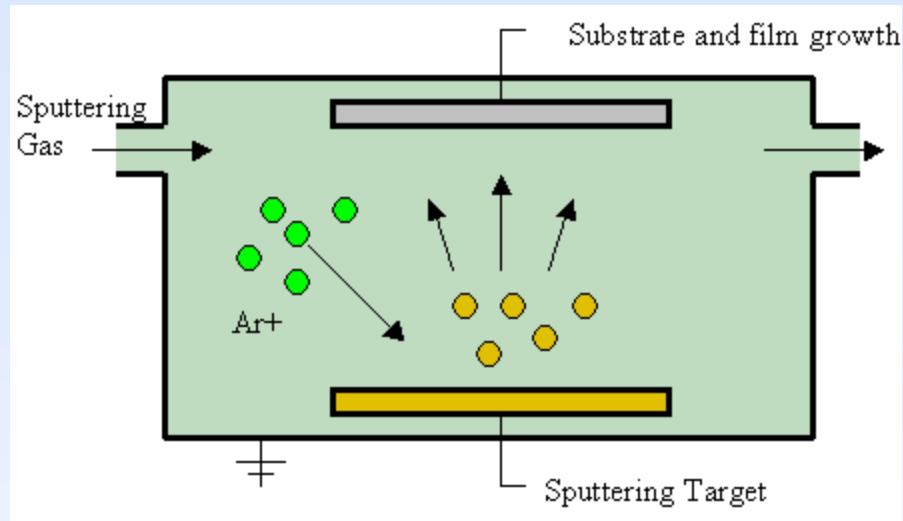
# Sputtered CdS film



**Figure 1-14.** Secondary electron micrograph of as grown CdS film sputtered on SnO<sub>2</sub>:F coated glass substrate.



# Sputter deposition



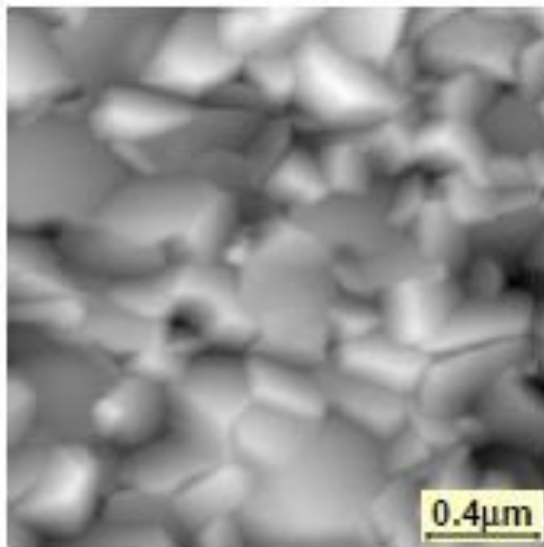
- Sputtered atoms have a wide range of energies;
- Ballistic atoms or ions can result in resputtering from thin film;
- Control of the atom energetic distribution can be accomplished through variation of chamber inert gas pressure (e.g., Ar);
- Note that CdTe sputters (and evaporates) congruently, i.e., 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://heraeus-targets.com/en/technology/_sputteringbasics/sputtering.aspx)

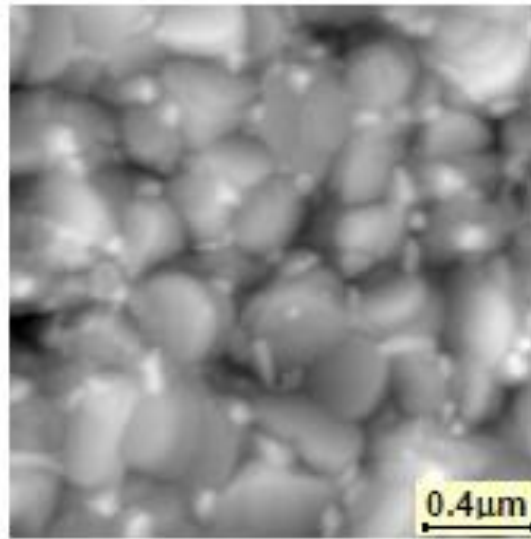




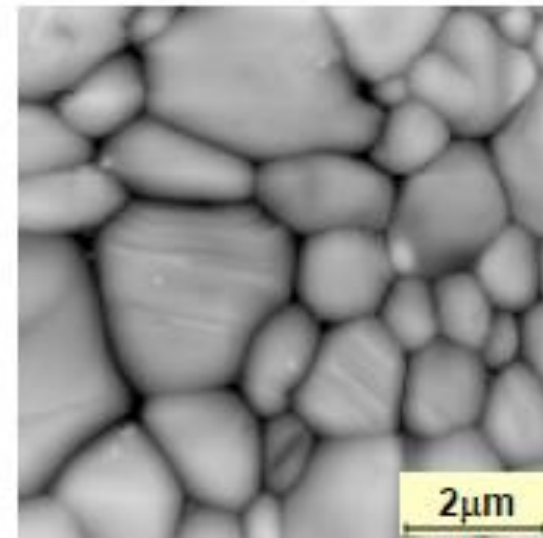
# $\text{CdCl}_2$ treatment (recrystallization of CdTe)



(a)



(b)



(c)

PVD CdTe films: (a) untreated, (b) and (c) after  $\text{CdCl}_2$  heat treatment at  $350^\circ$  and  $400^\circ\text{C}$ , respectively.

## Effects of $\text{CdCl}_2$ treatment on as-deposited CdTe films

- 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 ( $\sim \times 10$ ), perhaps due to reduction in deep level defect densities within the bandgap.

### **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*

# CdTe module production and scribing steps



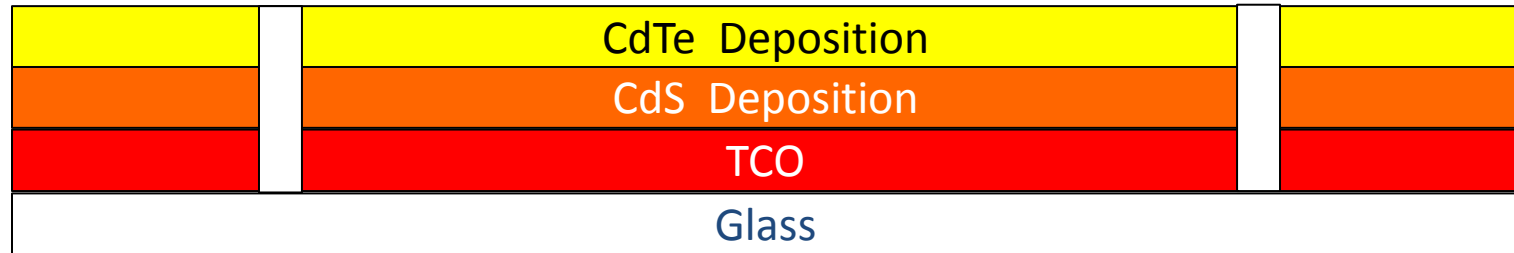
- Start with **TCO** Coated Glass



CdTe Deposition
CdS Deposition
TCO
Glass

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

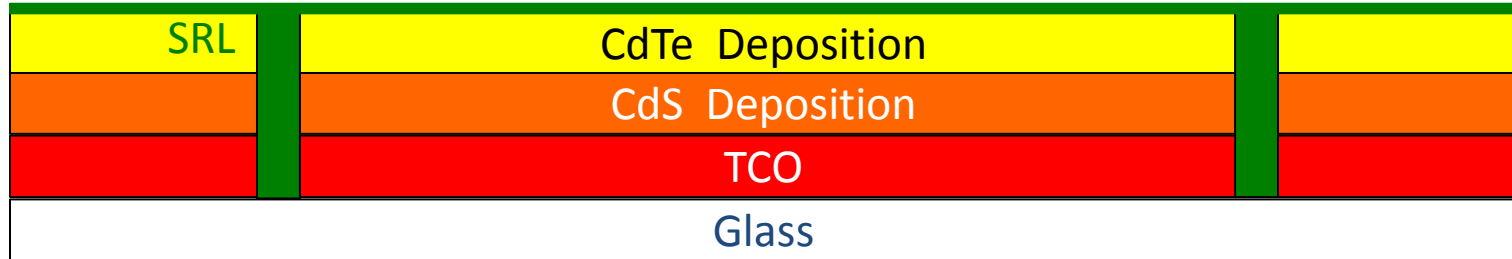
P1



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

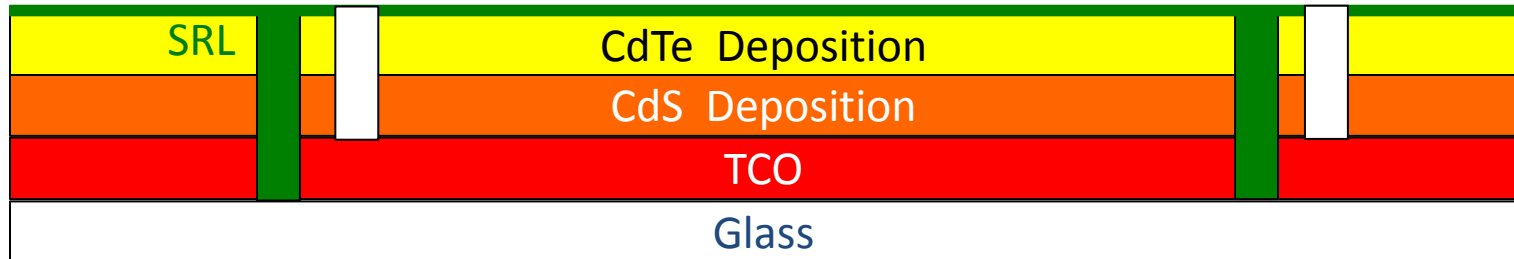
Note: All scribes from sunny side

P1

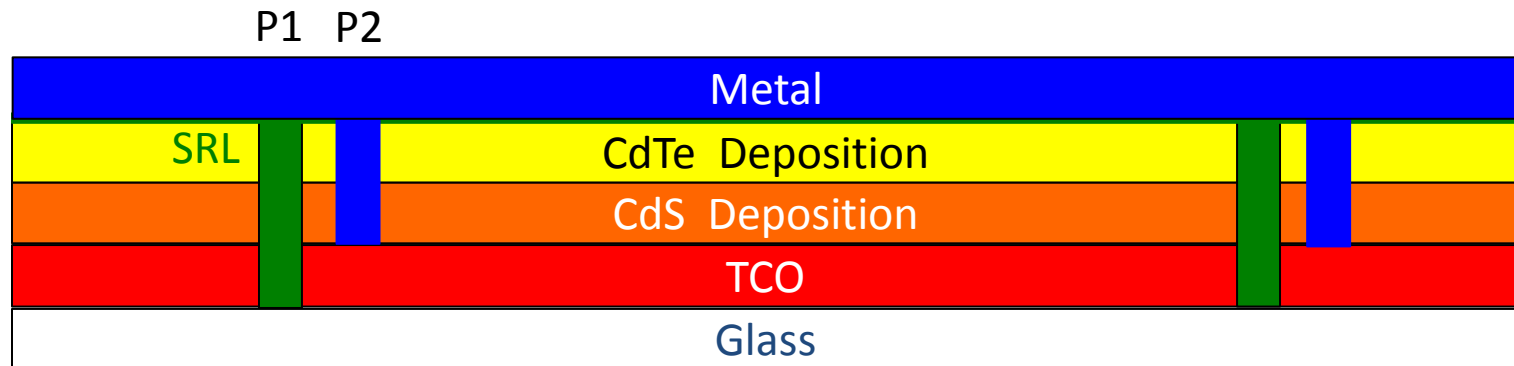


- Start with **TCO** Coated Glass
- Deposition 1 – **CdS**
- Deposition 2 – **CdTe**
- Process 1 – P1 – 1064 nm **Scribe** through TCO/CdS/CdTe
- Process 2 – **Shunt resistance layer**

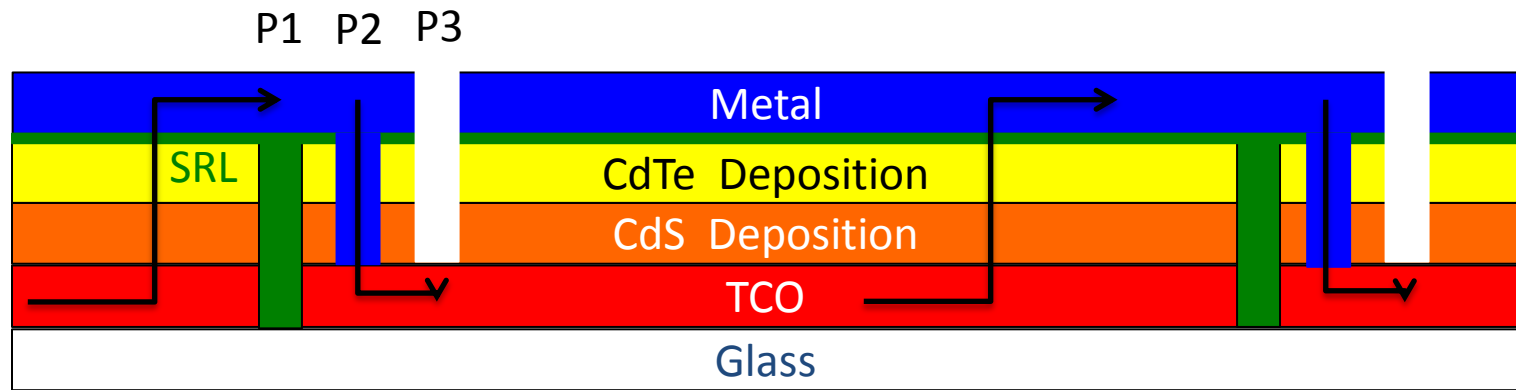
P1 P2



- 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 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.

