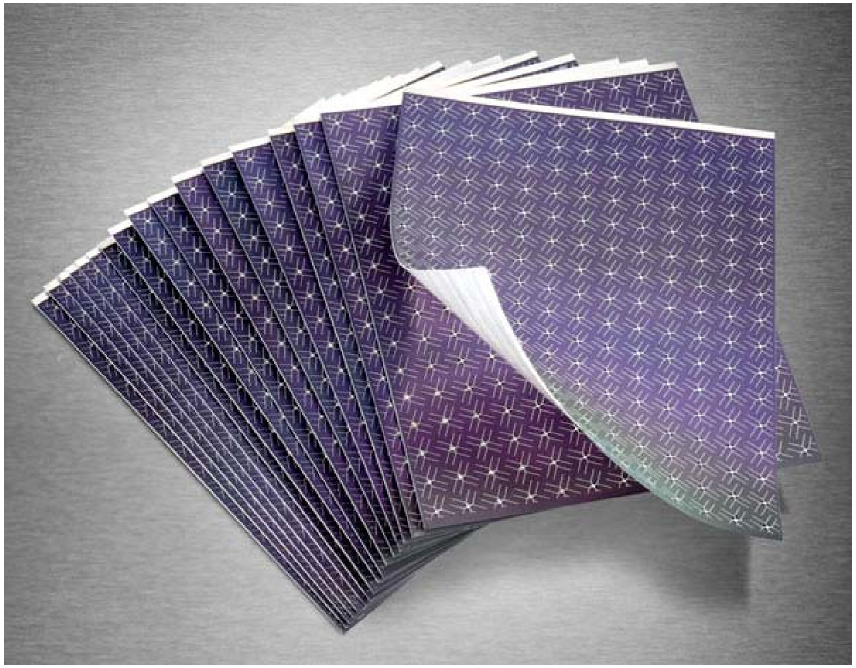
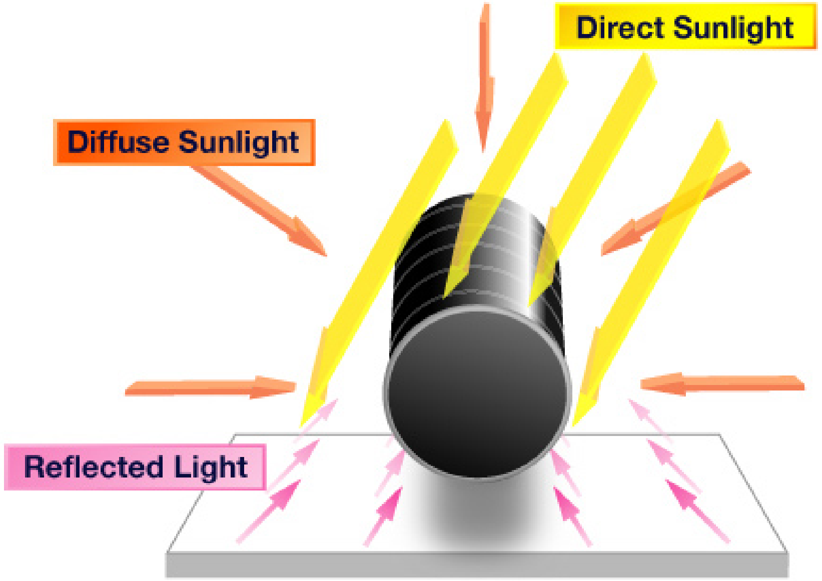
Solar Cells in 2009 and Beyond

Mike McGehee
Materials Science and Engineering





These slides are posted on my website (Google my name). You are welcome to use them. The video will be on iTunesU and Youtube.

To provide the world with 10 TW of solar electricity by 2030

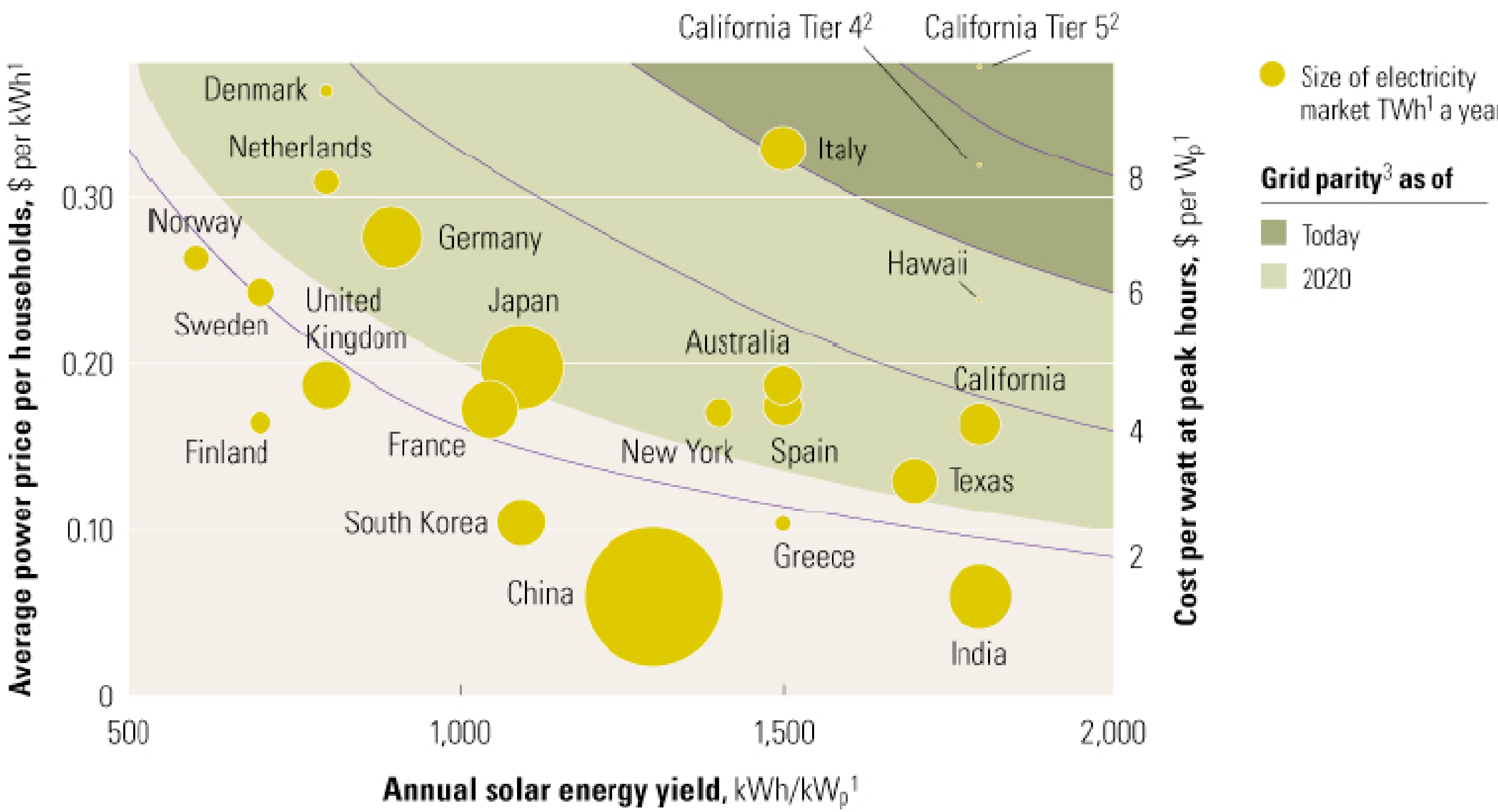
- We need to grow the industry by ~ 35 %/year.

- Not run out of essential materials.

- Make enough money in 2 years to double the factory size.

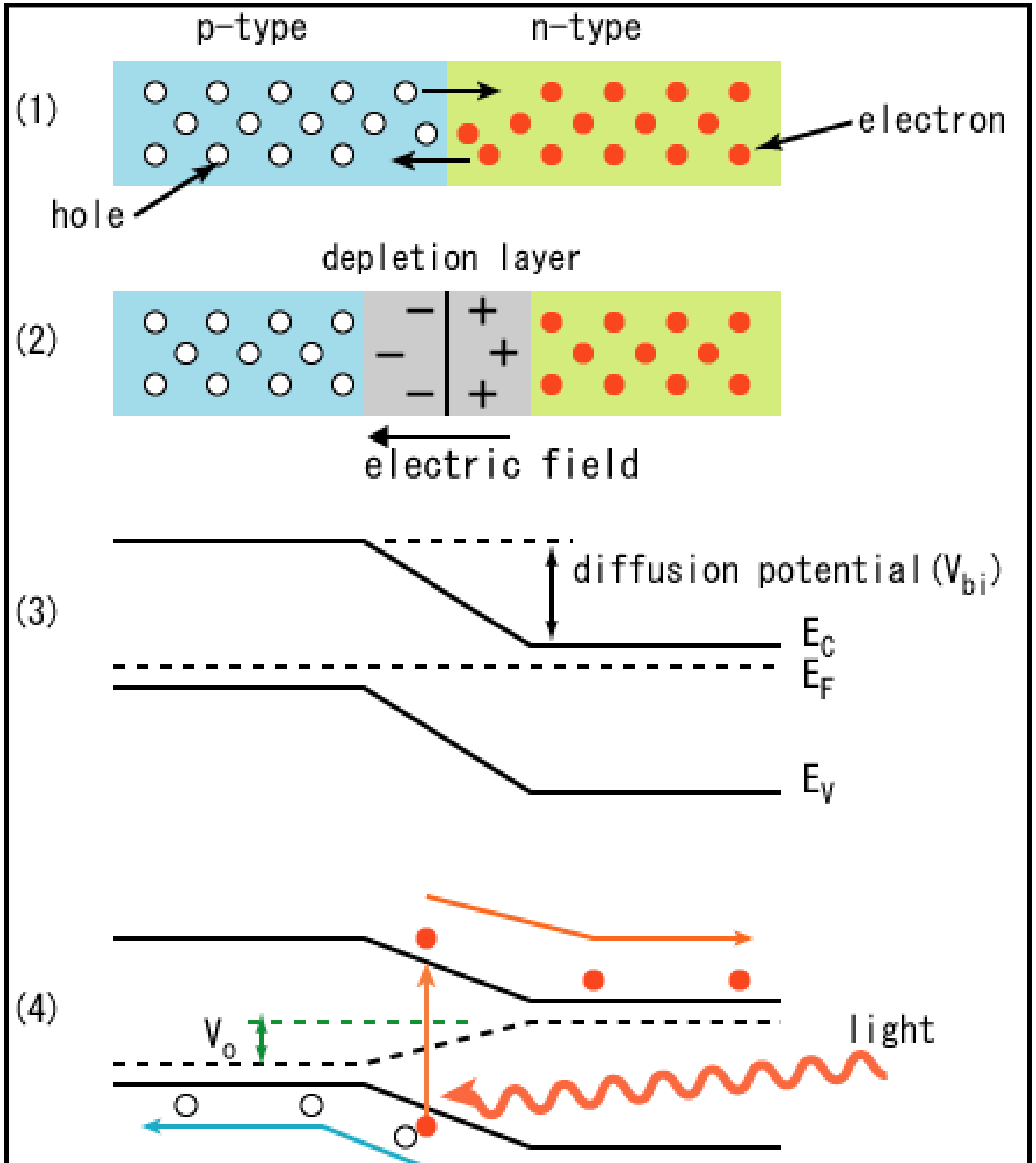
- Get energy payback within two years so that we generate more power than we use.

The grid parity cost depends on location

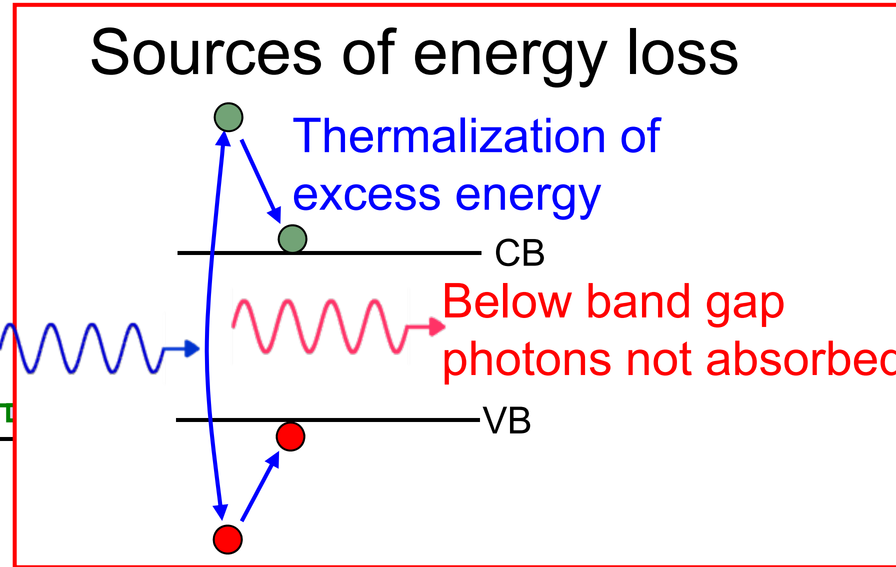


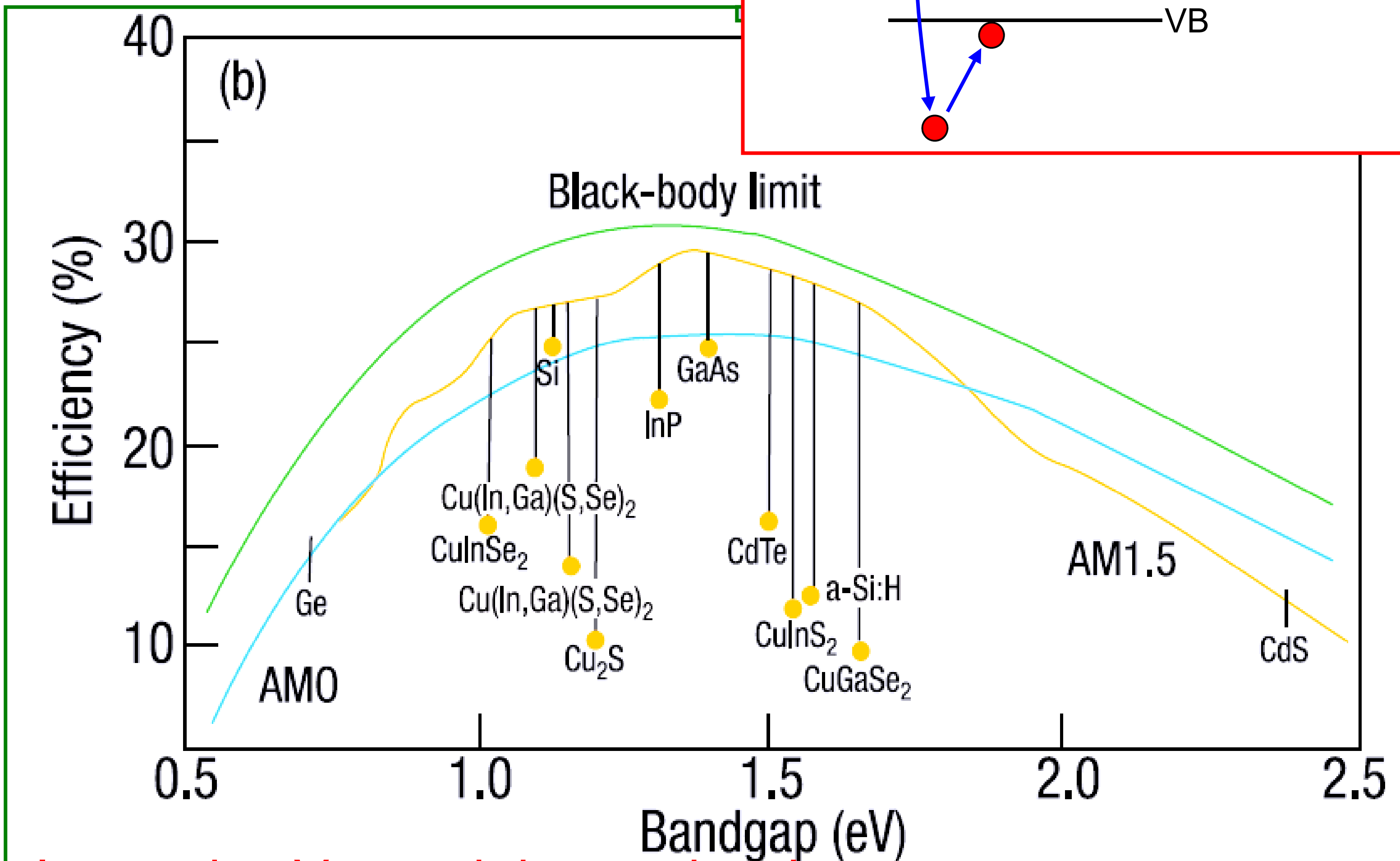
Source: CIA country files; European Photovoltaic Policy Group; Eurostat; Pacific Gas & Electric (PG&E); Public Policy Institute of New York State; McKinsey Global Institute analysis

Conventional p-n junction photovoltaic (solar) cell



Efficiency limits

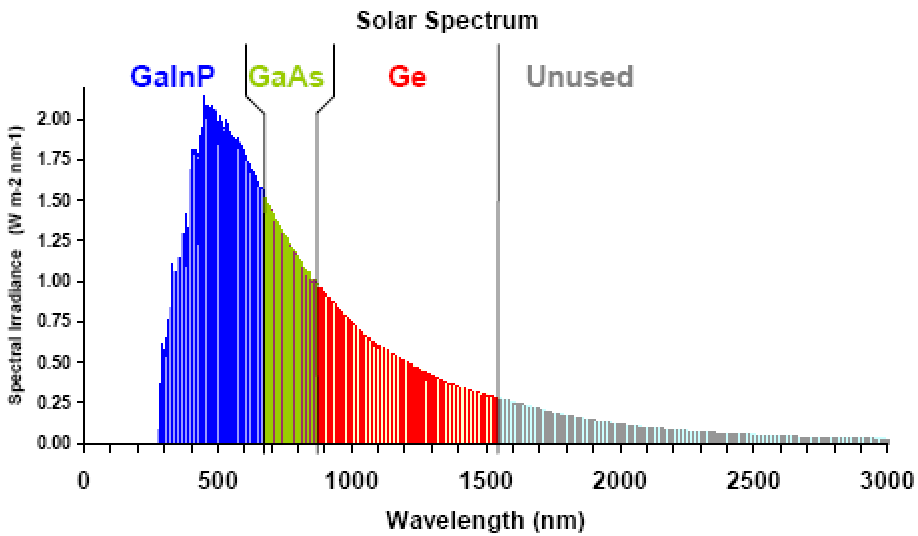




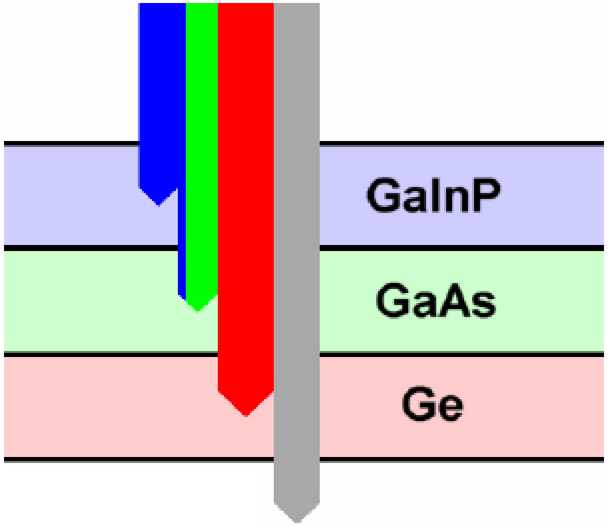
Increasing V_{OC} and decreasing J_{SC} →

Triple-junction cells

New World Record: 41.6% under 346 suns!



- The cells are in series; current is passed through device
- The current is limited by the layers that produces the least current.
- The voltages of the cells add
- The higher band gap must see the light first.



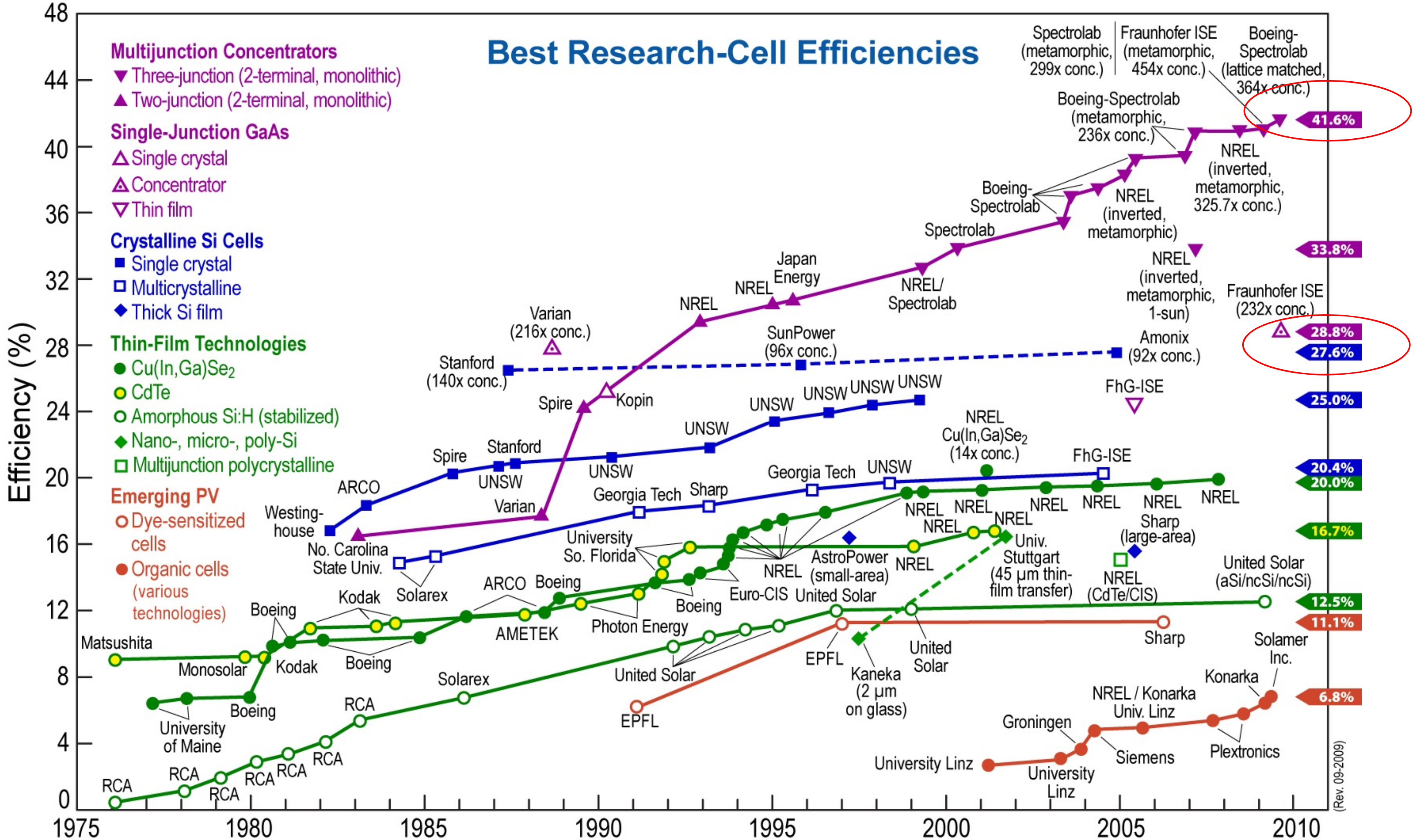
1.7-1.9 eV

1.3-1.4 eV

0.67 eV

Appl. Phys. Lett. 90, 183516 (2007)
Emcore Corporation, May (2006)

Efficiency vs time for various technologies



(Courtesy of Sarah Kurtz, NREL)

Factors to consider when comparing technologies

- Efficiency (and its effect on balance of system costs
- Cost
- Throughput of equipment
- Availability of necessary elements
- Toxicity
- Does it require direct (not diffuse) sunlight?
- Aesthetics

There might be different winners for various applications.

The Terawatt Challenge for Thin-Film PV, K. Zweibel (NREL)

Multicrystalline silicon solar cells: today's most popular technology

15-18 % efficiency } $3/W
$500/m^2$

	Price ($/W)
Module	$3.00
Inverter	$0.50
Retro fit installation	$4.00
TOTAL	$7.50

Average cost over 30 yrs of PV cell electricity in CA including 6 % interest payments:	$0.28/kW-hr w/out subsidies	actually lower if the interest is deducted from taxes
Average grid electricity in CA: Peak rates in CA:	$0.13/kW-hr $0.29/kW-hr	will rise over 30 years

$/Wp Ranges From $4-9 Depending On Type Of Installation

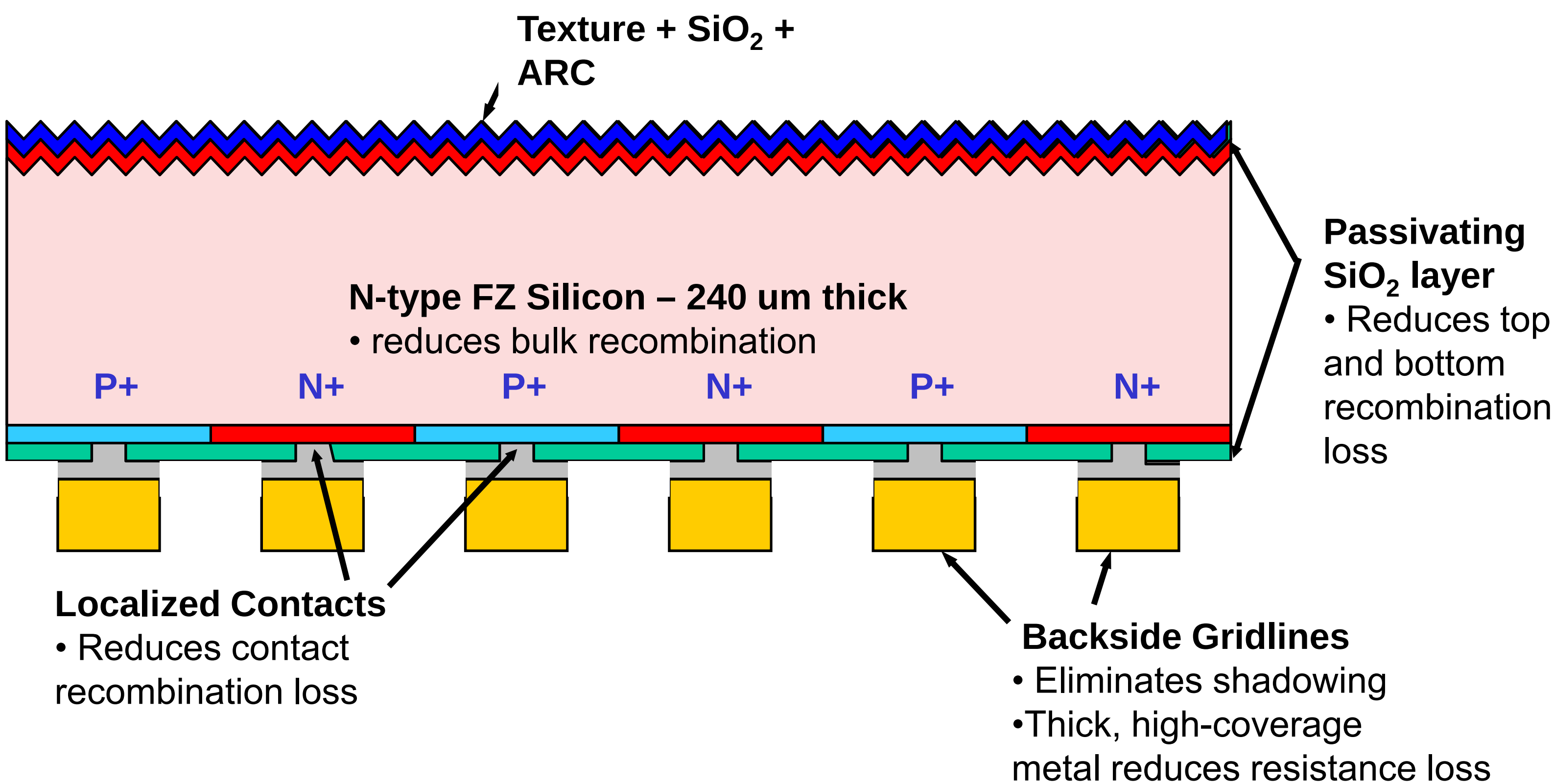
Representative Costs, 2008

	Residential	Commercial	Utility
System size	3.8KW	210KW	10MW
$/Wp, in US	**$8.98**	**$6.68**	**$4.93**
¢/kWh - Phoenix, AZ	31.78	22.91	26.09
¢/kWh - Boston, MA	41.89	30.44	36.49

Costs for 2009 are lower, some installations are being done as low as $3 / watt

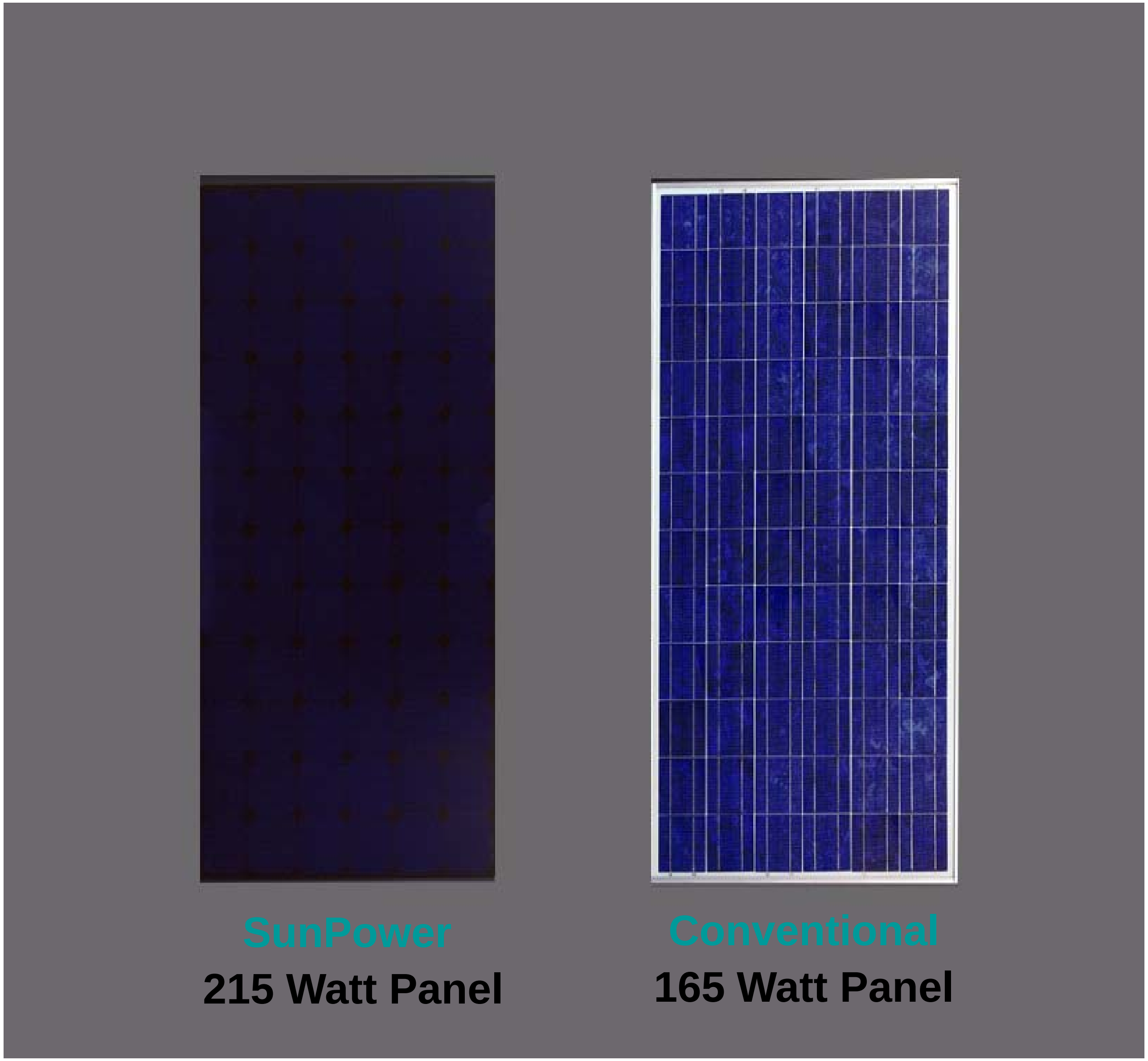
Source: SAM model, built by DOE and Sandia National Labs. Costs are representative of realistic figures, not average costs from sample installations. Does not include incentives.

SunPower's Backside Contact Cell



- Technology invented at Stanford by Dick Swanson.
- Sunpower sells 21 % efficient cells. I think they cost $1/W more than m-Si

Aesthetic advantage of not having top contacts



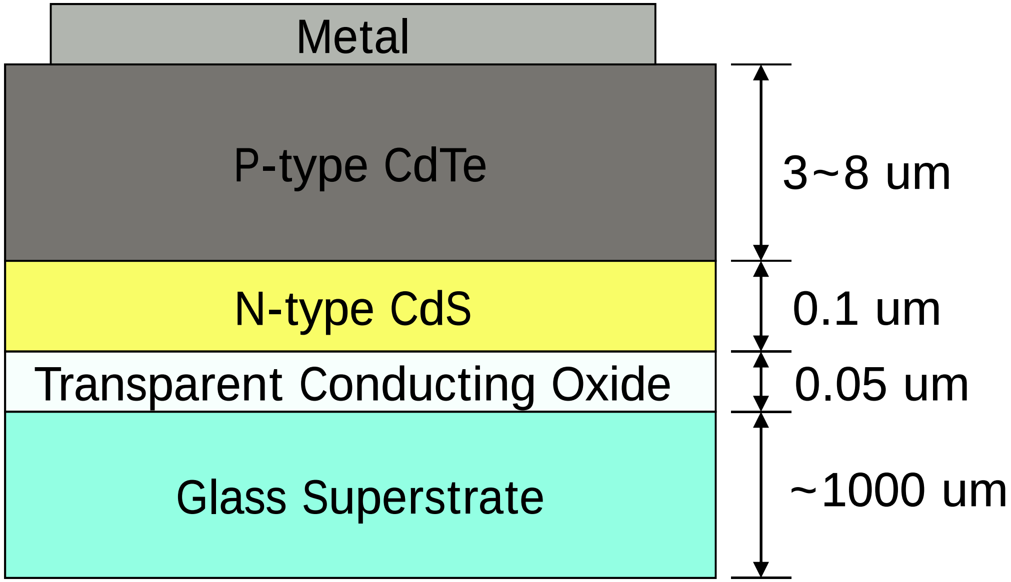
Inorganic Thin Film Solar Cells

- A thin film of semiconductor is deposited by low cost methods.

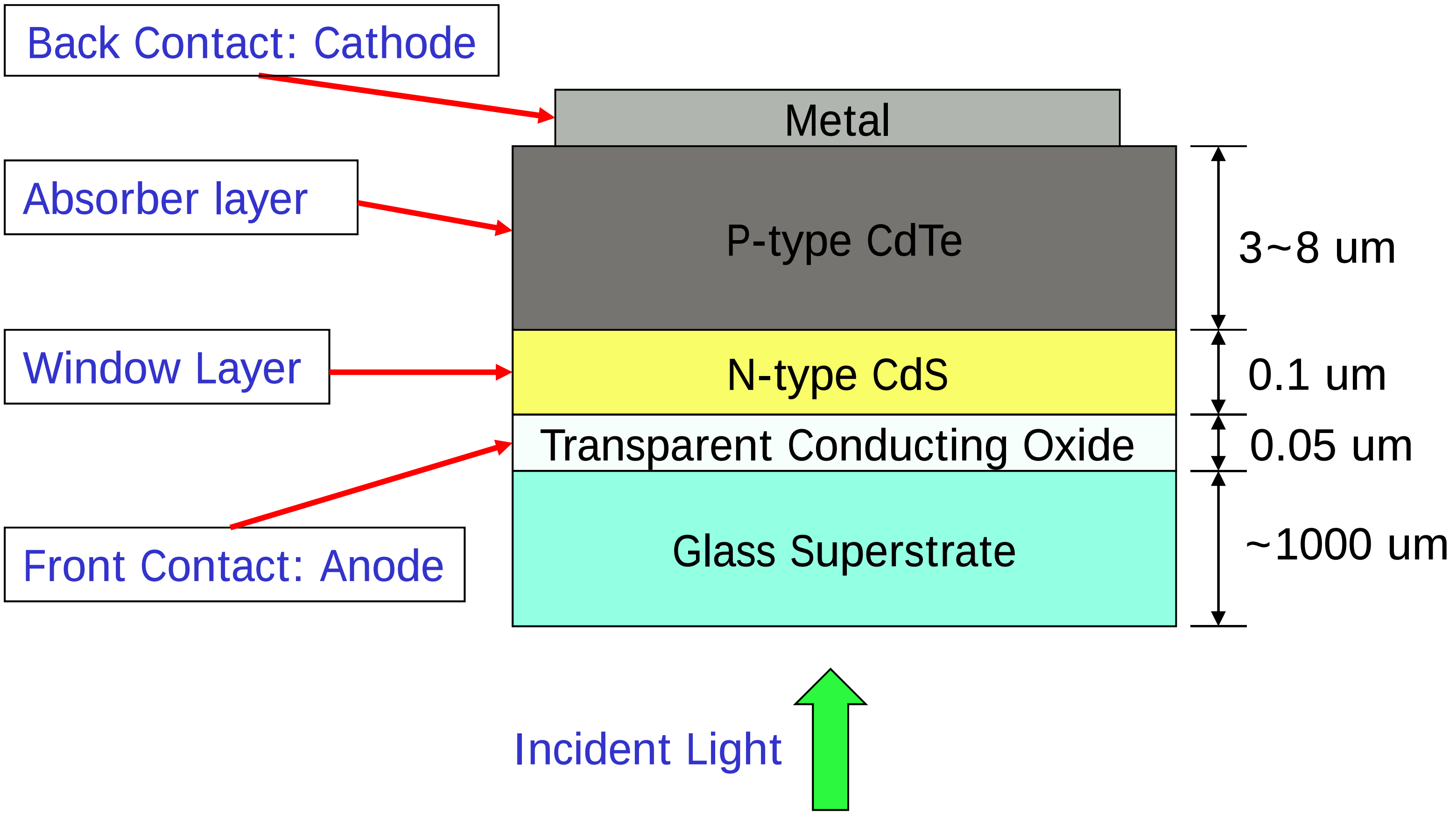
- Less material is used.

- Cells can be flexible and integrated directly into roofing material.

CdTe
CIGS (CuInGaSe_2)
amorphous Si

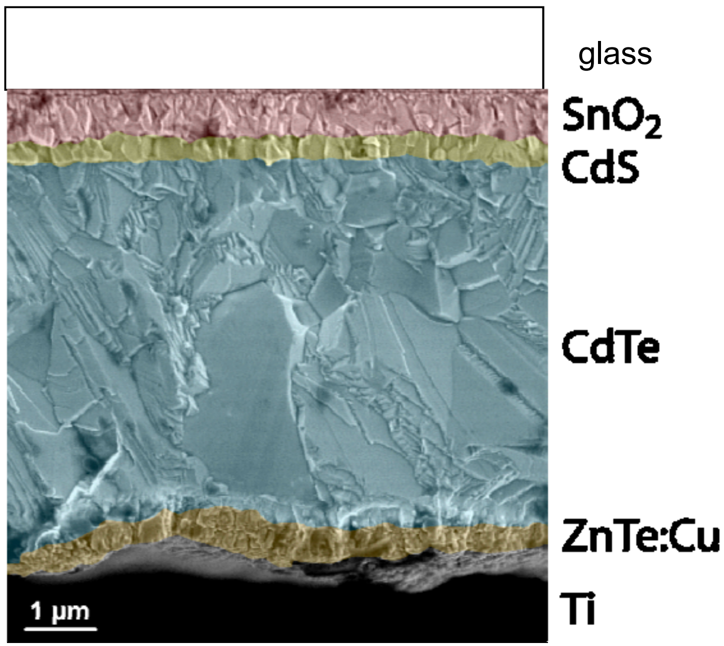


CdTe Solar Cell with CdS window layer



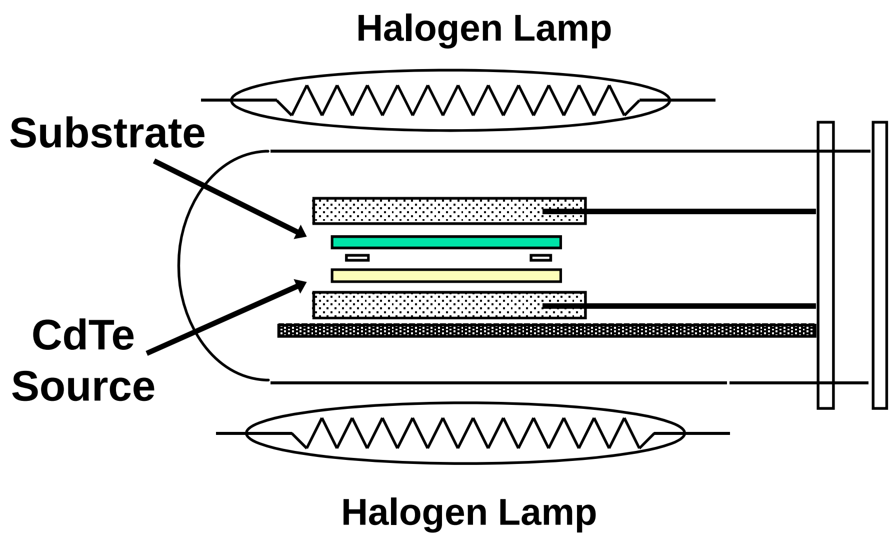
CdS: tends to be n-type, large bandgap(2.42eV)

Cadmium Telluride Solar Cells



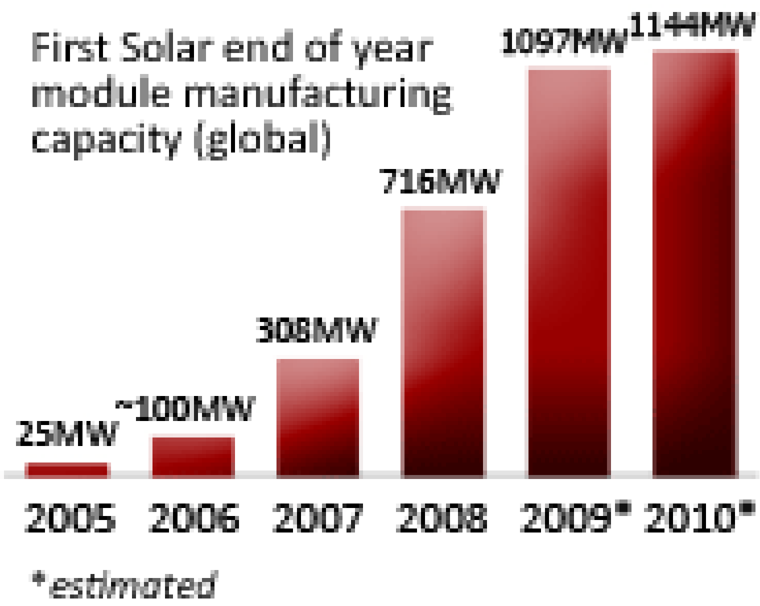
CdS/CdTe

- Direct bandgap, E_g=1.45eV
- High efficiency (Record:16.5%; Industry: 11%)
- High module production speed
- Long term stability (20 years)



CdTe: Industrial Status

First Solar is the leader. It takes them 2.5 hours to make a 11 % module.

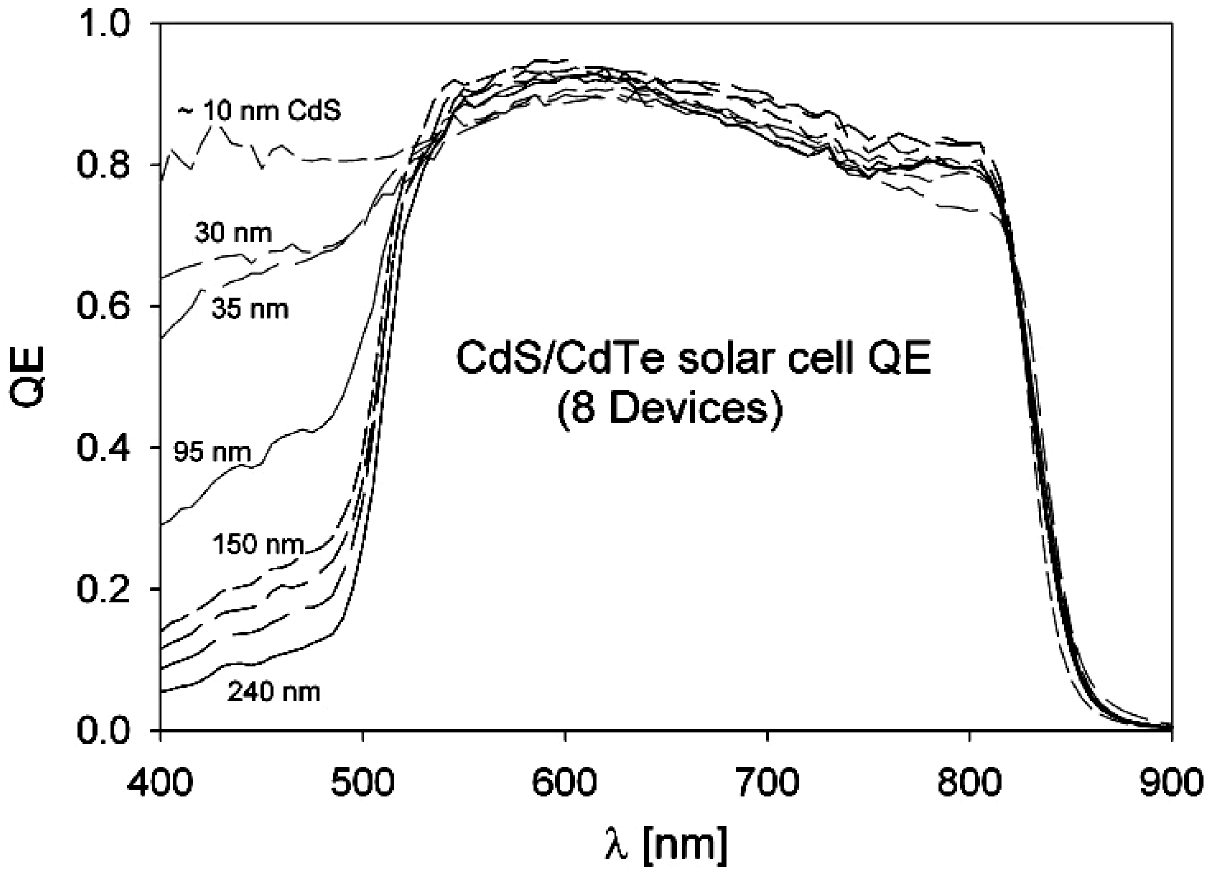


Average Manufacturing Cost
2006: $1.40/watt
2007: $1.23/watt
2008: $1.08/watt

The energy payback time is 0.8 years.

www.firstsolar.com

One reason cells on the roof don't have 16.5 % efficiency



The challenge in industry is to implement thin CdS layers without having a pinhole.

From Reuben Collins

How much of a problem is the toxicity of Cd?

- It is probably manageable. First Solar will recycle the panels when the customer is done with them.

- Ask John Benner next week.

Is there enough Te?

The amount of Te in a cell is

(thickness)(density)(mass fraction Te).

2-μm thick cells require

(2 μm)(5.7 g/cm^3)(0.52) = 5.7 g/m^2.

The sun gives us 1 kW/m^2, so a **10 % efficient** cell produces

$$\frac{100\ \mathrm{W}/\mathrm{m}^2}{5.7\ \mathrm{g}/\mathrm{m}^2} = \frac{16\ \mathrm{W}}{\mathrm{g\ Te}}.$$

The Reserve of Te

- According to the United States Geologic Survey, the world reserve of Te is 47,000 tons.

- If **all of it** was used to make solar cells, we could generate 0.68 TW during peak conditions or about **0.14 TW** averaged throughout the day.

- We want >5 TW.

- The Reserve is defined as the amount that can be **economically** recovered.

The cost of Te

• In 2008 Te cost $250/kg. Continuing the example from before, that translates to **0.015 $/W**

• The cost of Te could go up a lot before affecting the price of solar cells

• By my estimate, First Solar used half of the world's annual production of Te last year. The near future should be interesting.

Can we find more Te?

- Te is a byproduct of Cu mining.

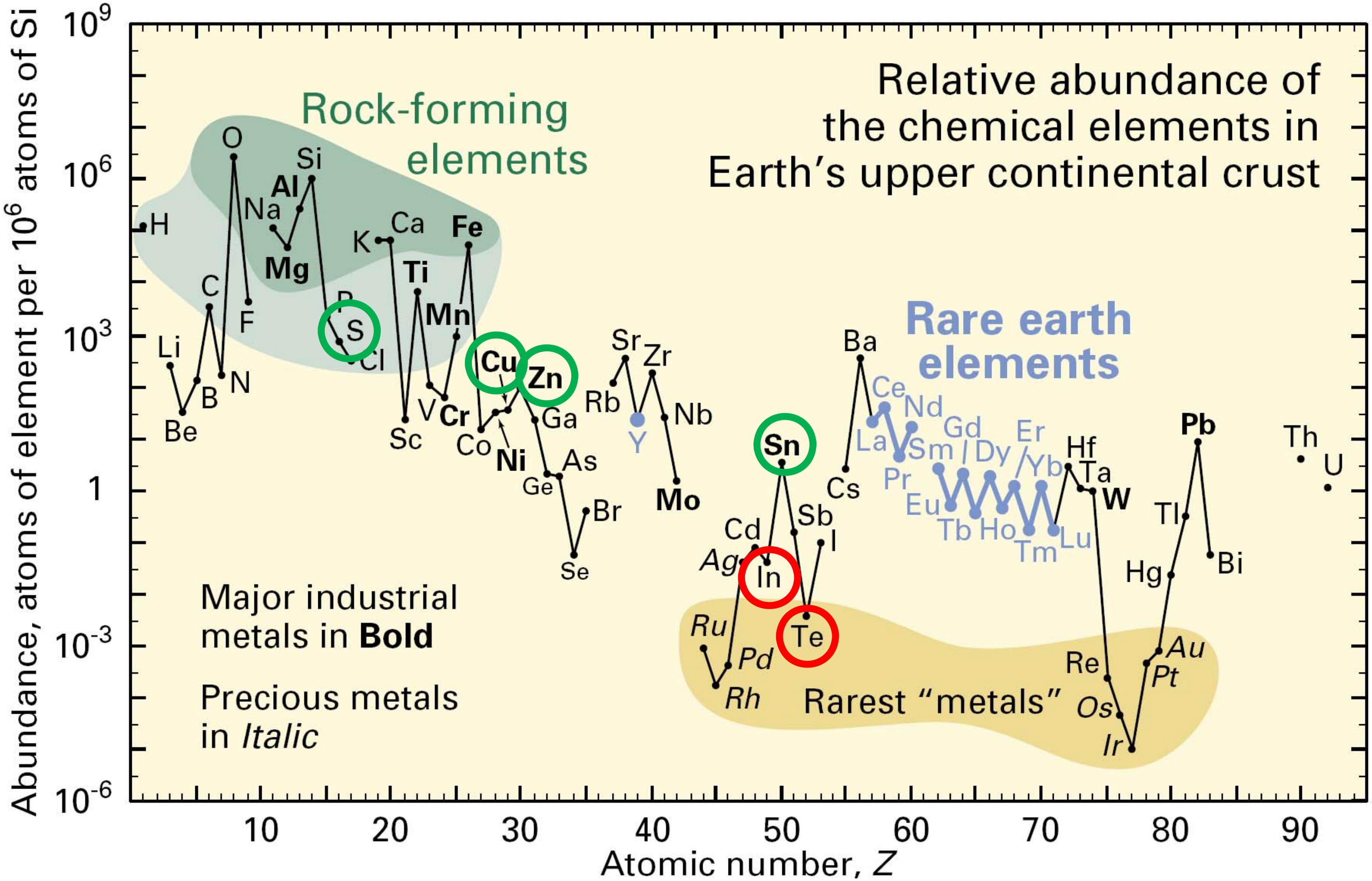
- As the price goes up, more Cu plants will install equipment to capture the Te.

- Until recently, no known Te ores were known.

- We might find a lot more Te when we look for it.

- Martin Green, "Estimates of Te and In Prices from Direct Mining of Known Ores," *Prog in PV* 17 (2009) p. 347.
- Cyrus Wadia, Paul Alivisatos and Dan Kammens, "Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment," Environmental Science and Technology, (2009)

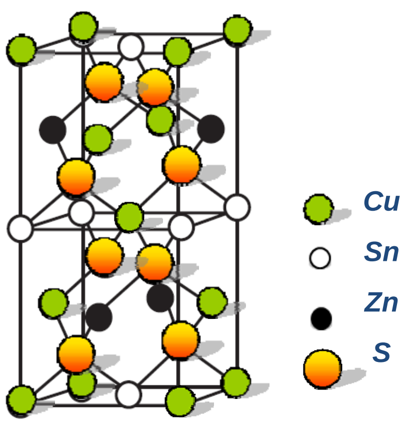
Searching for more abundant materials



U.S. Geological Survey Fact Sheet 087-02

Solar Cells Using *Non-Toxic Abundant* Materials

- $CuInGaSe_2$ – 19.5% efficient – thin film architecture
- Cu_2ZnSnS_4 (CZTS)
  - 6.7% efficiency (Katagiri et al.)
  - 1.45 eV Eg
- CZTS has kesterite structure

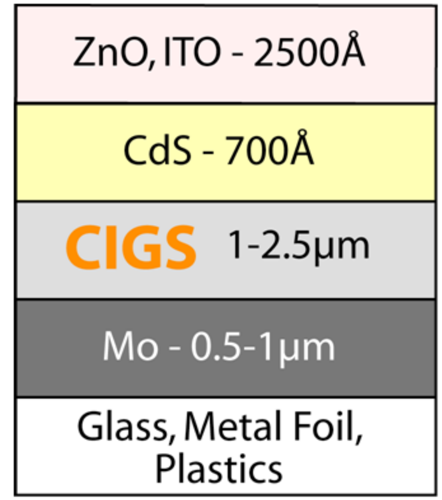


Raw Material Costs	Relative Abundance
Cu - \$3.35/lb	Cu - 6.0×10^{-5}
Zn - \$1.59/lb	Zn - 7.0×10^{-5}
Sn - \$6.61/lb	Sn - 2.3×10^{-6}
S – \$0.02/lb	S - 10^{-4}
Ga - \$209/lb	Ga - 1.9×10^{-5}
In - \$361/lb	In - 2.5×10^{-7}
Se - 2002 \$4, 2007 \$33/lb	Se - 5×10^{-8}

Source: www.usgs.gov (2007 data)

Stacey Bent and Bruce Clemens are making cells with CZTS at Stanford.

$Cu(In_xGa_{1-x})Se_2$

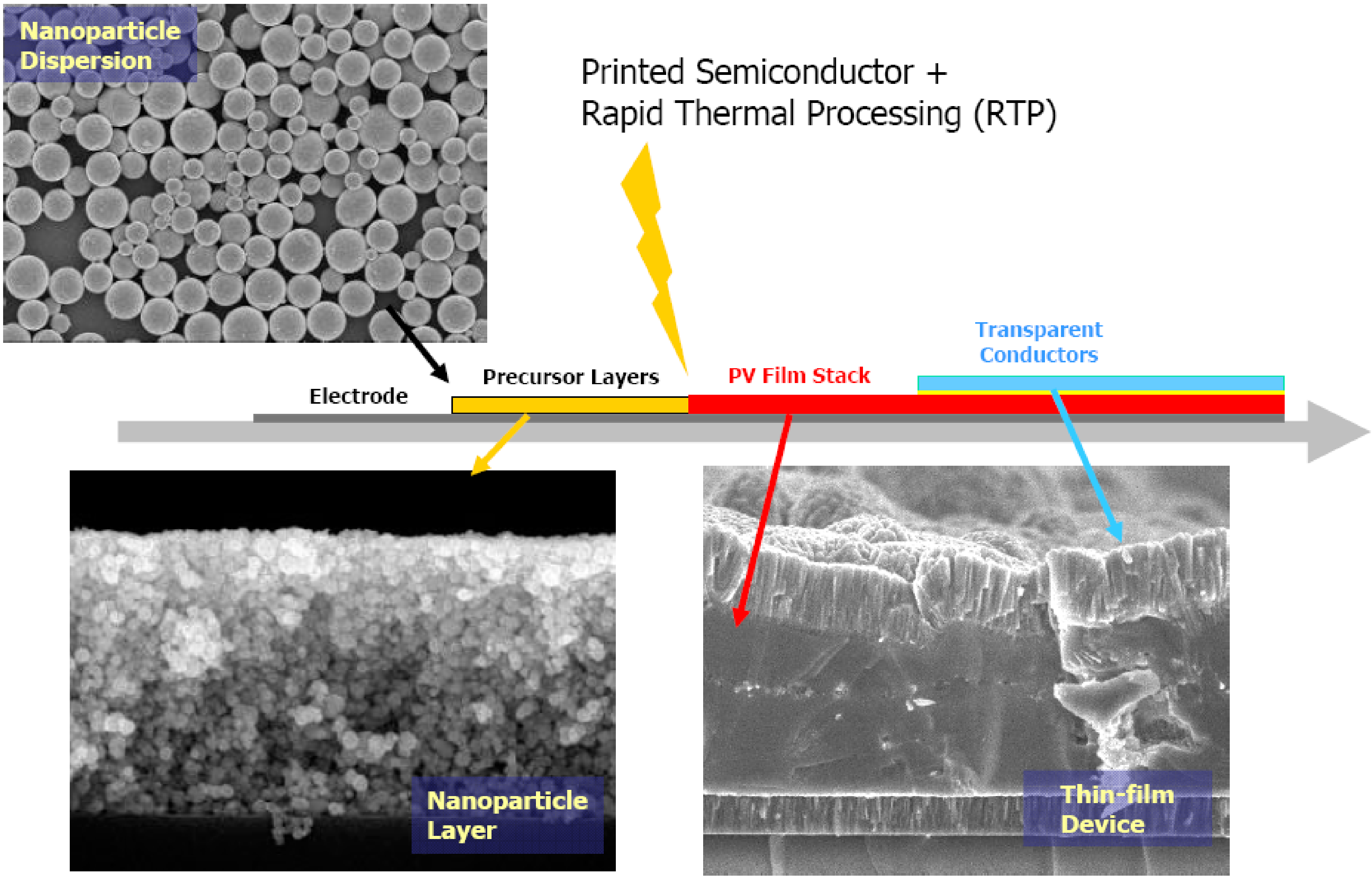


- World record efficiency = 20.0 %.
- Many companies are evaporating, printing, sputtering and electrodepositing it.
- Some are just starting to ship cells.
- Handling a 4-element compound is tough.

Shell Solar, CA
Global Solar Energy, AZ
Energy Photovoltaics, NJ
ISET, CA
ITN/ES, CO
NanoSolar Inc., CA
DayStar Technologies, NY/CA
MiaSole, CA
HelioVolt, Tx
Solyndra, CA
SoloPower, CA

Wurth Solar, Germany
SULFURCELL, Germany
CIS Solartechnik, Germany
Solarion, Germany
Solibro, Sweden
CISEL, France
Showa Shell, Japan
Honda, Japan

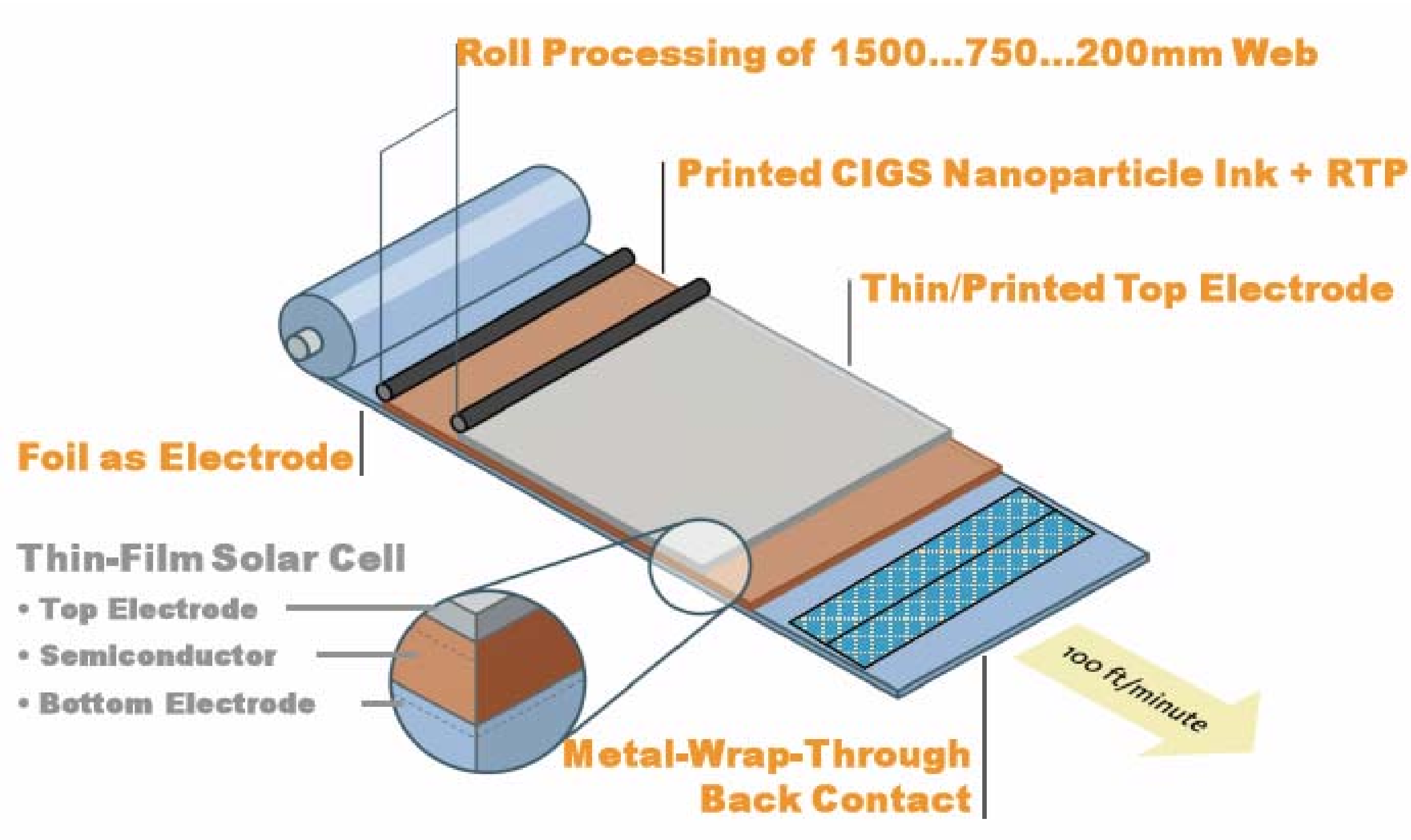
PRINTED SEMICONDUCTOR



Nanosolar's Roll-to-Roll Coating

See videos of the coating machine and module packaging on Nanosolar's website.

Nanosolar



There is a 16-page white paper on the Nanosolar website describing this technology.

Nanosolar's Design

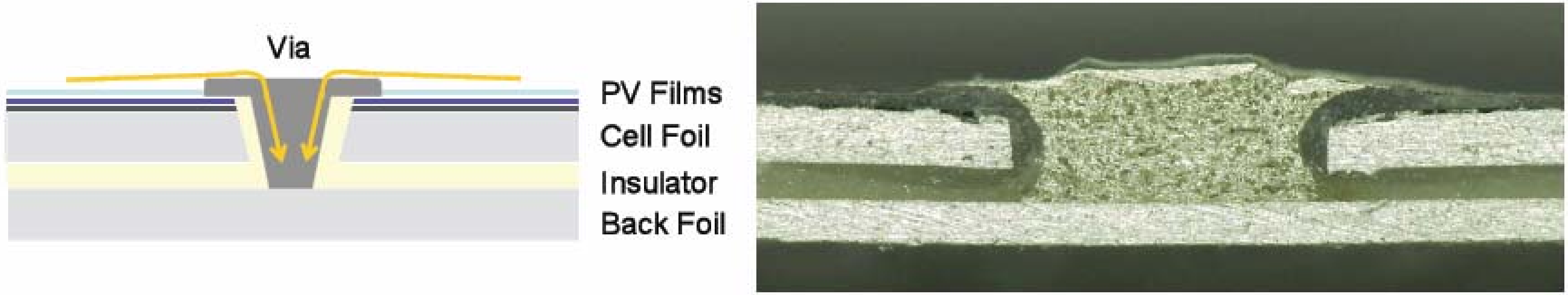
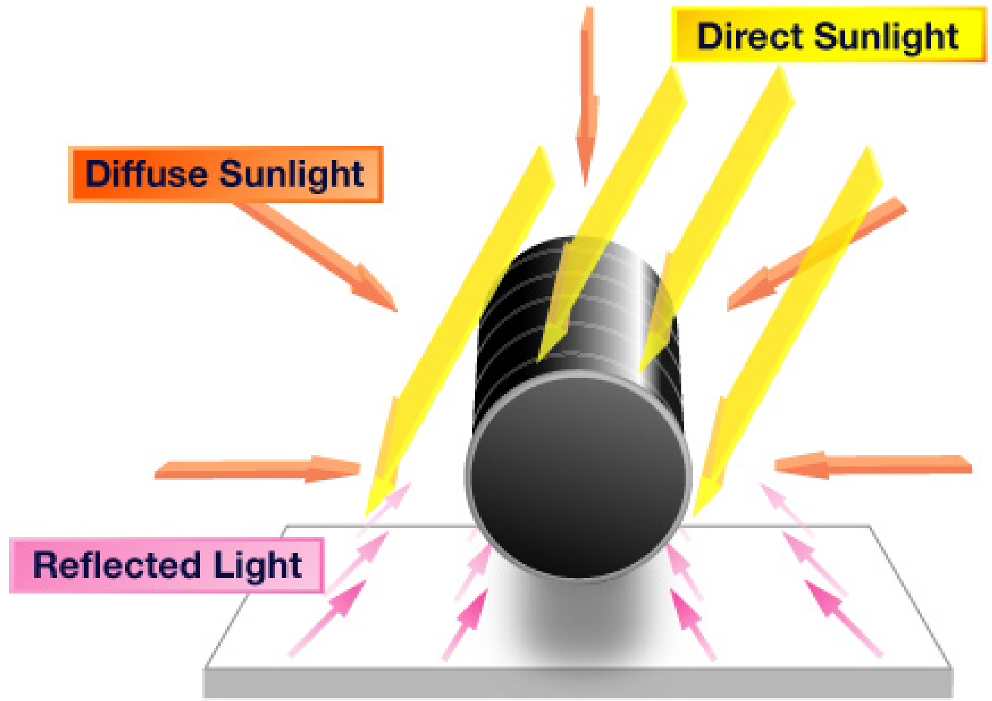
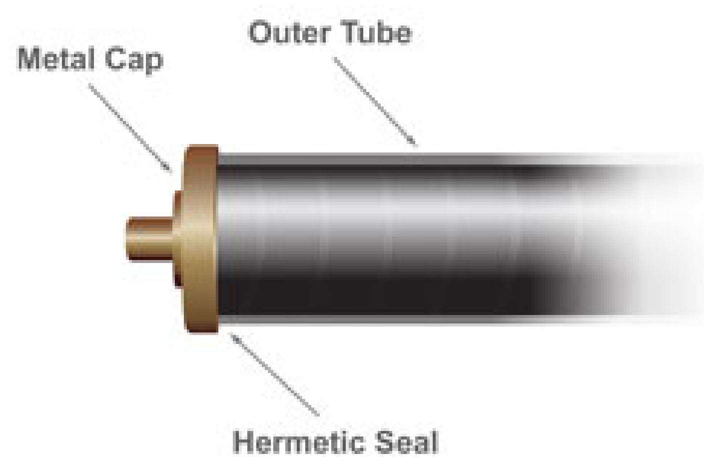


Figure 14: Nanosolar Back-Contact Cell Architecture: Two laminated aluminum foils with conductive vias.

Figure 15: Nanosolar MWT back-contact cells are interconnected into electrical circuits via tabs on each cell that are simply the overhang of one of the two laminated aluminum foils.

Solyndra's CIGS modules





www.solyndra.com

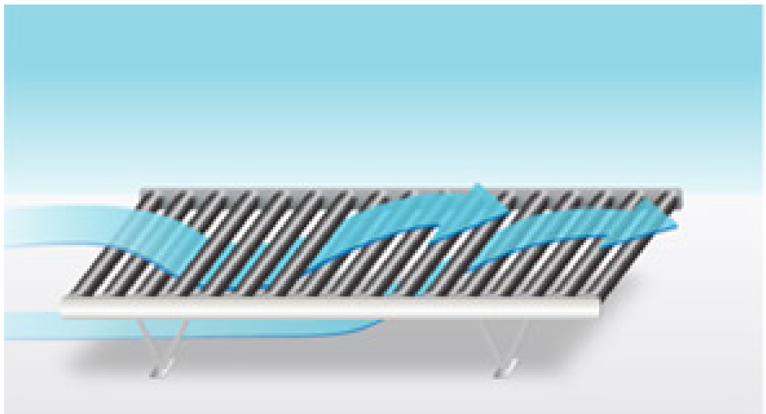
A comparison of Solyndra's modules to their competitors

SOLYNDRA

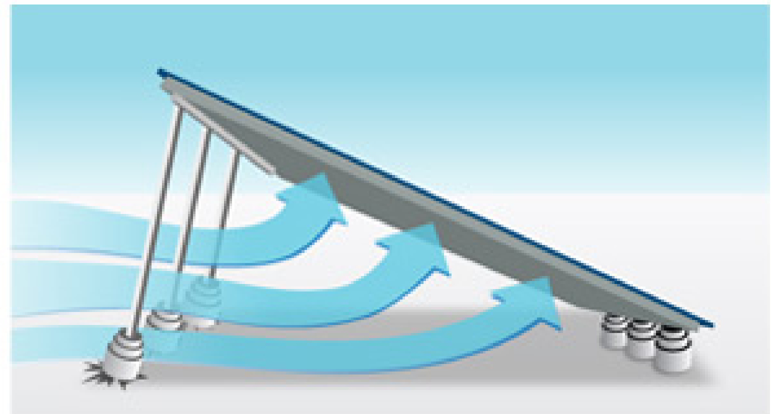
CONVENTIONAL

www.solyndra.com

Wind Performance



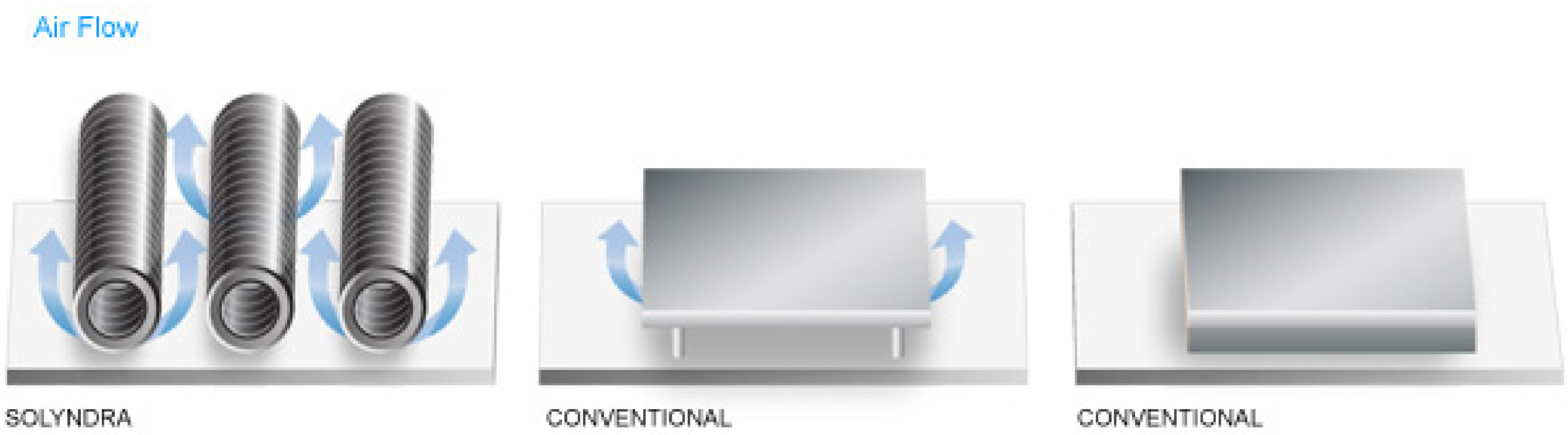
SOLYNDRA



CONVENTIONAL

www.solyndra.com

Ability to Avoid Heating



Please view the videos on their website to see the manufacturing and installation processes.

Read http://www.nanosolar.com/company/blog/tubular-pv for another view on this design.

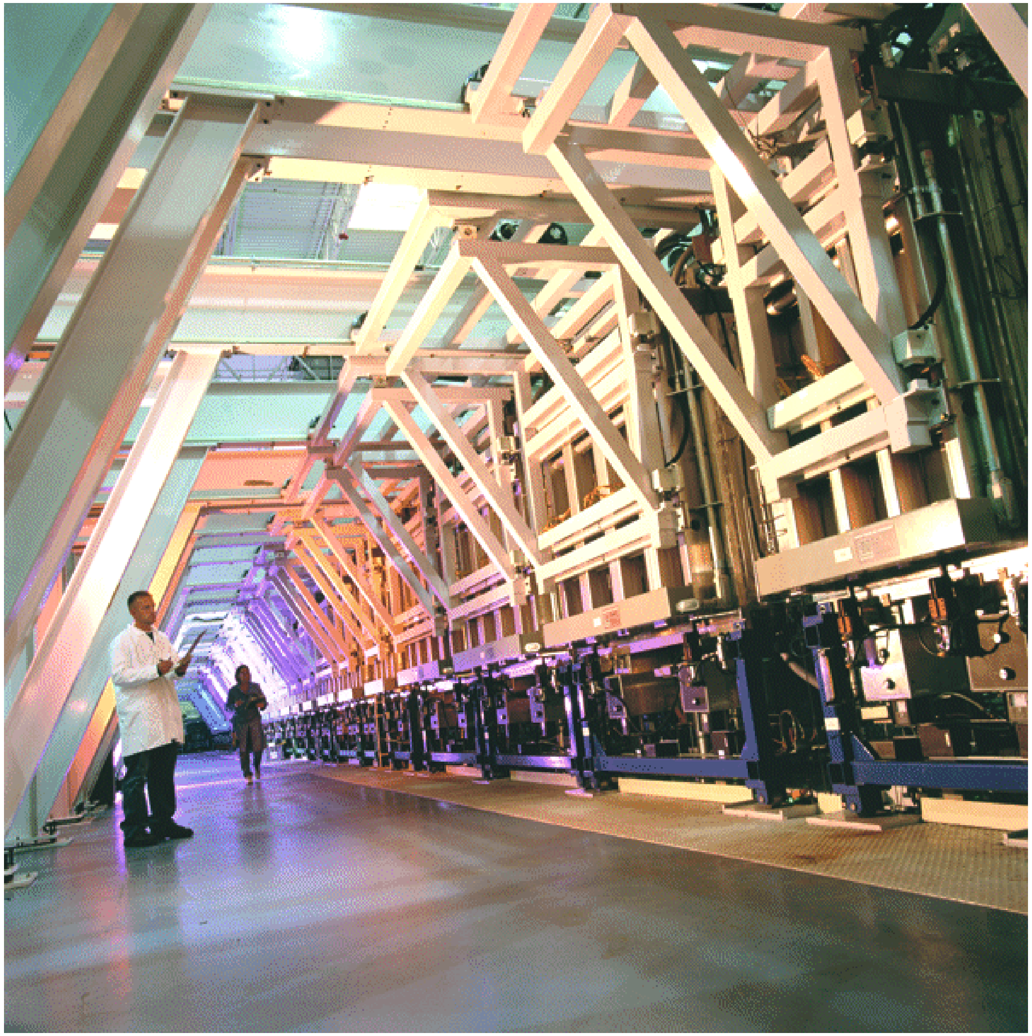
www.solyndra.com

Amorphous silicon (a-Si:H)

- No scarce elements are needed
- Efficiencies in the lab for multijunction cells are up to ~13%, but modules are only 5-9%
- 10-15 % degradation occurs

Recommended reading: Shah et al. "Thin Film Silicon Solar Cell Technology," *Progress in PV* 12 (2004) 113-142.

• a-Si is deposited by PECVD at 0.1 nm/sec
• It takes 50 min to deposit 0.3 mm.



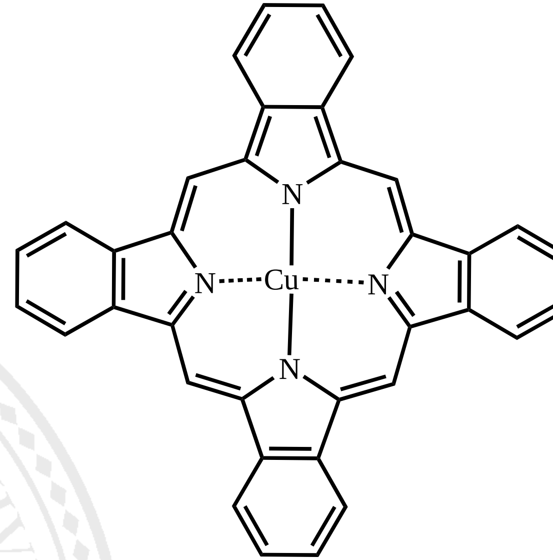
UNI-SOLAR
United Solar Systems Corp.

25MW pilot plant

5.7 m^2 a-Si panels dropped into place with a crane

- Large modules might be the key to reducing installation costs.
- Google “Applied Materials solar” to see videos of a solar farm being installed

Organic Semiconductors



CuPc
Copper Phthalocyanine

Attractive properties:

- •Abundant: ~100,000 tons/year
- •Mature industry/markets
- •Low materials cost: ~1$/g → 17¢/m^2
- •Low-cost manufacturing
- •Non-toxic

Large Scale Printing of Semiconductors!

Konarka

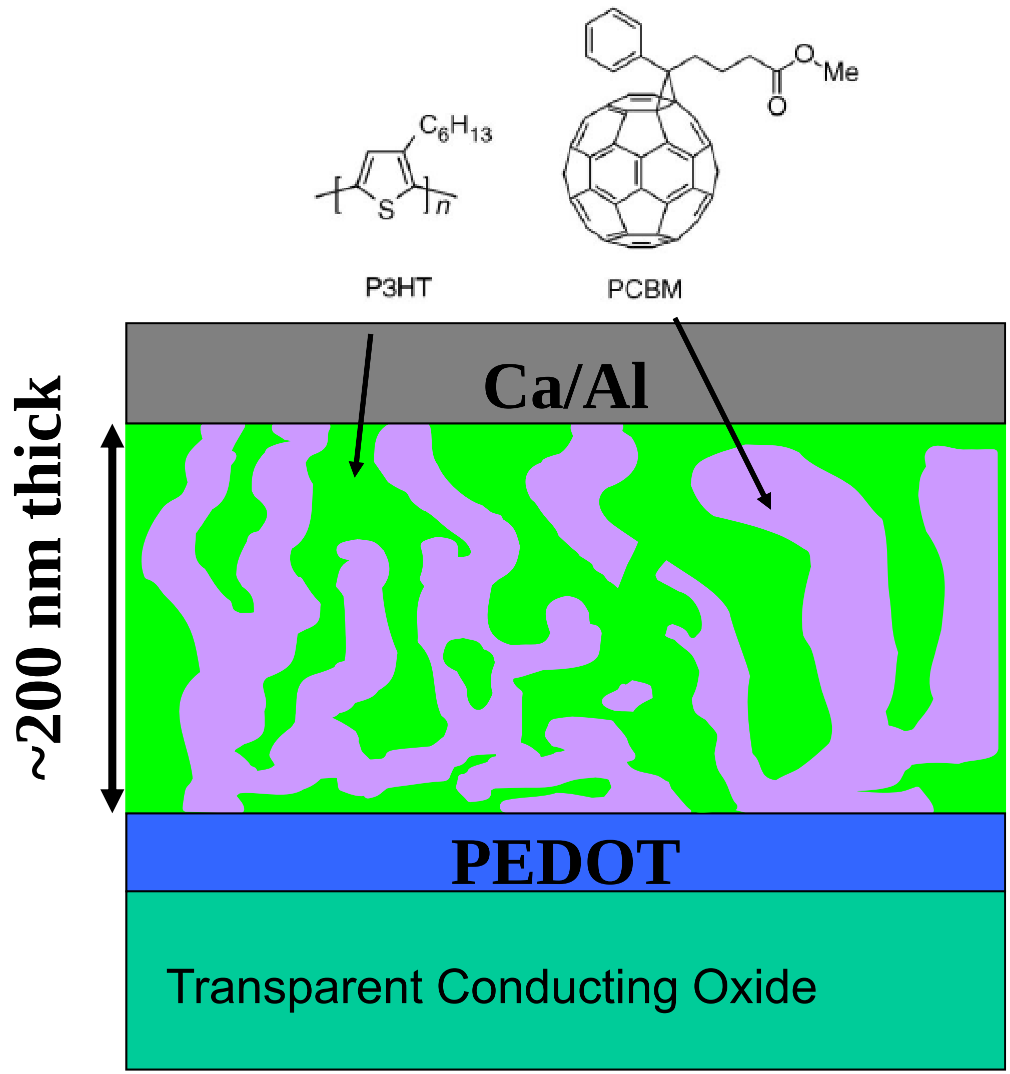
Polymer-Fullerene Bulk Heterojunction Cells

- Donor polymer (i.e. P3HT) absorbs light generating an exciton (i.e. bound electron hole pair).

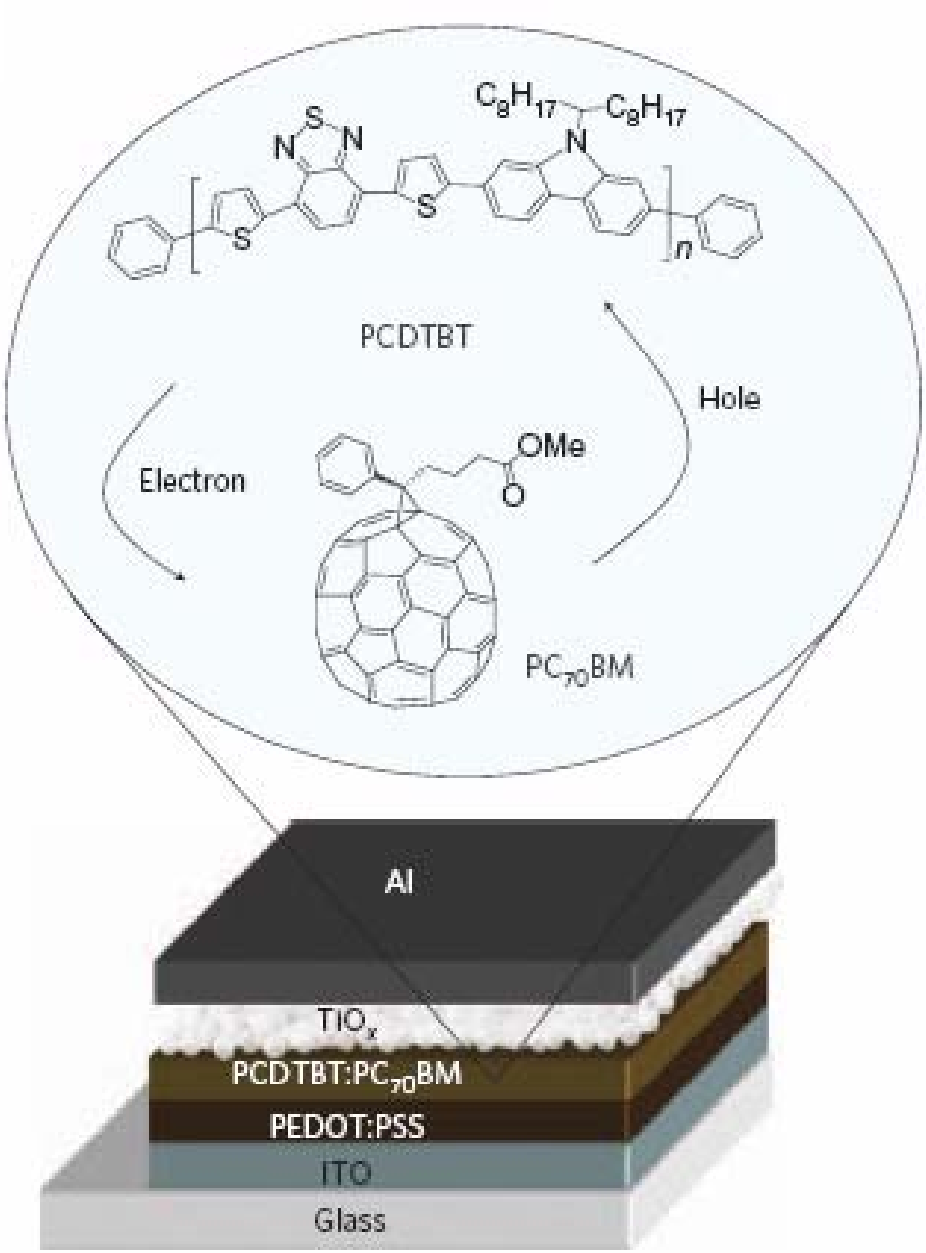
- Exciton must diffuse to the Donor/Acceptor (e.g. PCBM) interface to split.

- Electrons travel to the back electrode.

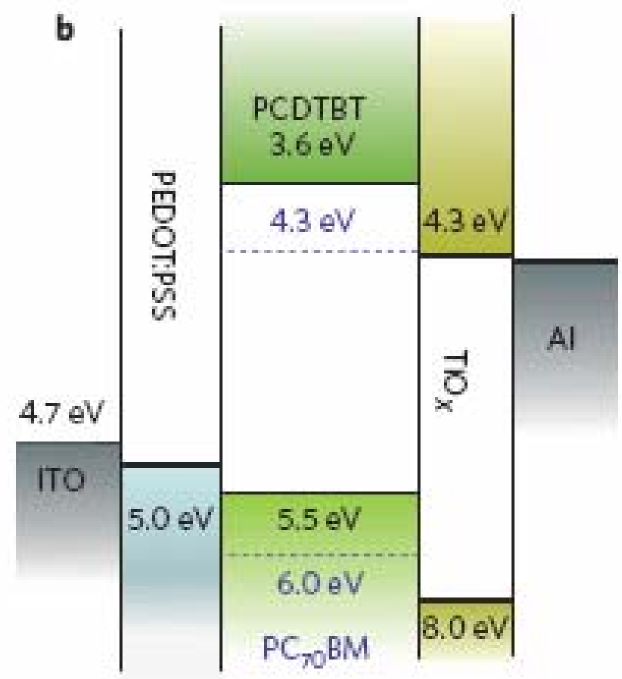
- Holes travel to the front electrode.



The world record cell in June 2009: 6.1 %

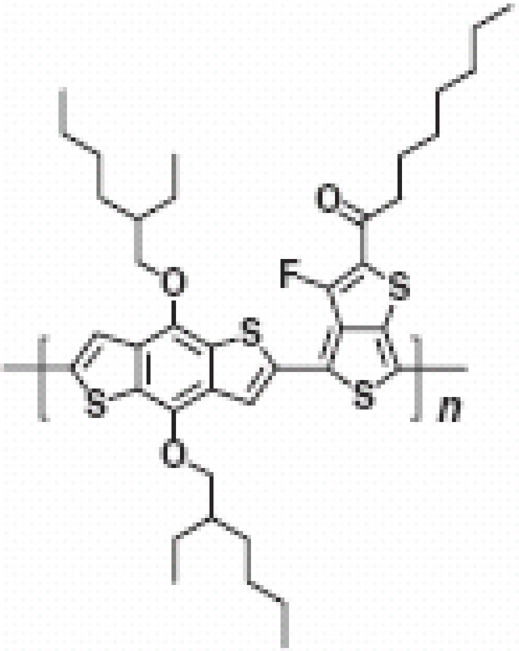


- Eg = 1.9 eV
- The LUMO-LUMO offset is 0.7 eV.

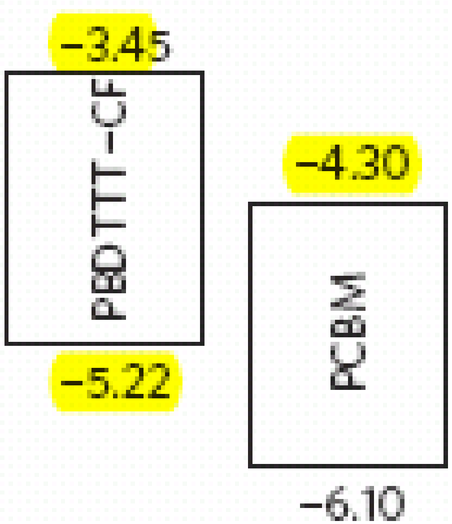


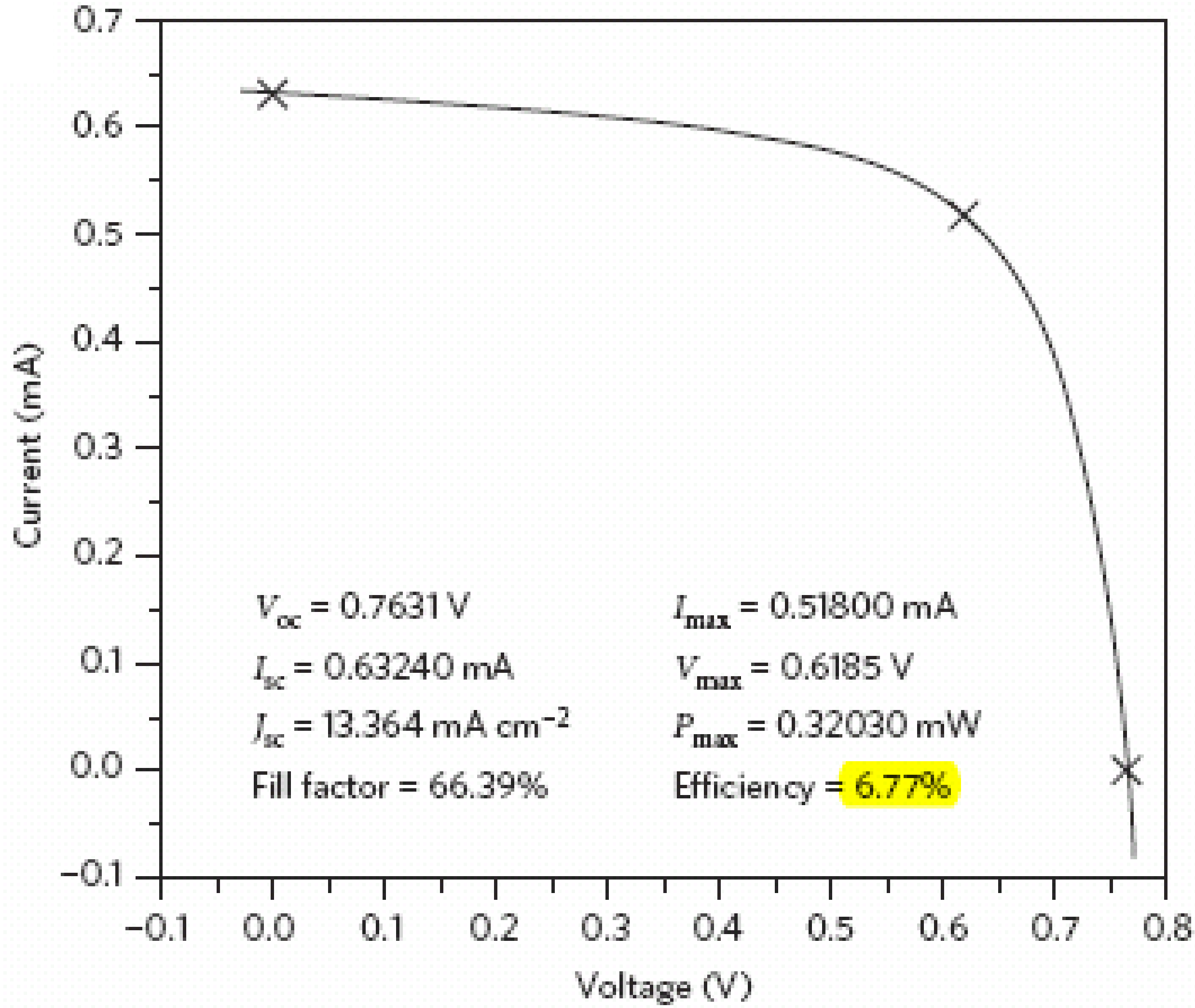
Heeger, LeClerc et al *Nature Photonics* 3 (2009) p. 297

November 2009: 6.77 %



PBDTTT–CF

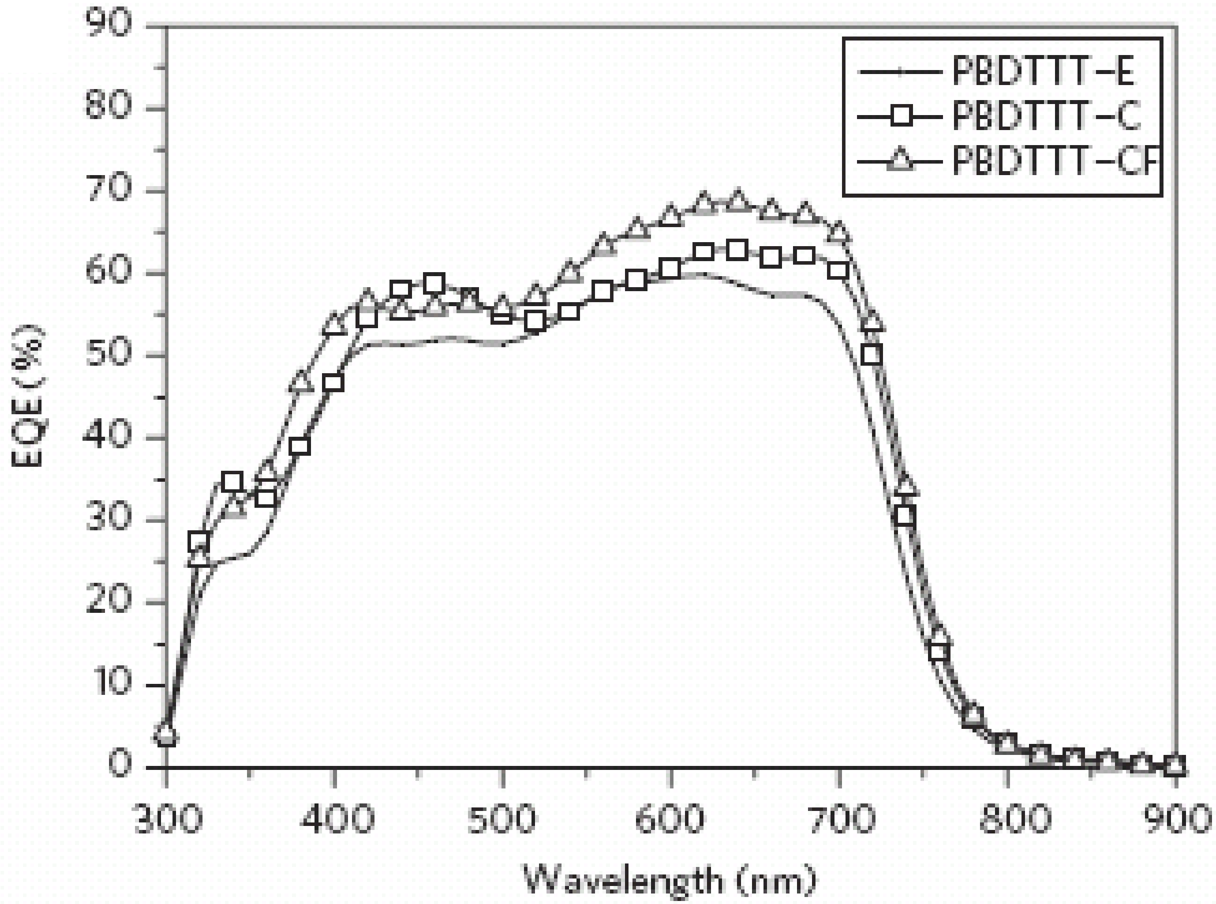




Yang Yang, Luping Yu et al
Nature Photonics, 3 (2009)
p. 649

Quantum Efficiency vs λ

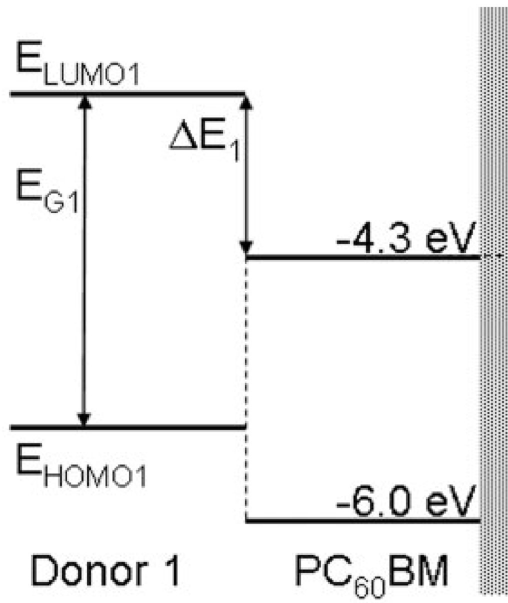
- Internal quantum efficiency is essentially 100 %.
- The active layer thickness for CF is 97 nm.
- ~ 1/3 of the light not absorbed.
- For CF, the polymer hole mobility is $7x10^{-4}$ cm^2/Vs.
- There are still opportunities for improvement!!



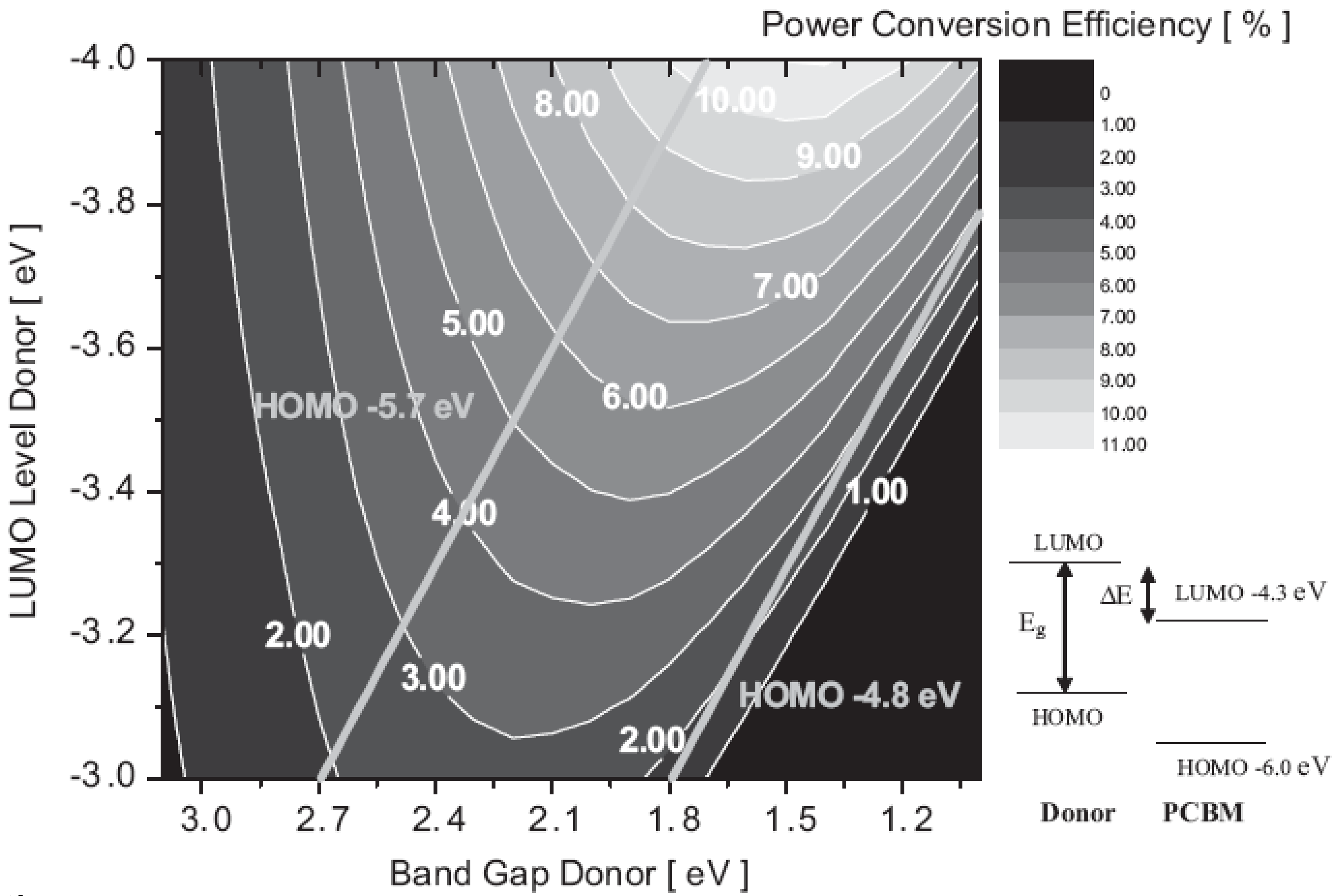
Yang Yang, Luping Yu et al *Nature Photonics*, 3 (2009) p. 649

How high can the efficiency be?

Need to optimize the band gap and LUMO-LUMO offset



How good can a **practical** single junction cell be?



Assumptions

EQE = **65 %** for photons with energy > Eg

FF = **0.65**

$$Voc = \frac{1}{e}\left(\left|E_{HOMO}^{Donor}\right| - \left|E_{LUMO}^{PCBM}\right|\right) - 0.3$$

Scharber, Brabec et al. *Advanced Materials* 18 (2006) 789.

How good can a practical double junction cell be?

Assumptions

• Two cells are stacked in series. The total current is given by that of the subcell with the lower current.

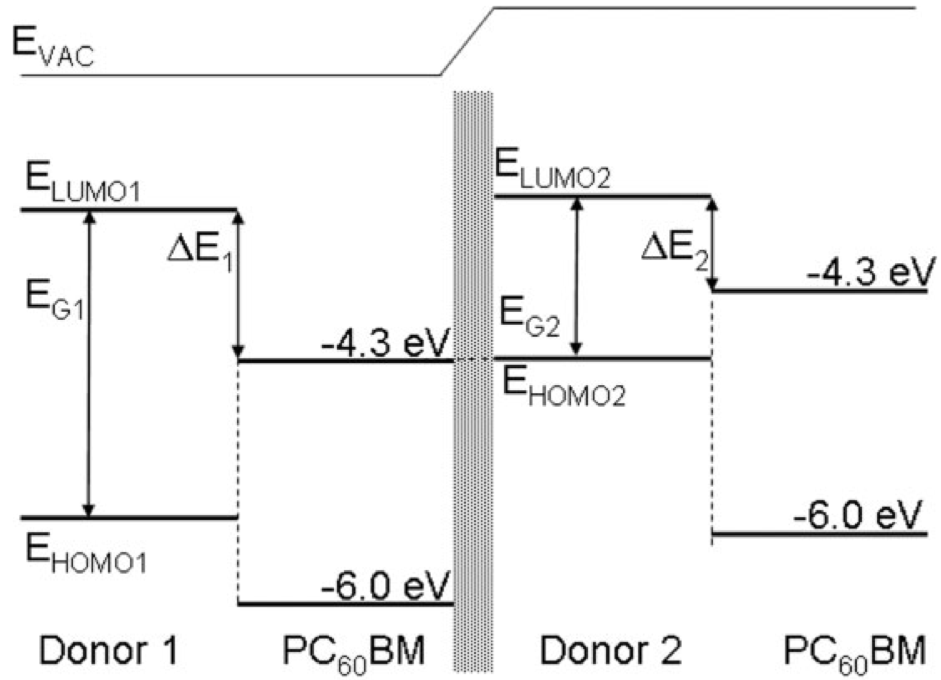
• Fill Factor = 0.65.

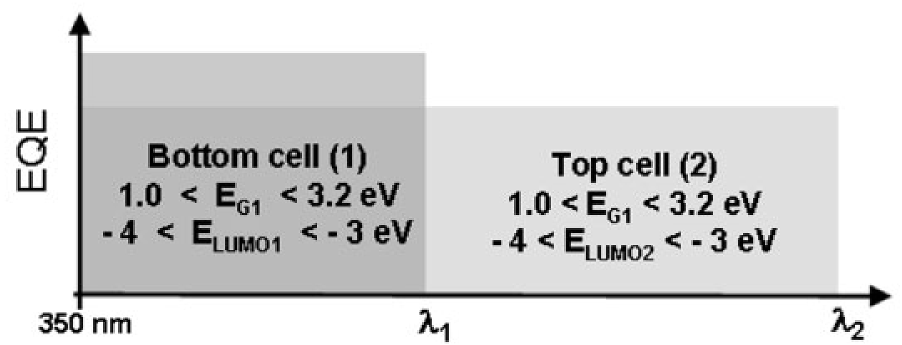
• EQE is approximately 85 % (see the paper for details)

•The acceptor is PCBM

• The Donor LUMO is at -4.0 eV

$$Voc = \frac{1}{e}\left(\left|E^{Donor}_{HOMO}\right| - \left|E^{PCBM}_{LUMO}\right|\right) - 0.3$$

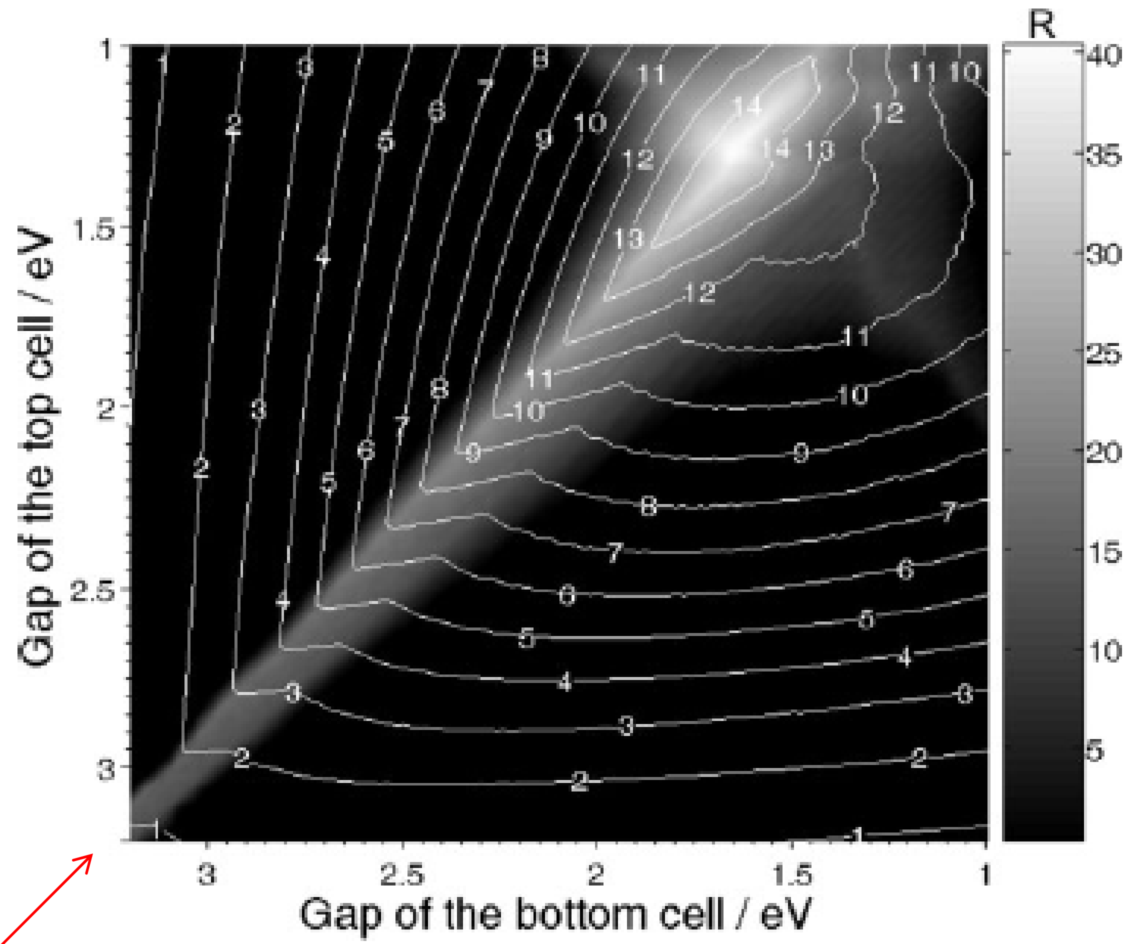




Dennler, Brabec et al. *Advanced Materials* 20 (2008) 579.

Efficiency of double junction cells from previous slide

The two band gaps should be 1.3 and 1.7 eV.

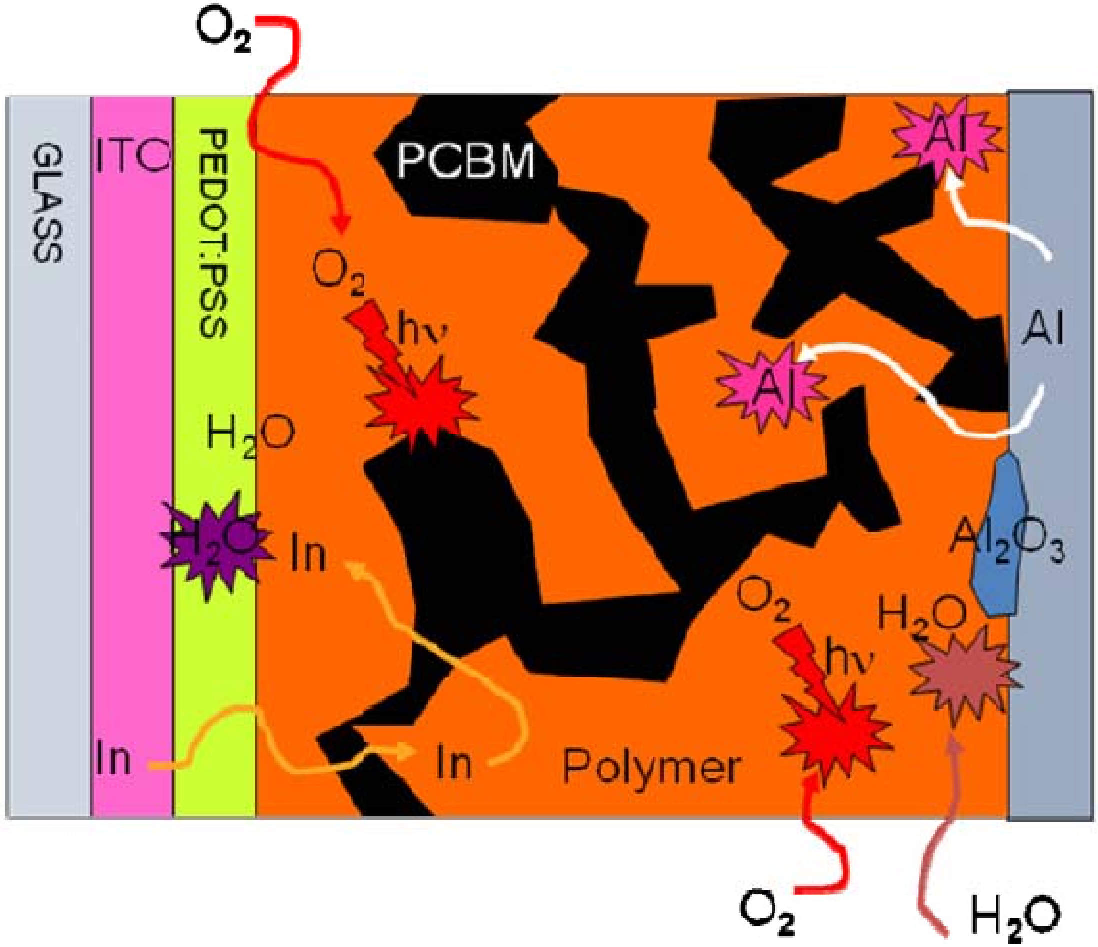


The current is matched along this diagonal.

Dennler, Brabec et al. *Advanced Materials* 20 (2008) 579.

Reliability

- Encapsulation will be needed.
- A UV filter will probably be needed.
- Many molecules are very stable in light.

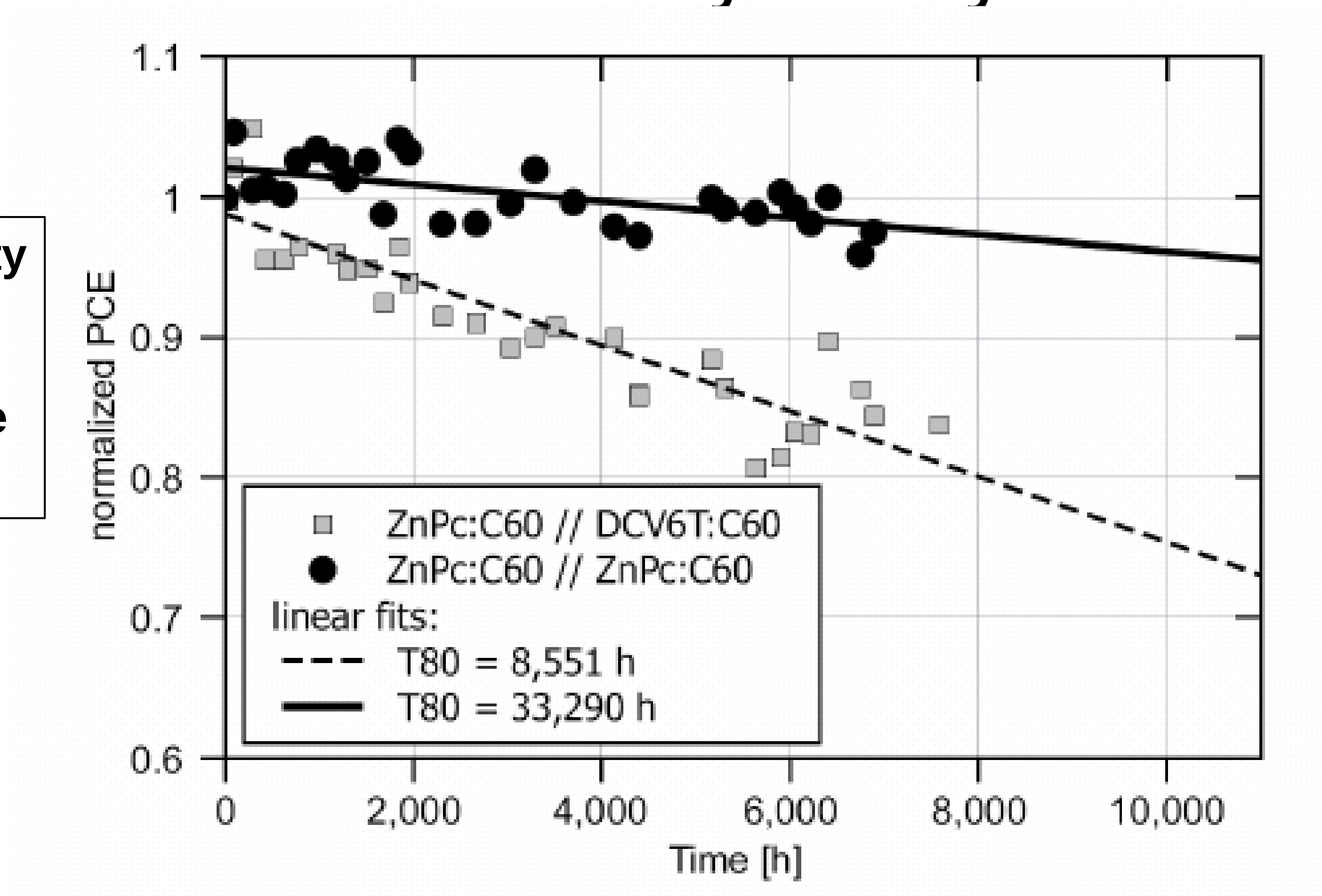


F.C. Krebs, et al., Solar Energy Materials (2008)

Heliatek Reliability Study

Light intensity
2.2 suns

Temperature
48 °C



(33,290 hrs)(2.2)= 73,000 hrs or **8.4 years continuous use**

At 5 hrs/day of peak sunlight, the **lifetime is 40 years**.

G. Schwartz et al., *Proc. of SPIE*, 7416 (2009)p. 74160K-1

Important OPV papers of the last year

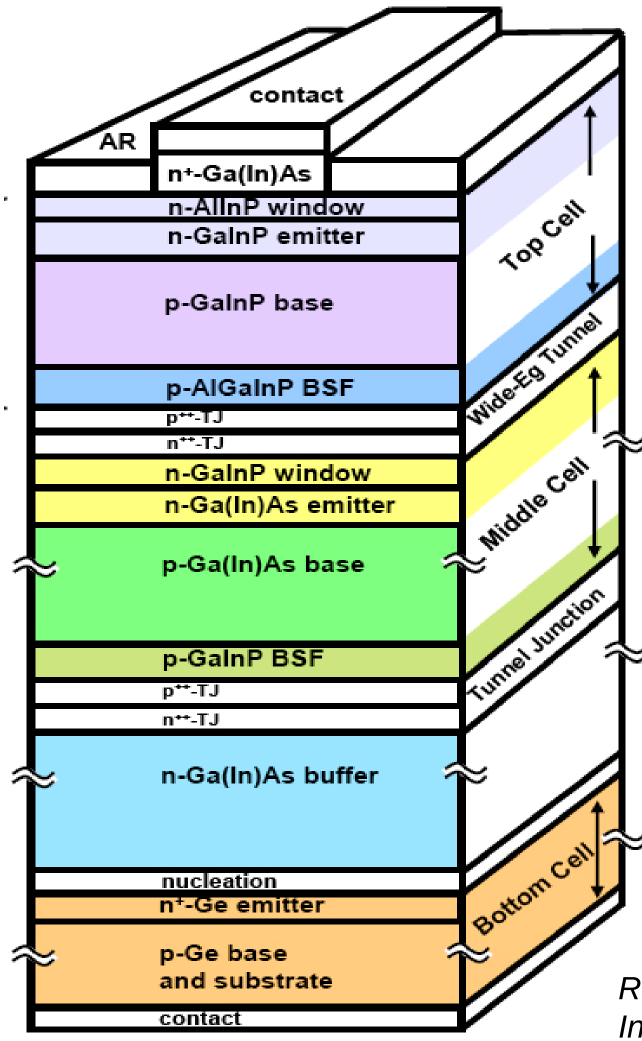
- Dennler, Scharber, Brabec, *Adv. Mater.* 21 (2009) 1.
- AJ Moule and K. Meerholz, *Adv. Mater.* 20 (2008) 240.
- Heeger, LeClerc et al *Nature Photonics* 3 (2009) p. 297.
- Alex Mayer et al. *Advanced Functional Materials* 19, 1 (2009).
- Yang Yang, Luping Yu et al *Nature Photonics*, 3 (2009) p. 649.
- Brabec et al. *Energy and Env. Sci.* 2 (2009) p. 347-363.
- G. Schwartz et al., *Proc. of SPIE*, 7416 (2009) p. 74160K-1.
- B.E. Hardin, M. Grätzel, M.D. McGehee, J Frechet et al.
Nature Photonics 3 (2009) p. 406.

Schematic of Multijunction Cell

$Ga_{0.50}In_{0.50}P$: Top Cell

$Ga_{0.99}In_{0.01}As$: Middle Cell

Ge substrate: Bottom Cell



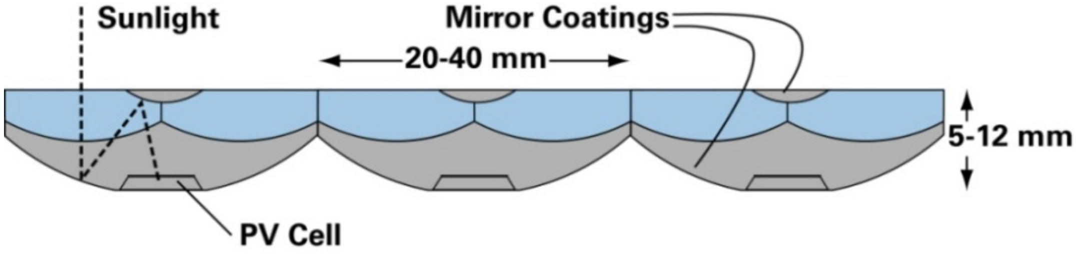
- World record efficiency: 41.6 %
- 37 % cells can be purchased for $50,000/m^2$
- These complex structures are grown very slowly under high vacuum

R.R. King; Spectrolab Inc., AVS 54th International Symposium, Seattle 2007

Concentrating Light

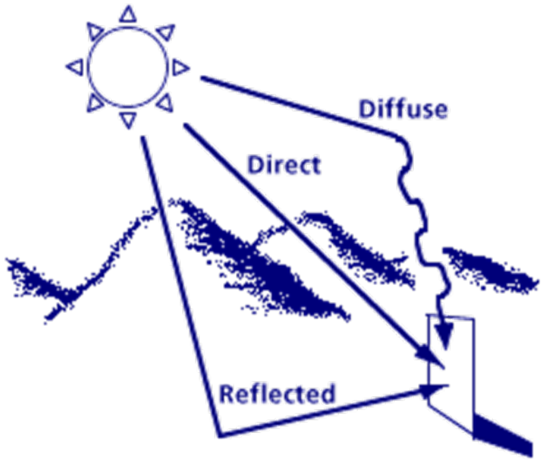
It is possible to track the sun and concentrate the light by 500X

Dish Shape



Sol Focus

Concentration only makes sense in sunny places



Concentration is only effective for direct sunlight

1 sun = 1 kW/m²	Yearly Average Solar Radiation Resource [kWh/day-m²]	
	Seattle	Albuquerque
Fixed flat panel PV @ Lat.	3.7	6.4
2-axis flat panel PV	4.9	8.8
2-axis Conc. PV	2.9	6.7

Source: NREL Solar Radiation Data Manual

Cost Estimate

• The cost of multijunction solar cells is approximately \$50,000/m^2 (\$5/cm^2). 500X concentration reduces this to \$100/m^2.

• Let's say the tracker and concentration cost \$200/m^2.

• The sun gives us 1000 W/m^2, but this is reduced to 850 W/m^2 direct sunlight.

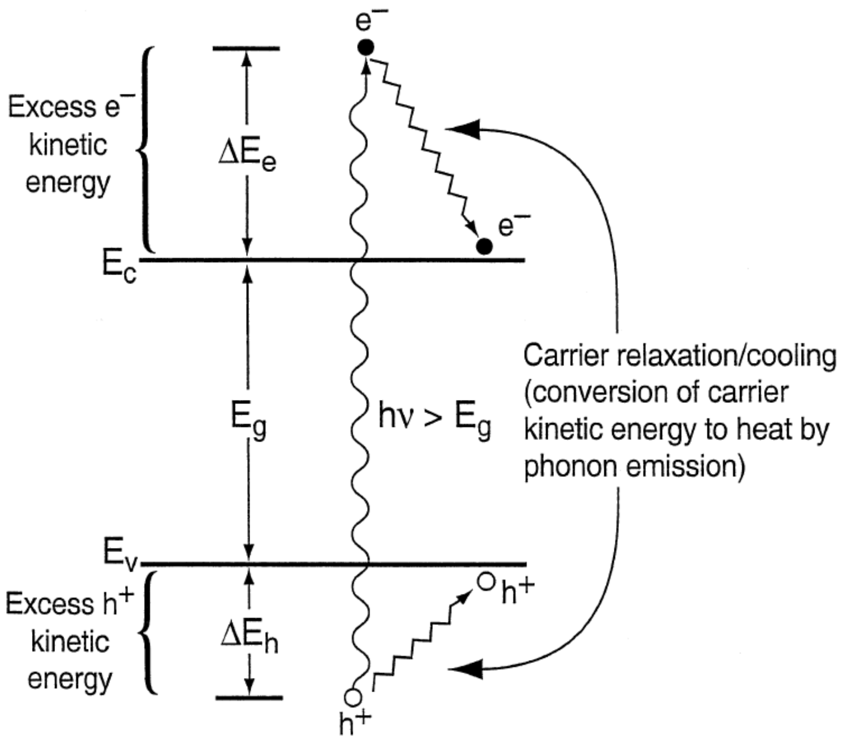
• The best commercially available cells are 37% efficient at 25°C, but this decreases to 30% at typical operating temperatures. If the optical system is 75% efficient, then we are at $0.30 \times 0.75 \times 850 \approx 200$ W/m^2 of electrical power.

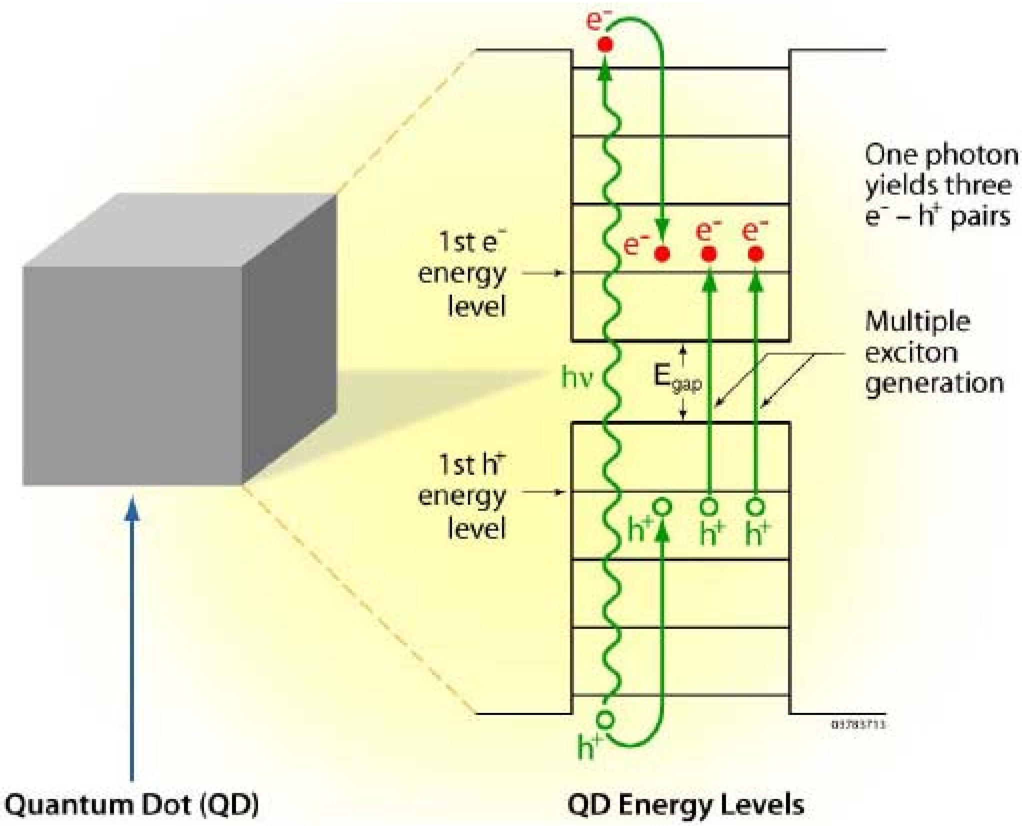
• At \$200/m^2 the capital cost would be \$1.50/W.

Although this calculation is wildly optimistic, it represents the hopes and dreams of CPV advocates.

Steve Eglash

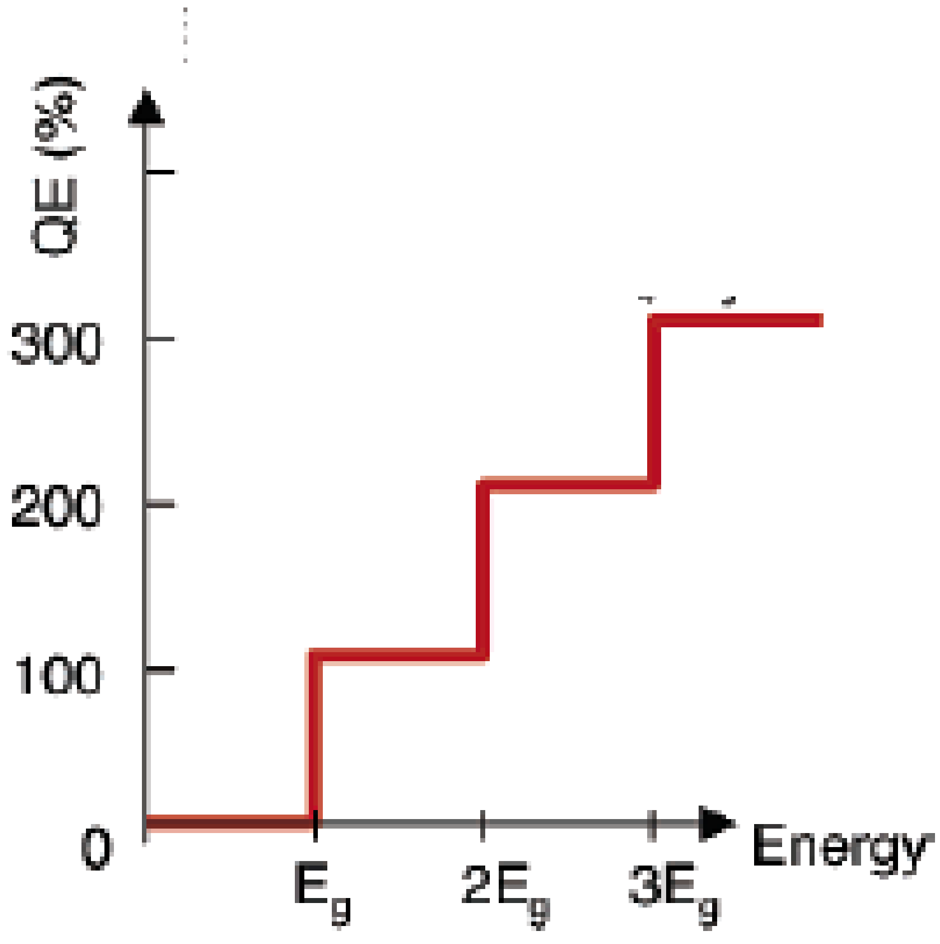
Multiple Exciton Generation in nanocrystals



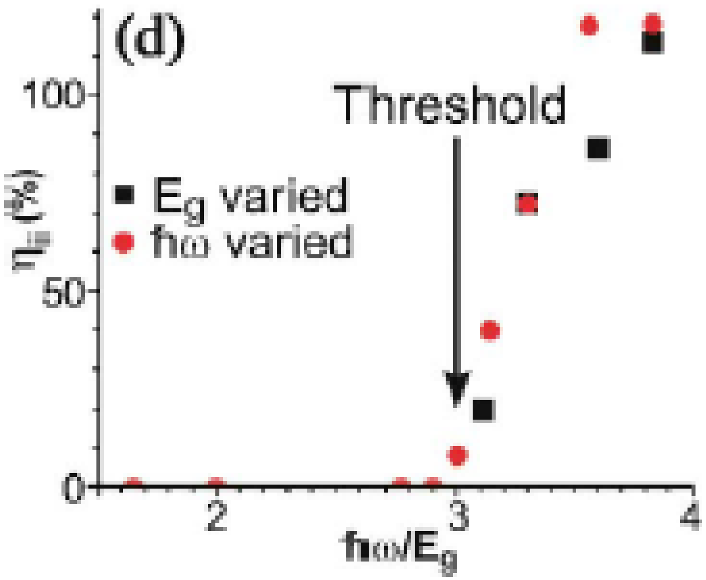


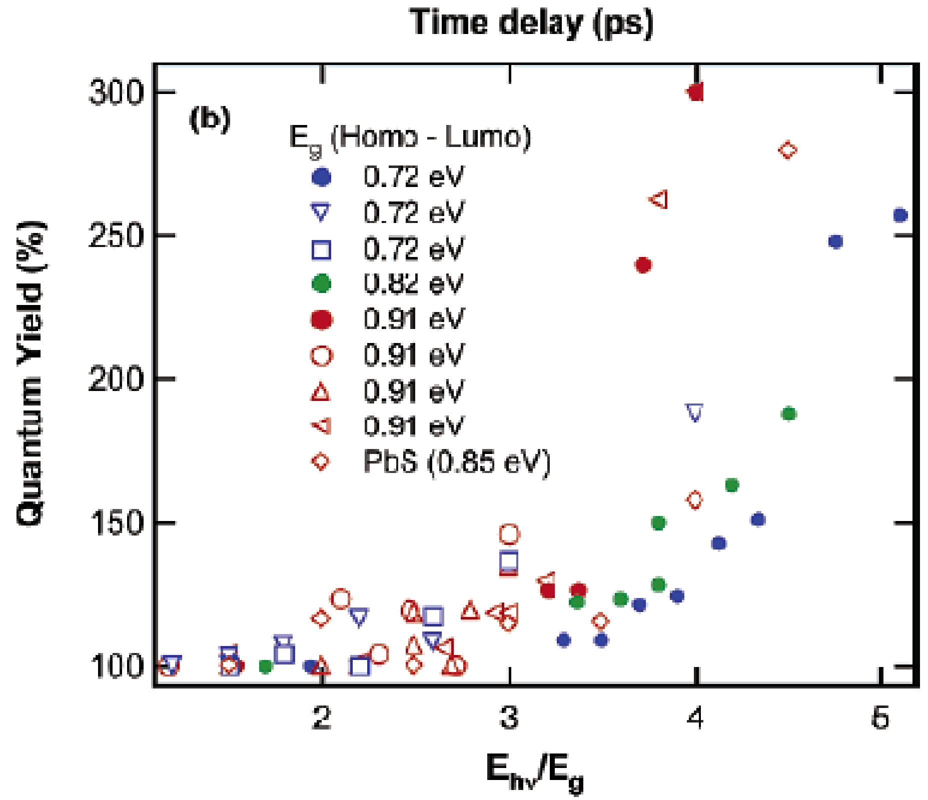
R. D. Schaller, V. I. Klimov, Physical Review Letters, 2004, Vol. 92.

The quantum efficiency profile we want



MEG has been observed



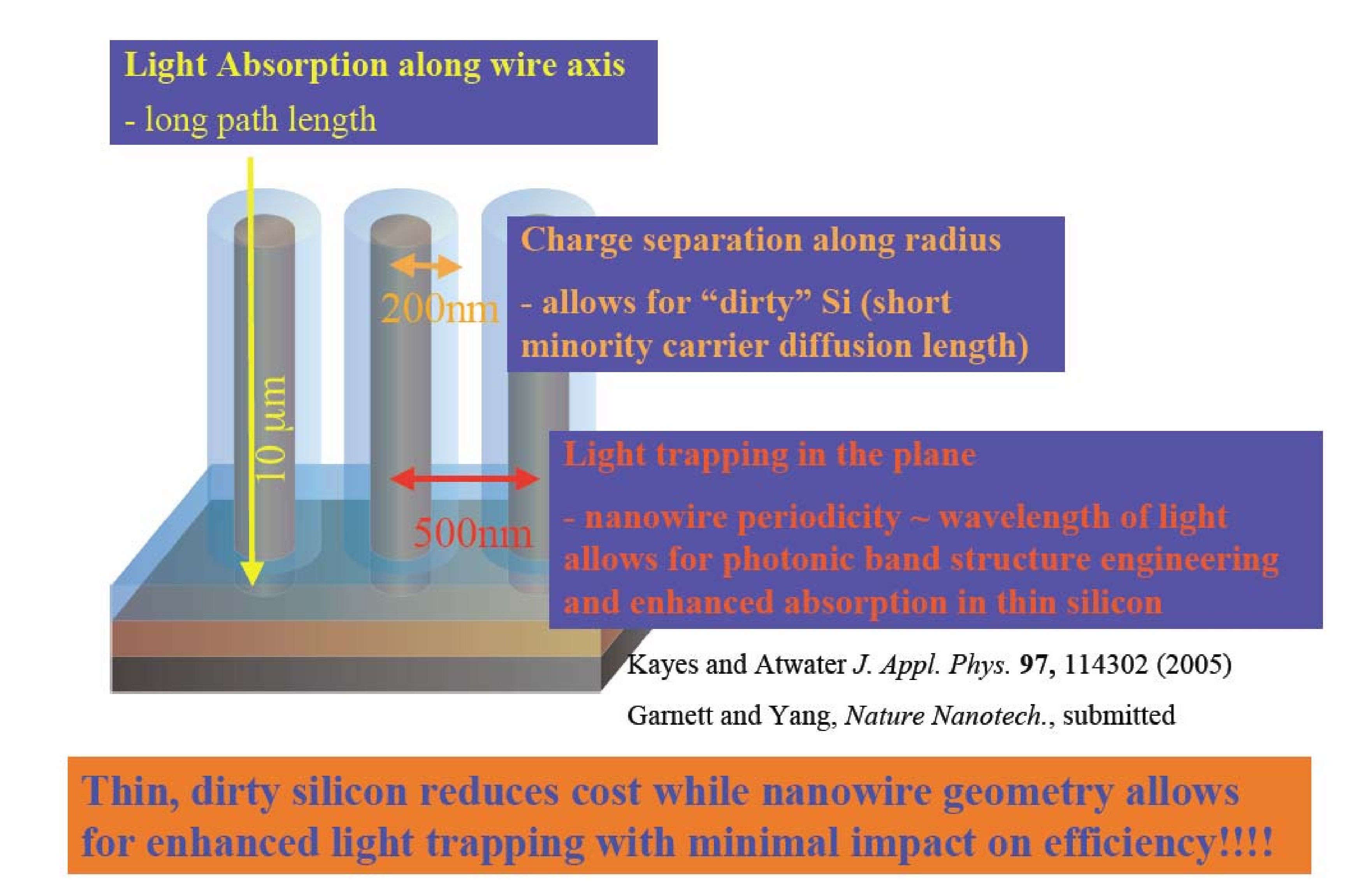


Shaller and Klimov, Phys. Rev. Lett. 92 (2004) p. 186601

Art Nozik et al., *Nanoletters* **5** (2005) p. 865.

No decent solar cells have been made.

Advantages of Nanowires



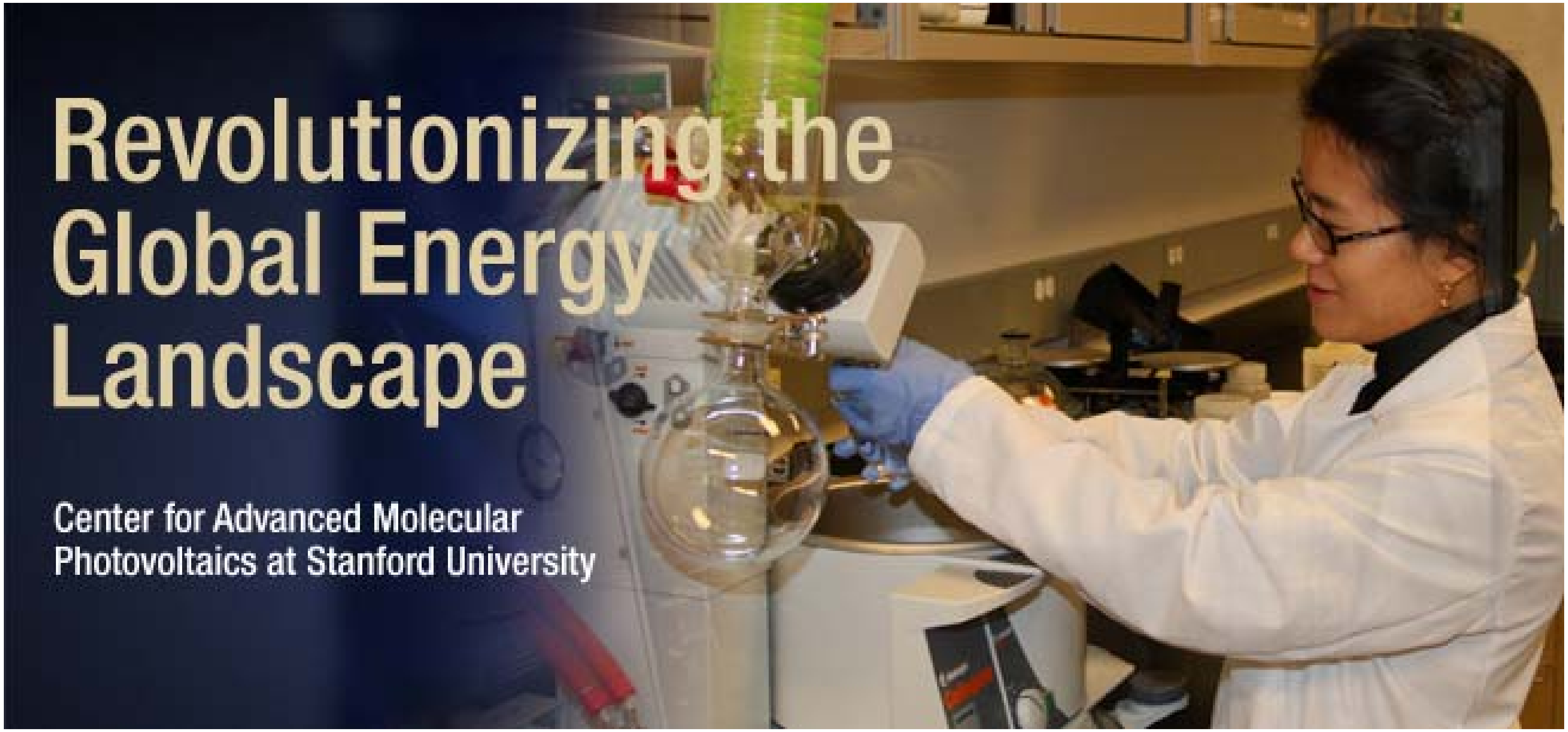
6.4 % efficient cells have been made.

Review article on solar cells

David Ginley, Martin Green, Reuben Collins, “Solar Energy Conversion Toward 1 Terawatt,” MRS Bulletin, 33 (April 2008) p. 355.

That whole MRS Bulletin is devoted to energy.

How can you get involved?



Organic and Dye Sensitized Solar
12 professors work with the Center for Advanced Molecular Photovoltaics
See http://camp.stanford.edu/

Reliability/Degradation
Dauskardt, McGehee (MSE)

Solar Research at Stanford

Inorganic Thin Film

- CIGS and CZTS: Bent (MSE)and Clemens (MSE)
- a-Si: Cui (MSE)
- polycrystalline Si: Clemens and Salleo (MSE)

Nanowires

- Cui (MSE), Brongersma (MSE), McGehee (MSE), Nishi (EE), McIntyre (MSE), Harris (EE), Philip Wong (EE), Zheng (ME)

Multiple Exciton Generation

- Prinz (ME), Gaffney (SLAC)

Photon Enhanced Thermionic Emission

- Melosh (MSE), Shen (AP) See GCEP website

Solar Thermal

- Peumans and Fan

Advanced Optics

- Brongersma (MSE), Fan (EE) and Peumans (EE)
- Arriving in Spring: Jen Dionne (MSE)

Courses

MATSCI 156/256: Solar Cells, Fuel Cells, and Batteries: Materials for the Energy Solution (Prof. Bruce Clemens, Autumn)

MATSCI 302: Solar Cells (Prof. Mike McGehee, Autumn)

EE ? (Prof. Peter Peumans, Winter)

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Annie Hazlehurst (Stanford GSB)

Steve Eglash

The Center for Advanced Molecular Photovoltaics (CAMP)

KAUST

King Abdullah University of Science and Technology

Director: Mike McGehee
Executive Director: Alan Sellinger
Deputy Director: Peter Peumans

KAUST August 2007

KAUST September 2009

Truly amazing things can be done when many people work towards a common goal.