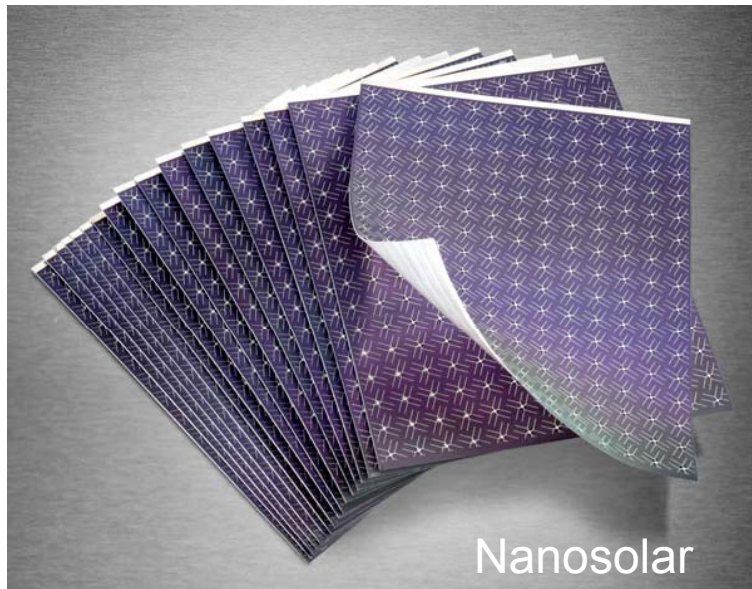


An Overview of Solar Cell Technology

Mike McGehee
Materials Science and Engineering
Global Climate and Energy Project
Center for Advanced Molecular Photovoltaics
Precourt Institute
Stanford University



John Benner provided the slides with the NREL logo.

Primary Photovoltaic (PV) Markets

Residential Rooftop



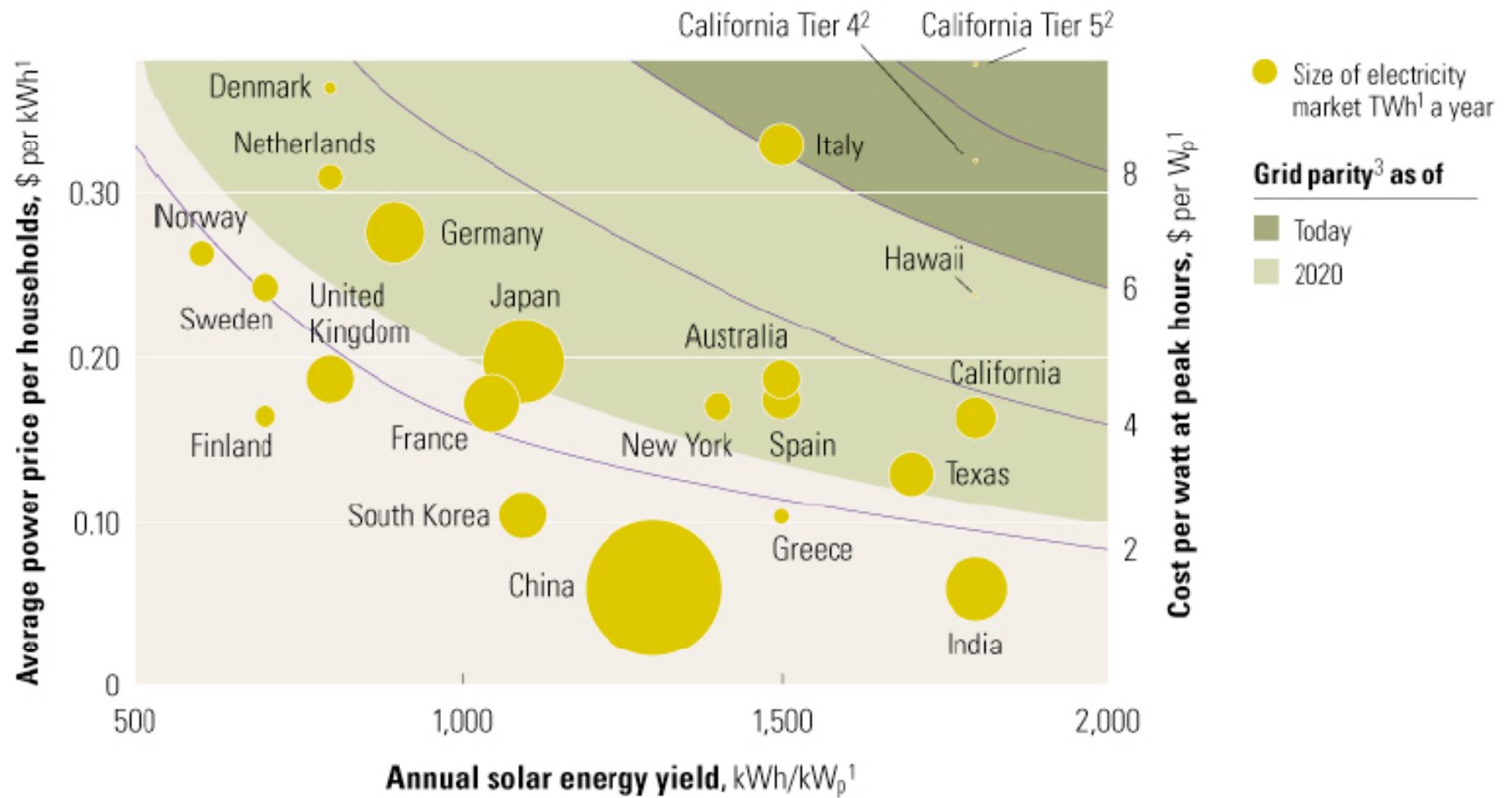
Commercial Rooftop



Ground-mounted
(Usually utility scale)

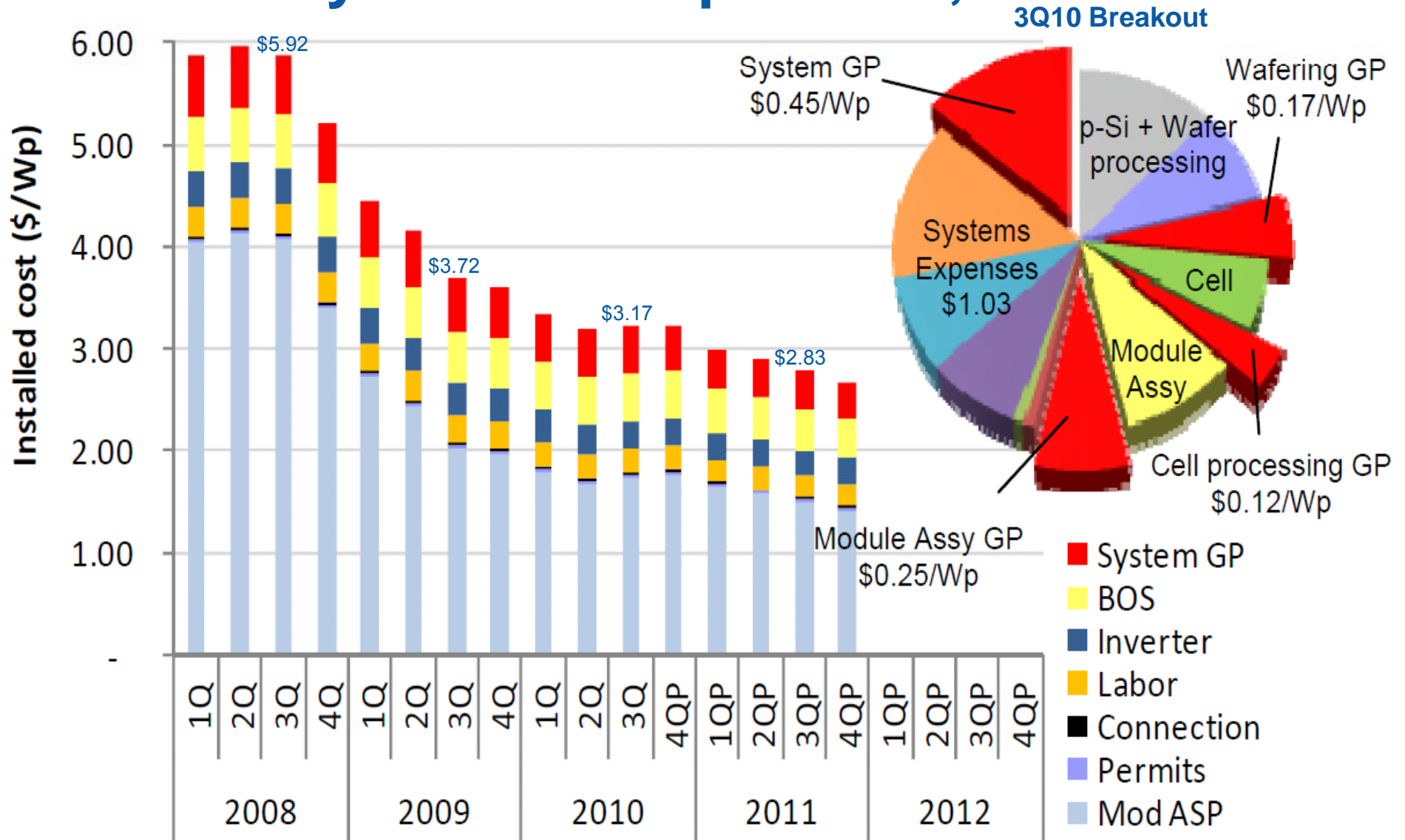


How cheap does PV need to be to compete w/ coal?



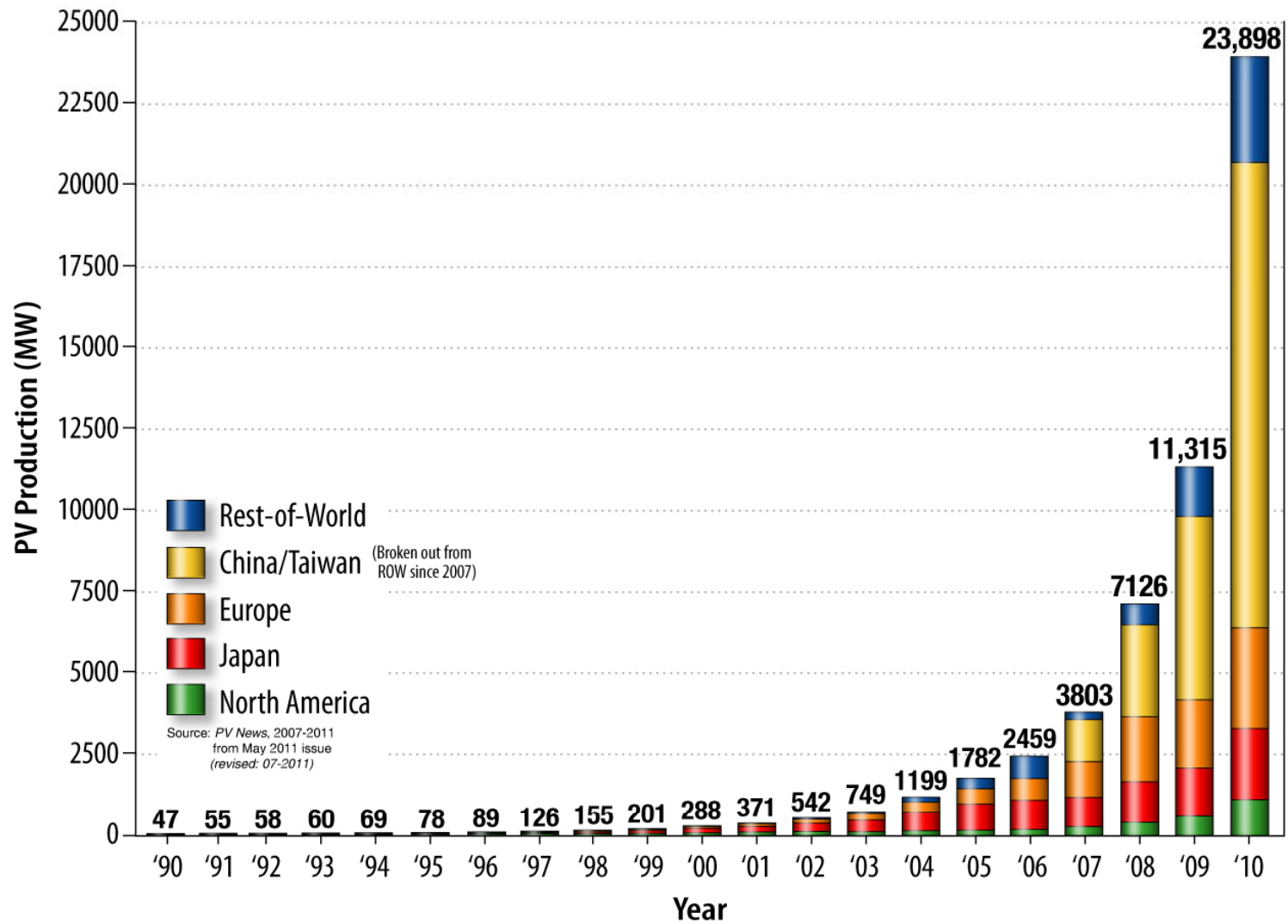
Source: CIA country files; European Photovoltaic Policy Group; Eurostat; Pacific Gas & Electric (PG&E); Public Policy Institute of New York State; McKinsey Global Institute analysis

Installed System Price per Watt, 2008-2011



Original Source: Deutsche Bank, January 2011; Systems are global (i.e., blended across geographies)
 My source: R. Swanson, IEEE PV Specialists Conf., June 2011

PV is a booming industry, especially in China



But not everyone prospered in 2011



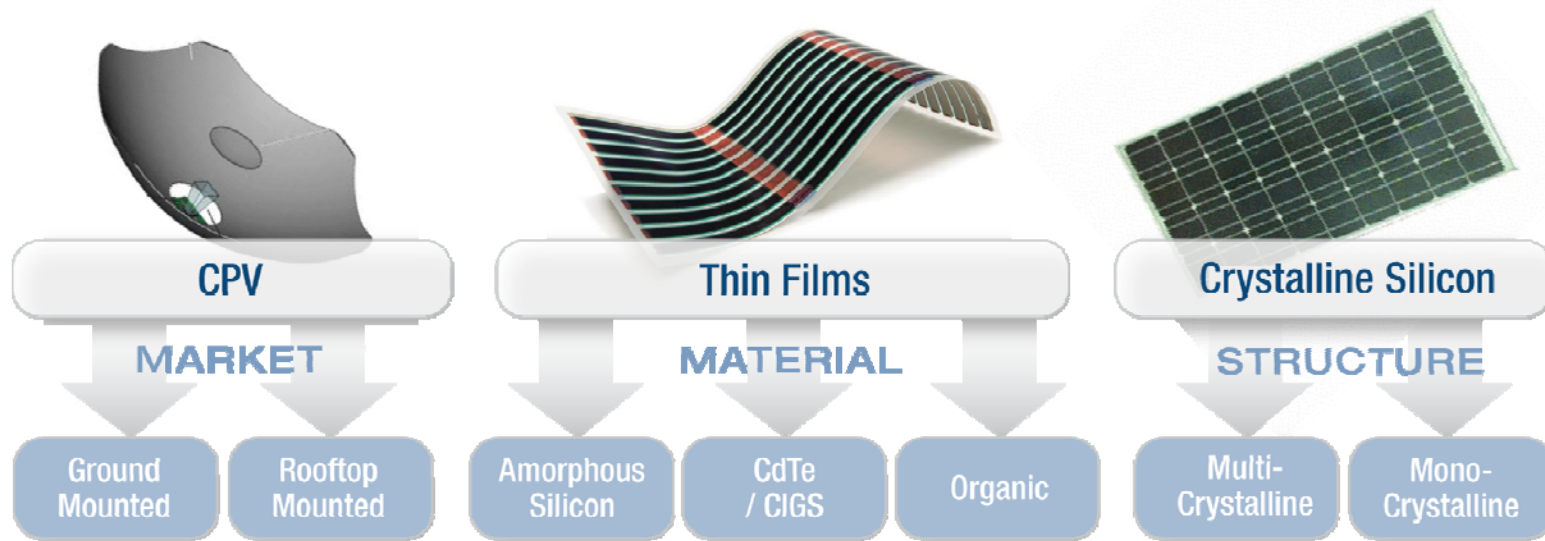
Solyndra, SpectraWatt and Evergreen Solar went bankrupt.

Jon Stewart, The Daily Show

What makes the PV industry so interesting?

- PV addresses the energy problem, which many passionately want to solve.
- By 2050 the world will need ~ 30 TW of power.
- Some think PV could provide 20 % of that. It takes a panel rated at 5 W, to average 1 W of power through the day and year, so we would need 30 TW of PV capacity.
- At \$1/W, the industry would take in \$30 trillion.
- The industry is now well over \$40 B/yr.

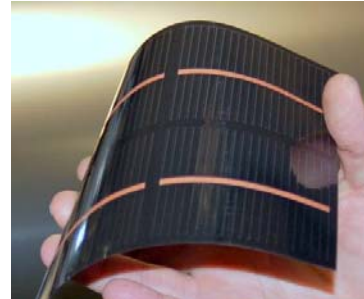
There are many approaches to making PV cells and experts do not agree on which one is the best



20x-100x



500x

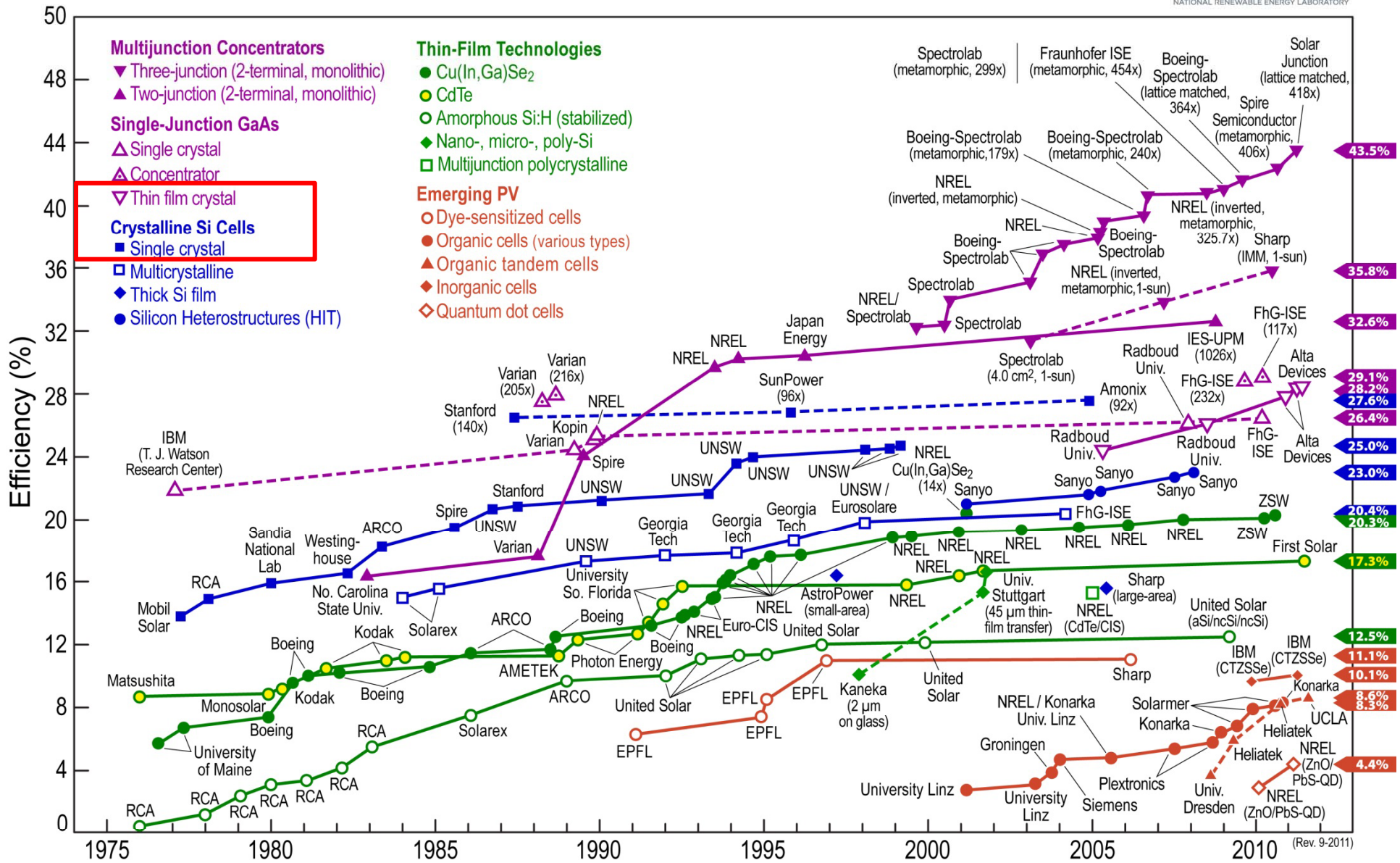


$\text{Cu(In,Ga)Se}_2 \sim 1\text{-}2 \mu\text{m}$



c-Si $\sim 180 \mu\text{m}$

Best Research-Cell Efficiencies

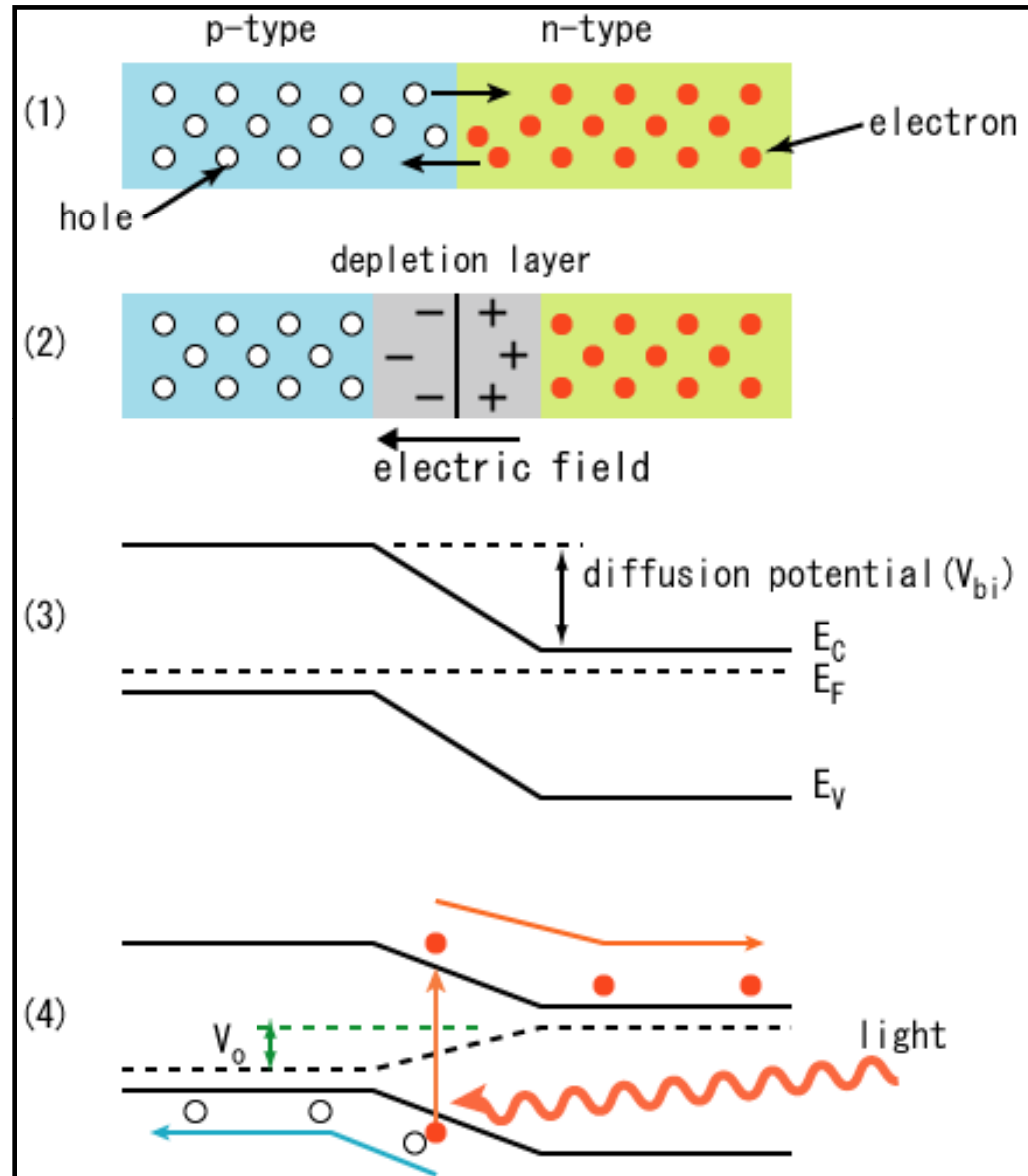


Lots of records in 2011!

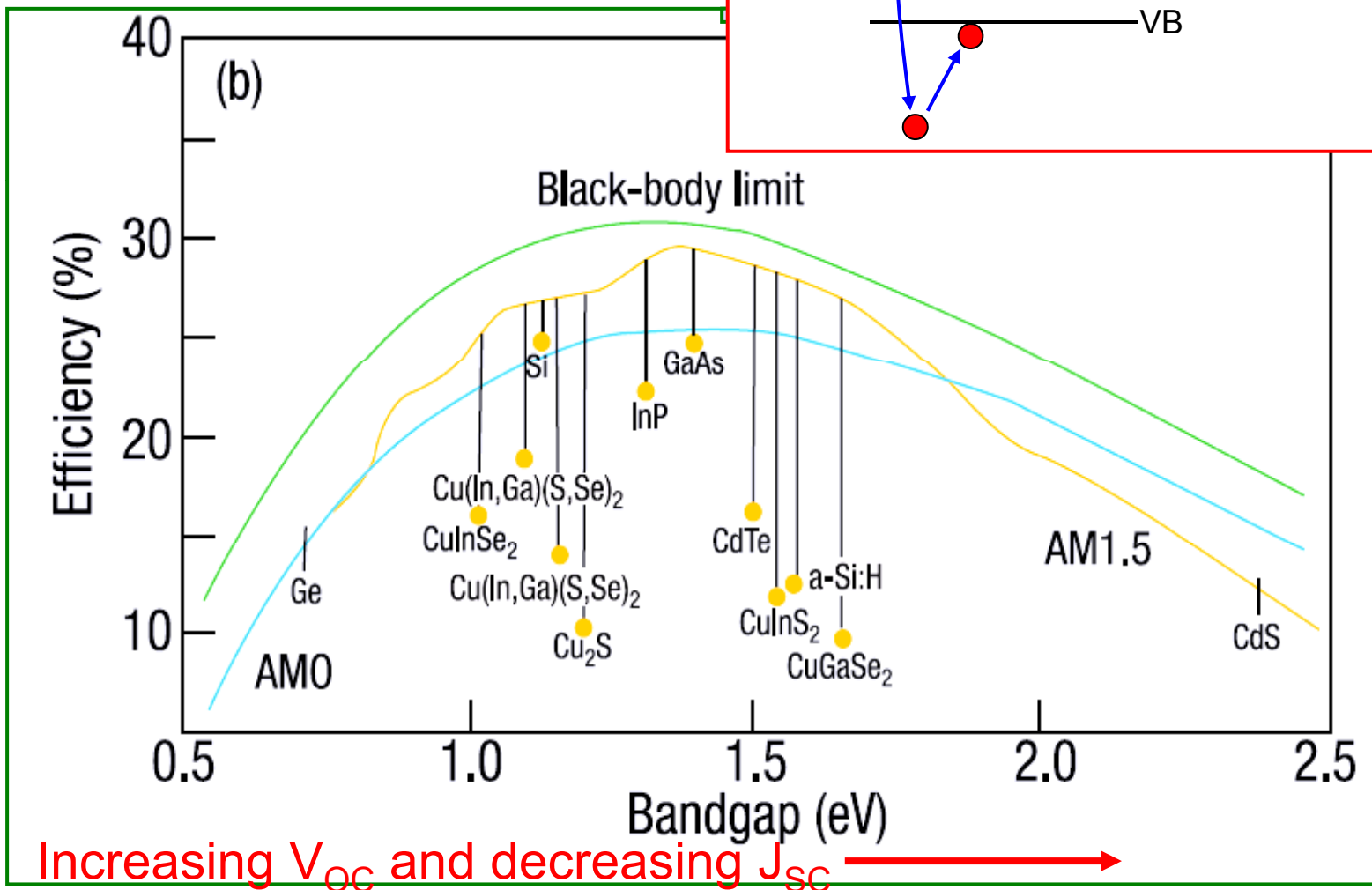
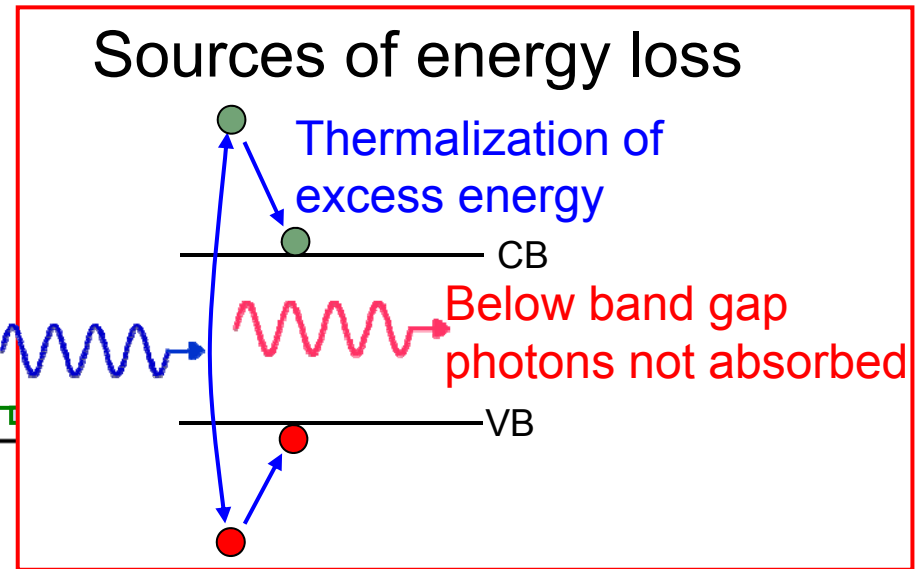
More factors that make the plot interesting

- The overall global economy has been turbulent for a few years.
- Government policies are constantly changing.
- When an industry based on manufacturing grows faster than 40 %/year in spurts, it is hard for the supply chain to always provide what is needed.

Conventional p-n junction photovoltaic (solar) cell



Efficiency limits

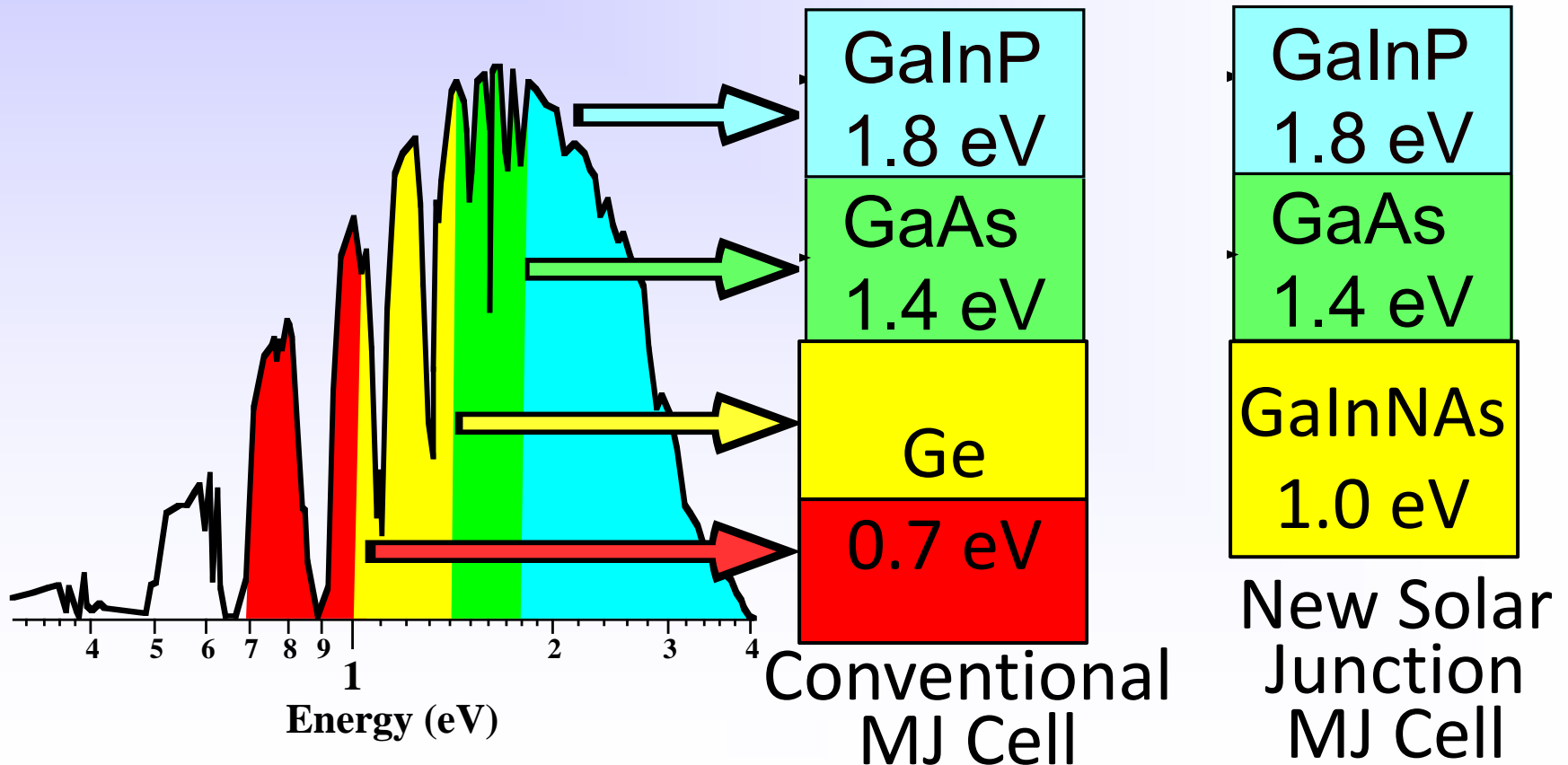


Multijunctions: The Road to Higher Efficiencies



Higher-efficiency MJ cells require new materials that divide the solar spectrum equally to provide current match

Ge provides lattice match but the bandgap is too small



Solar Junction World Record

World's most efficient solar cell ever produced:
43.5%
 at
 418-655 suns

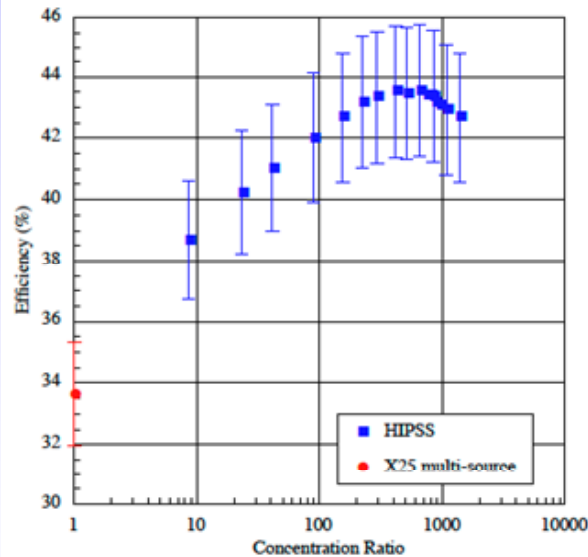


PV Cell & Module Performance Group

Efficiency vs. Concentration Ratio

Solar Junction
 April 1, 2011

HIPSS Data
 Temperature: 25°C



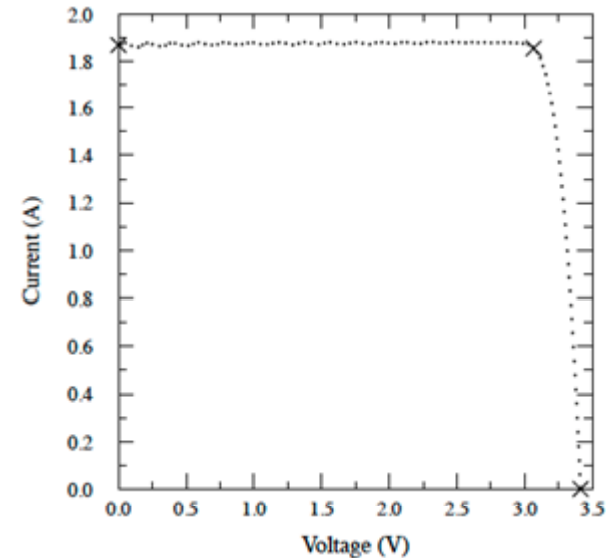
Area: 0.3124 cm²
 Spectrum: ASTM G173 Direct
 HIPSS PFN trigger settings: 250.3 & 376.0
 HIPSS error bars are ±5% of value
 Concentration = HIPSS I_{sc} / X25 1-sun I_{sc}

Solar Junction

Wed, Mar 16, 2011 11:28 AM
 ASTM G173 Direct

Device Temperature = 25.0°C
 Area used = 0.3124 cm²
 Irradiance: 417.9 kW/m²

NREL HIPSS Confidential
 PV Performance Characterization Team

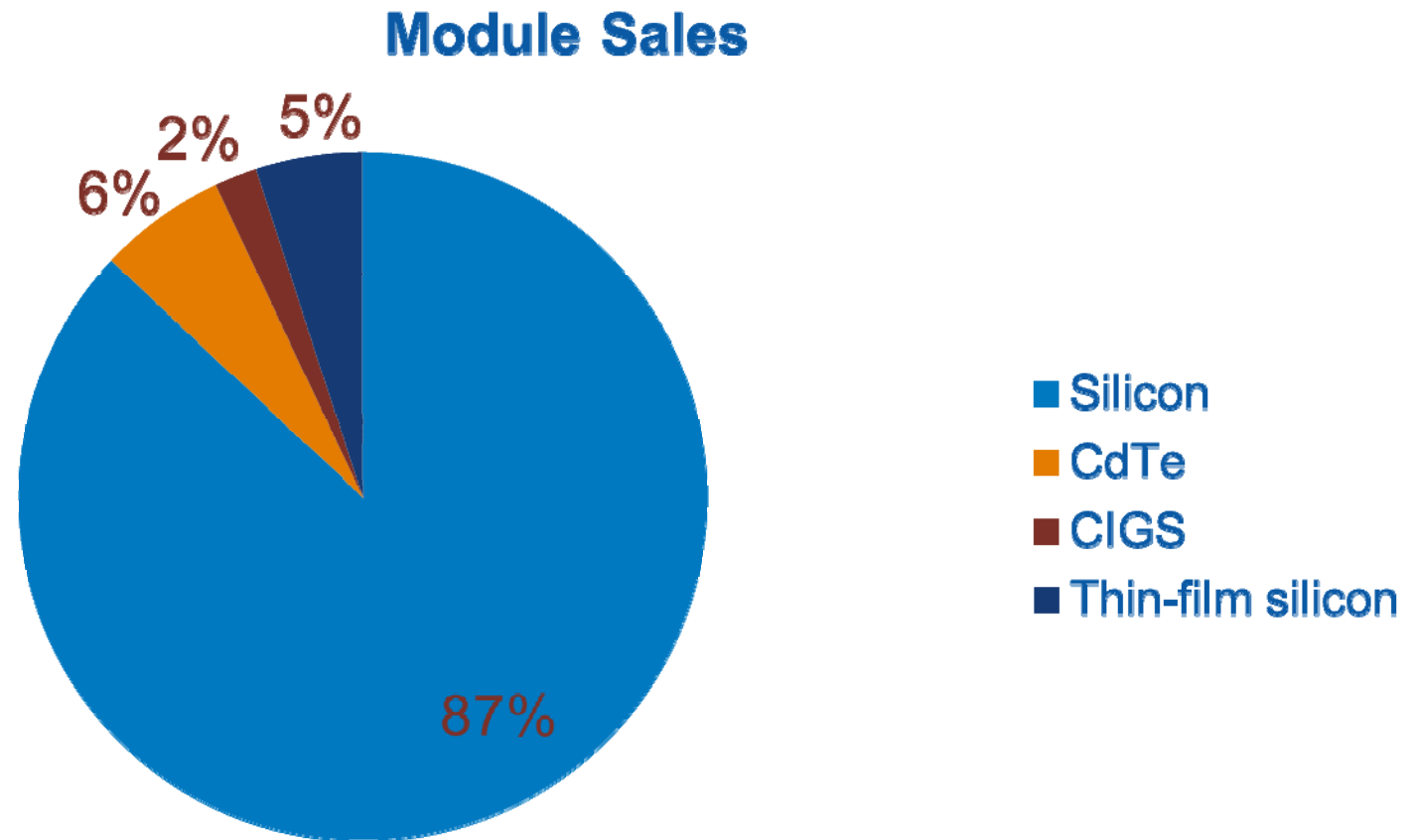


V_{oc} = 3.412 V
 I_{sc} = 1.869 A
 Fill Factor = 89.17 %
 Efficiency = 43.5 ± 2.2 %

V_{max} = 3.066 V
 I_{max} = 1.854 A
 P_{max} = 5.685 W



2010 Production by Cell Type

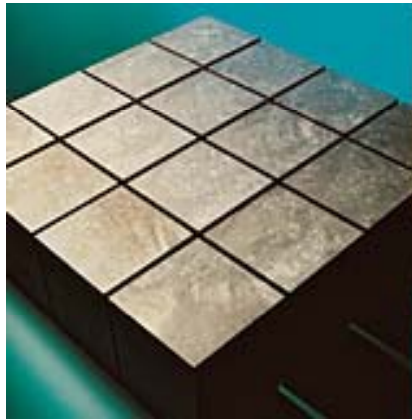


Source: PV News, May 2011

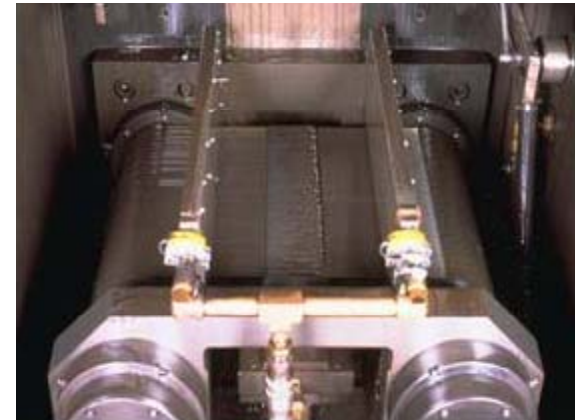
Silicon PV



Silicon Feedstock



Ingot Growth



Slicing Wafers

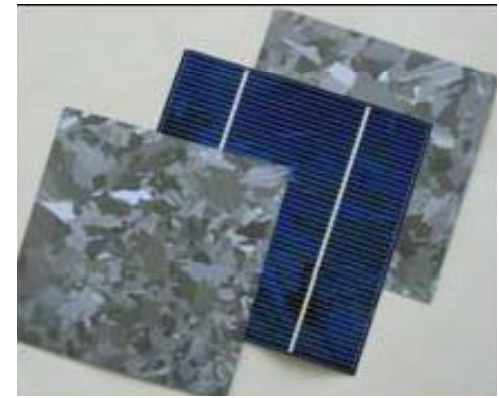
Photovoltaic System



Module Encapsulation

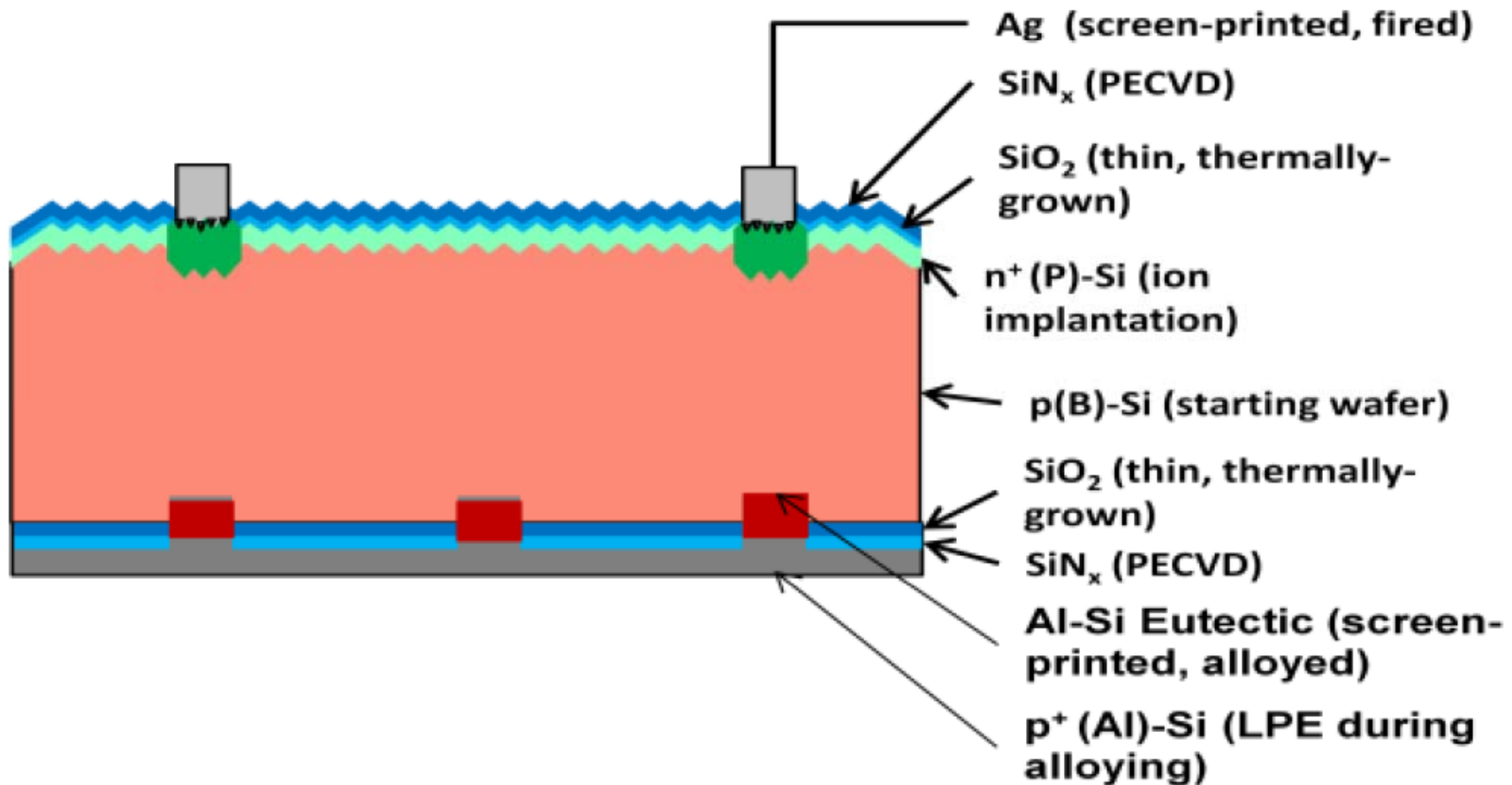


Cell Fabrication



Simple Cell Technologies continue to improve

- 19.6% efficient planar cells on CZ silicon



Source: J-H Lai, IEEE PVSC, June 2011

In September 2011 there were protests at a Chinese PV factory over pollution in the river



Chemical and Engineering News, September 26, 2011

Loan Transactions involving Chinese Banks to Chinese Solar Companies since Jan 2010*

Company	Amount (\$M)	Banks
China Sunergy	160	China Development Bank
Daqo New Energy	154	Bank of China
Hanwa SolarOne	1,000	Bank of China
Hanwa SolarOne	885	Bank of Shanghai
JA Solar	4,400	China Development Bank
Jinko Solar	7,600	Bank of China
LDK Solar	8,900	China Development Bank
Suntech	7,330	China Development Bank
Trina Solar	4,400	China Development Bank
Yingli Green Energy	179	China Citic Bank, Bank of China
Yingli Green Energy	5,300	China Development Bank
Yingli Green Energy	144	Bank of Communications
Yingli Green Energy	257	Bank of Communications
Total	40,709	

Source: Mercom Capital Group, llc

All amounts in millions of dollars.

*As of Sept. 26, 2011

<http://www.mercomcapital.com/news.php#CHINA>

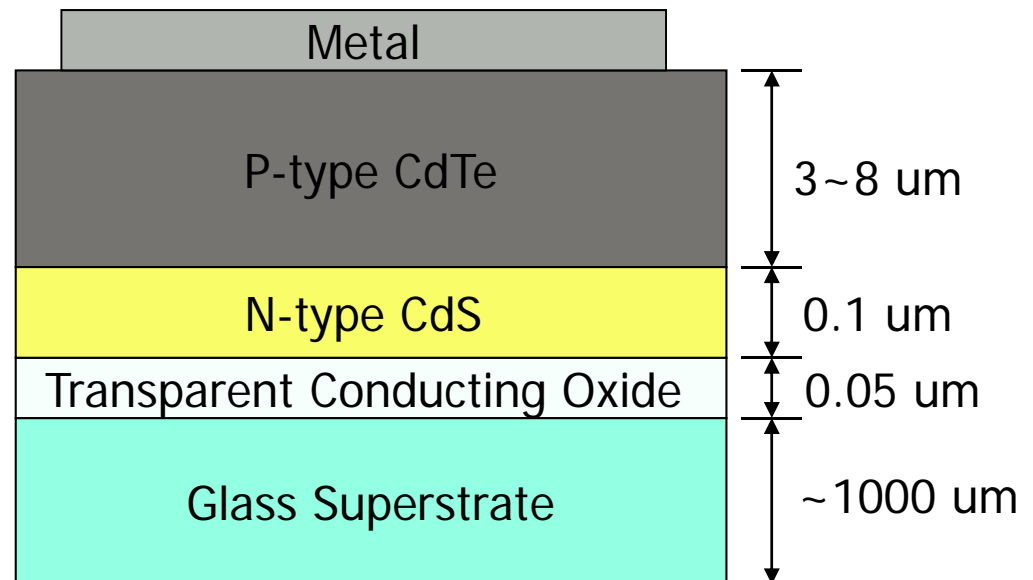
After this presentation was given, a article with a response from Suntech was published at <http://www.greentechmedia.com/articles/read/The-Reality-of-Chinas-Billions-in-Solar-Loans/>.

Conclusions on Silicon PV

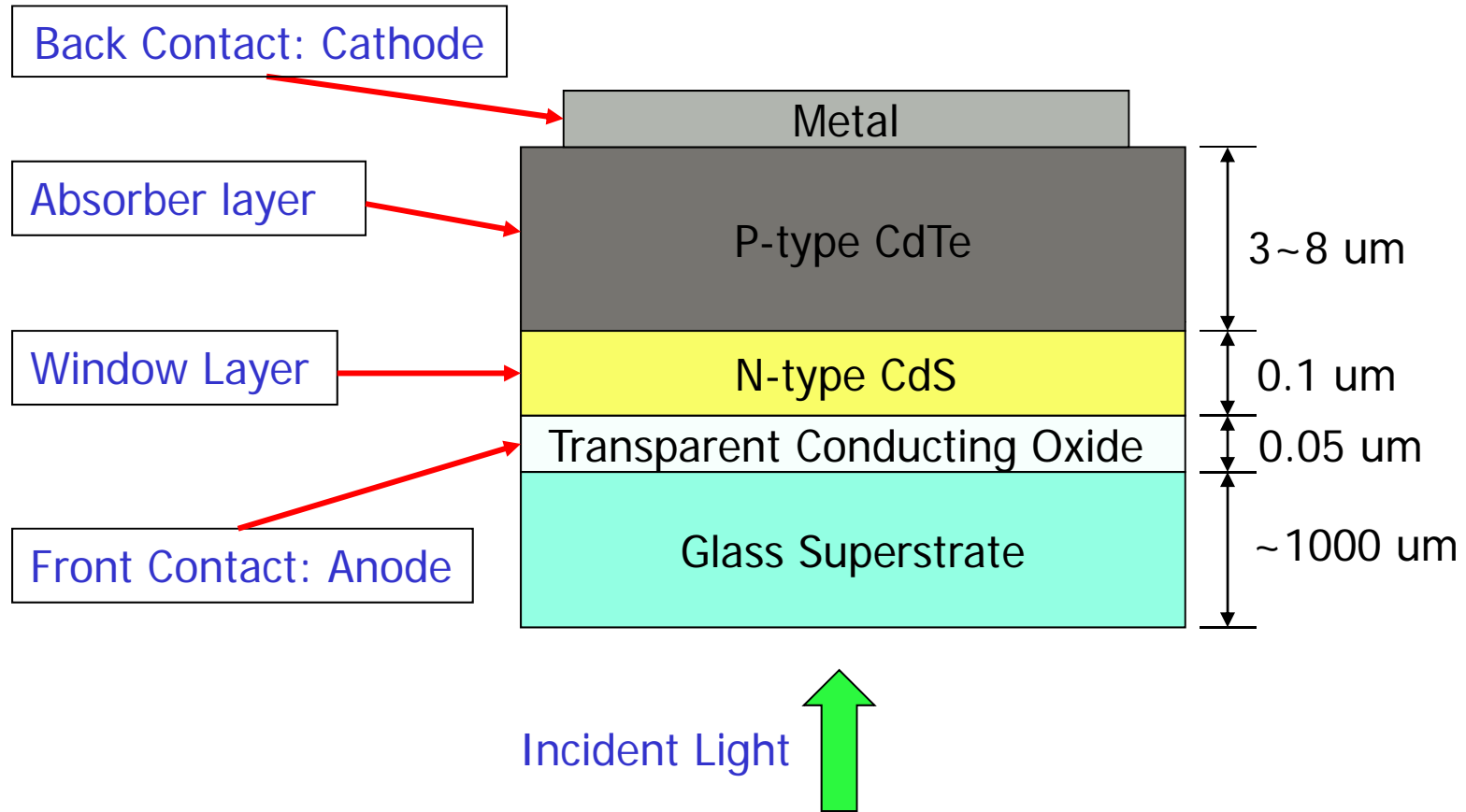
- Progress has been better than many expected.
- Modules are being sold at \$1/W, but not for profit.
- \$1/W w/ profit seems inevitable.
- It is not yet clear that \$0.5/W Si cells can be made sustainably.

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.

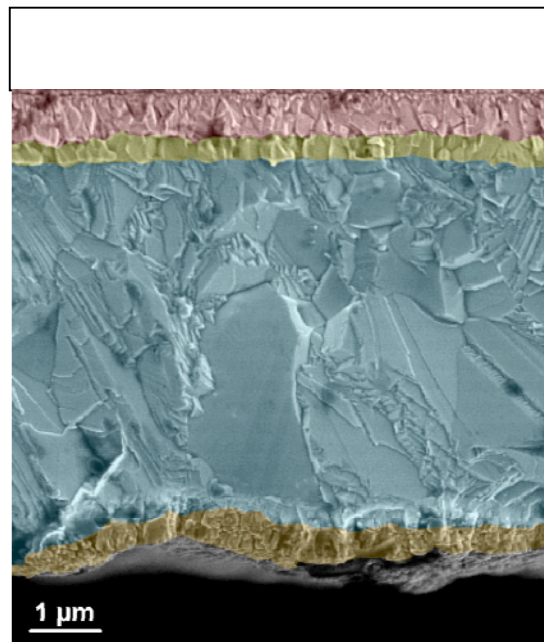


CdTe Solar Cell with CdS window layer



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

Cadmium Telluride Solar Cells



CdS/CdTe

glass

SnO₂

CdS

CdTe

ZnTe:Cu

Ti

- Direct bandgap, $E_g=1.45\text{eV}$
- Good efficiency (Record:17.3%)
- High module production speed
- Long term stability (20 years)

high P
 $P = 10-100 \text{ Torr}$
 $T = 800^\circ\text{C}$

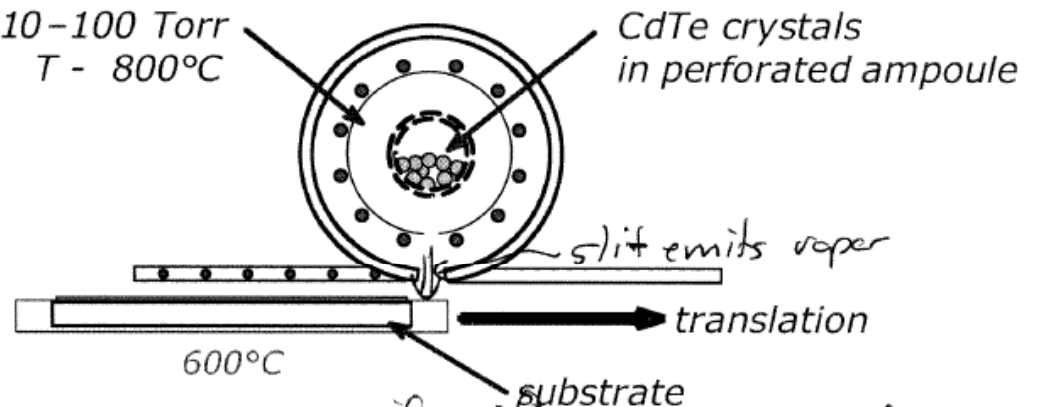
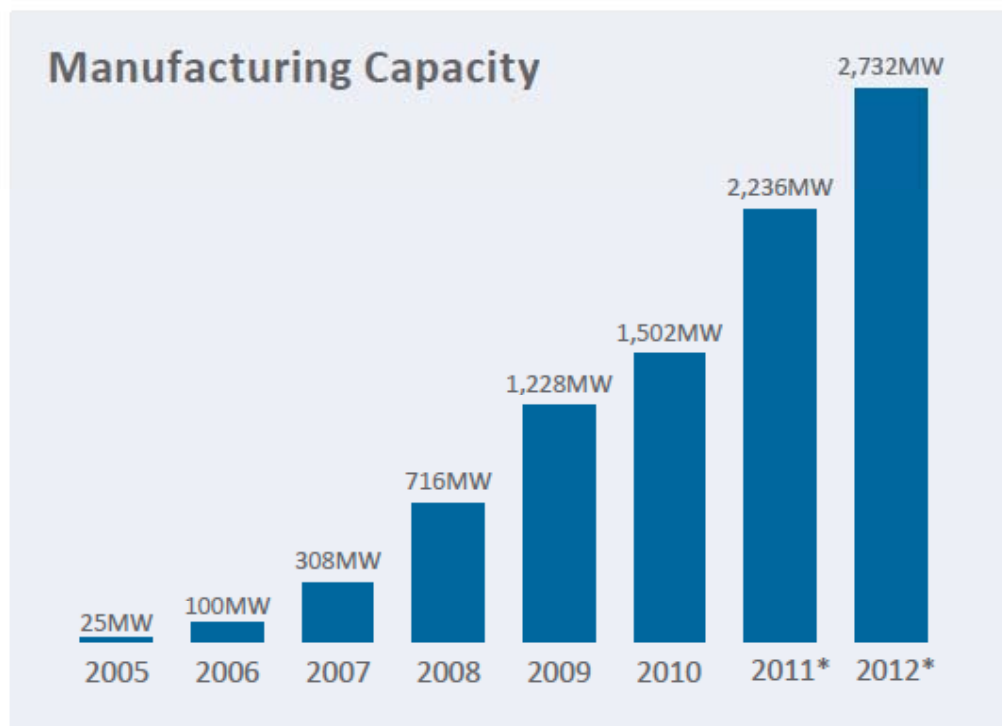


Image from Rommel Noufi
Schematic from Bulent Basol

CdTe: Industrial Status

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

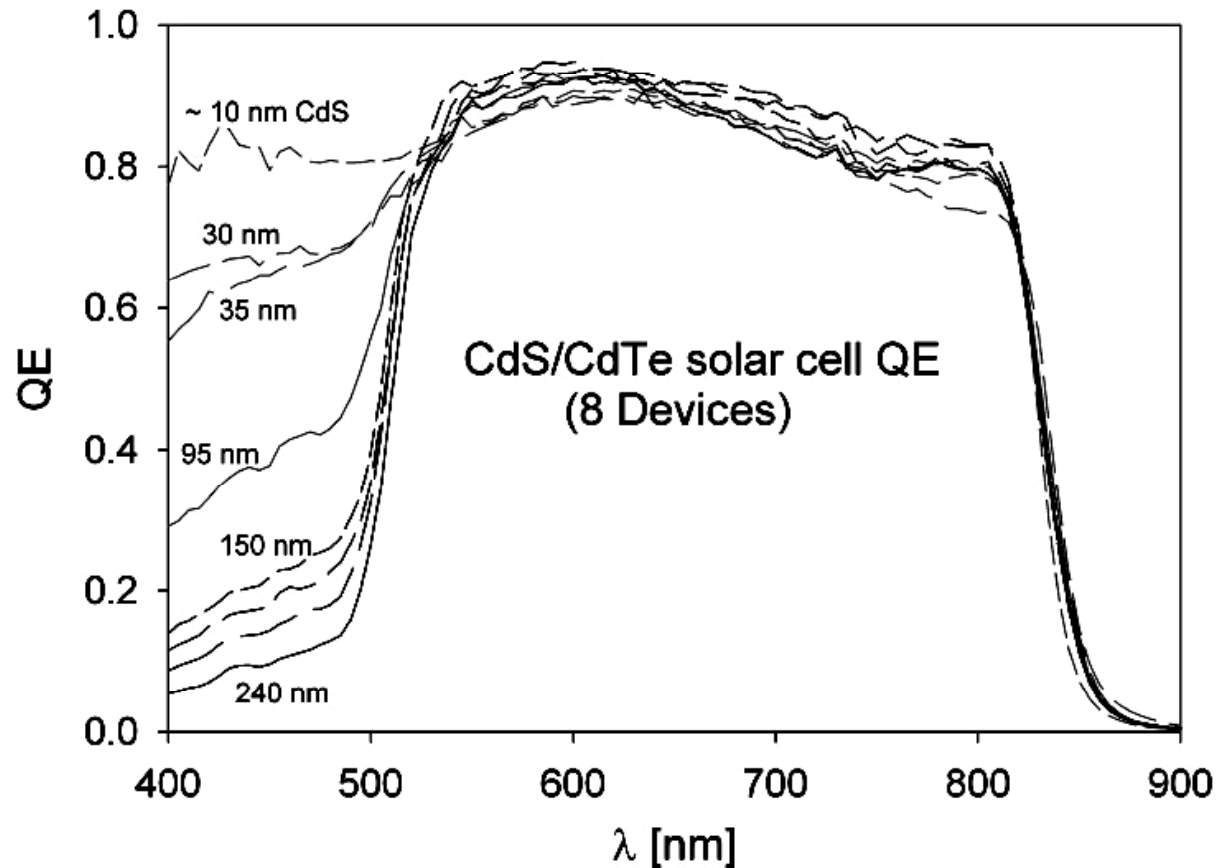


Average Manufacturing Cost

2006: \$1.40/watt
2007: \$1.23/watt
2008: \$1.08/watt
2009: \$0.87/watt
2010: \$0.77/watt

The energy payback time is 0.8 years.

One reason cells on the roof don't have 17.3 % efficiency



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

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.



- World record efficiency = 20.4 %.
- Many companies are evaporating, printing, sputtering and electrodepositing it.
- Some are manufacturing ~30-50 MW/yr.
- Handling a 4-element compound is tough.

ZnO, ITO - 2500Å
CdS - 700Å
CIGS 1-2.5µm
Mo - 0.5-1µm
Glass, Metal Foil, Plastics

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

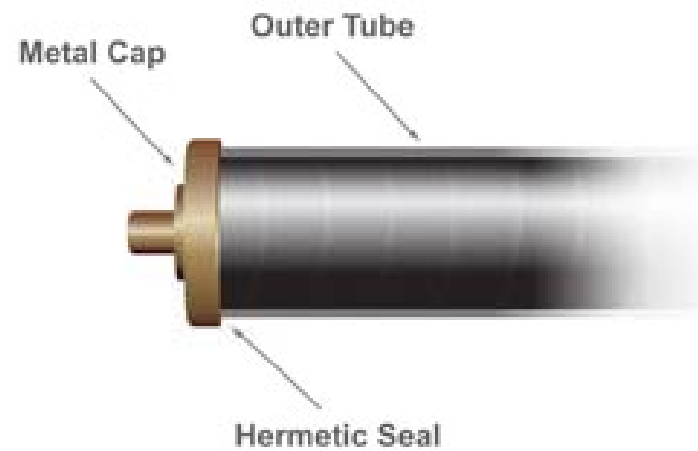
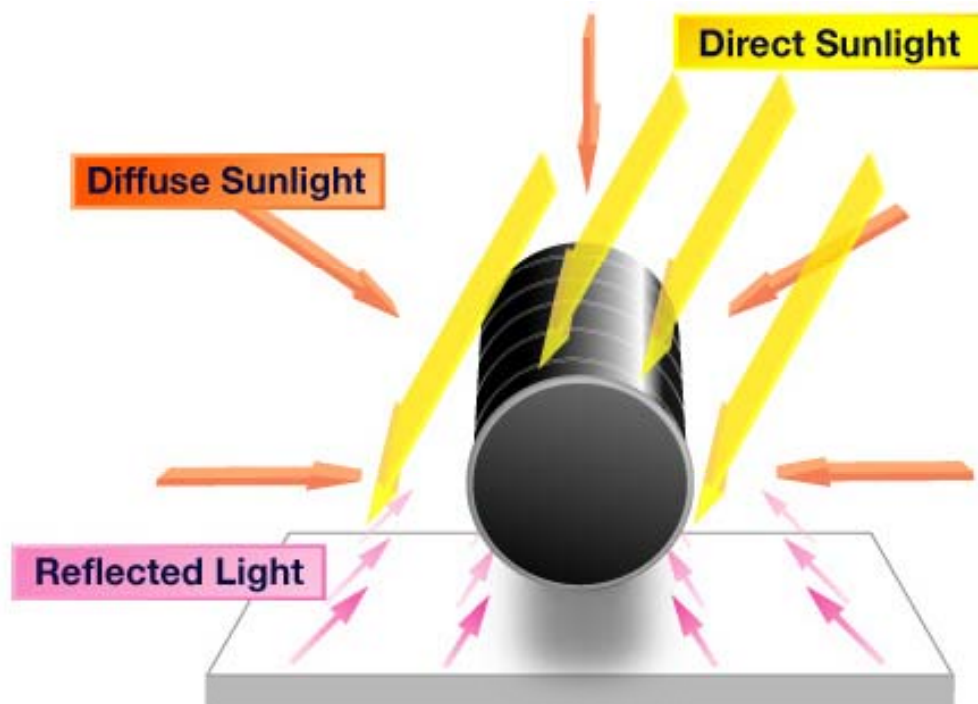
Solibro, Sweden

CISEL, France

Showa Shell, Japan

Honda, Japan

Solyndra's CIGS modules



A comparison of Solyndra's modules to their competitors

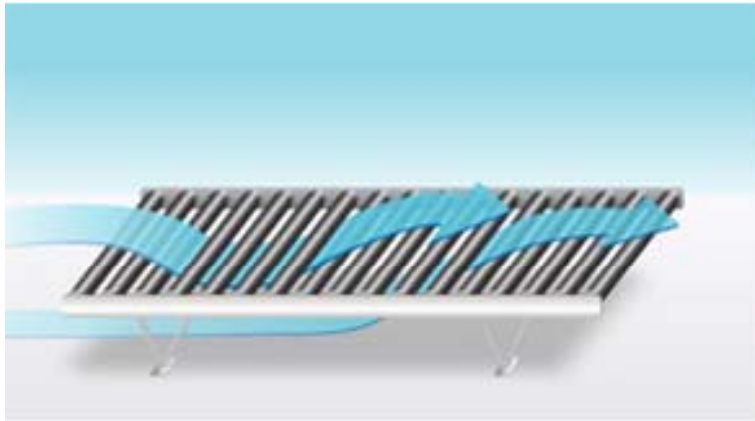


SOLYNDRA



CONVENTIONAL

Wind Performance

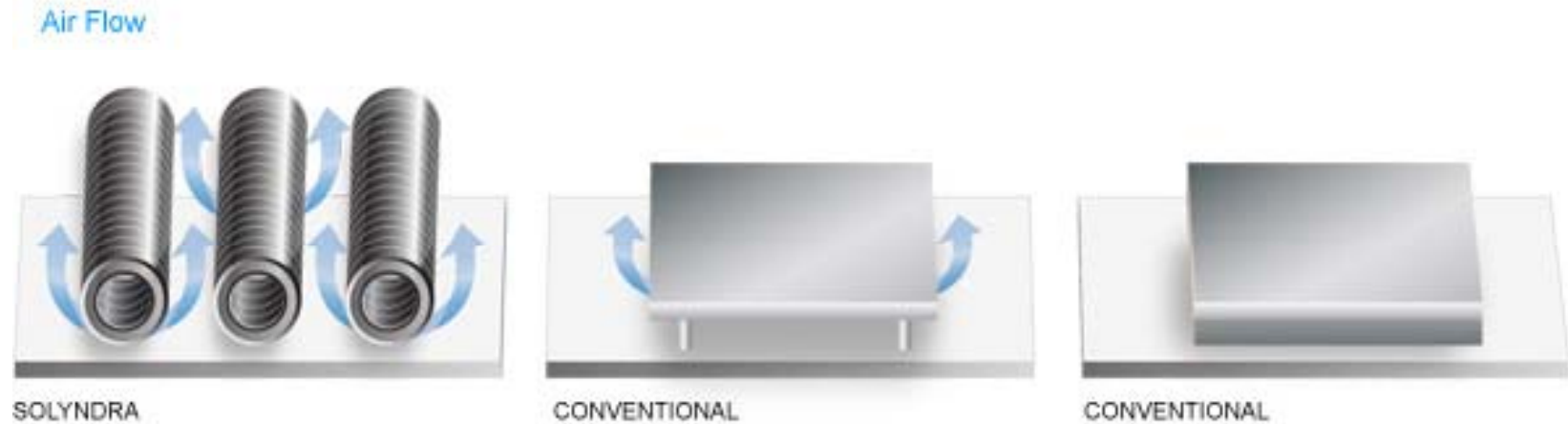


SOLYNDRA



CONVENTIONAL

Ability to Avoid Heating



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

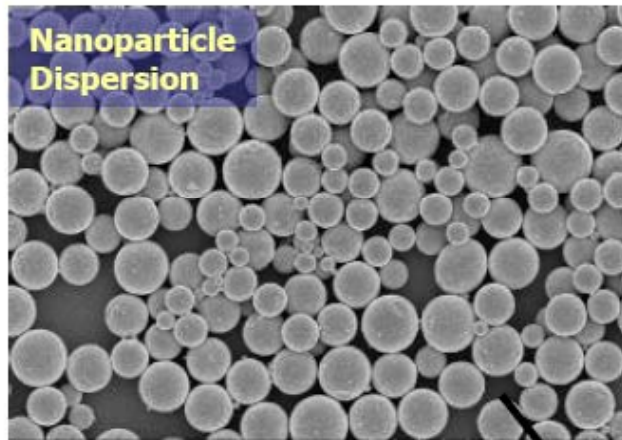
What went wrong?

- There are significant disadvantages to using cylinders (e.g. more area, more dark current).
- Just about everything in the factory had to be custom built to enable the use of cylinders.
- The glass cylinders are not as cheap as those used in fluorescent light tubes.
- The price of crystalline silicon dropped faster than Solyndra expected.
- Building a second factory wasn't a great idea.

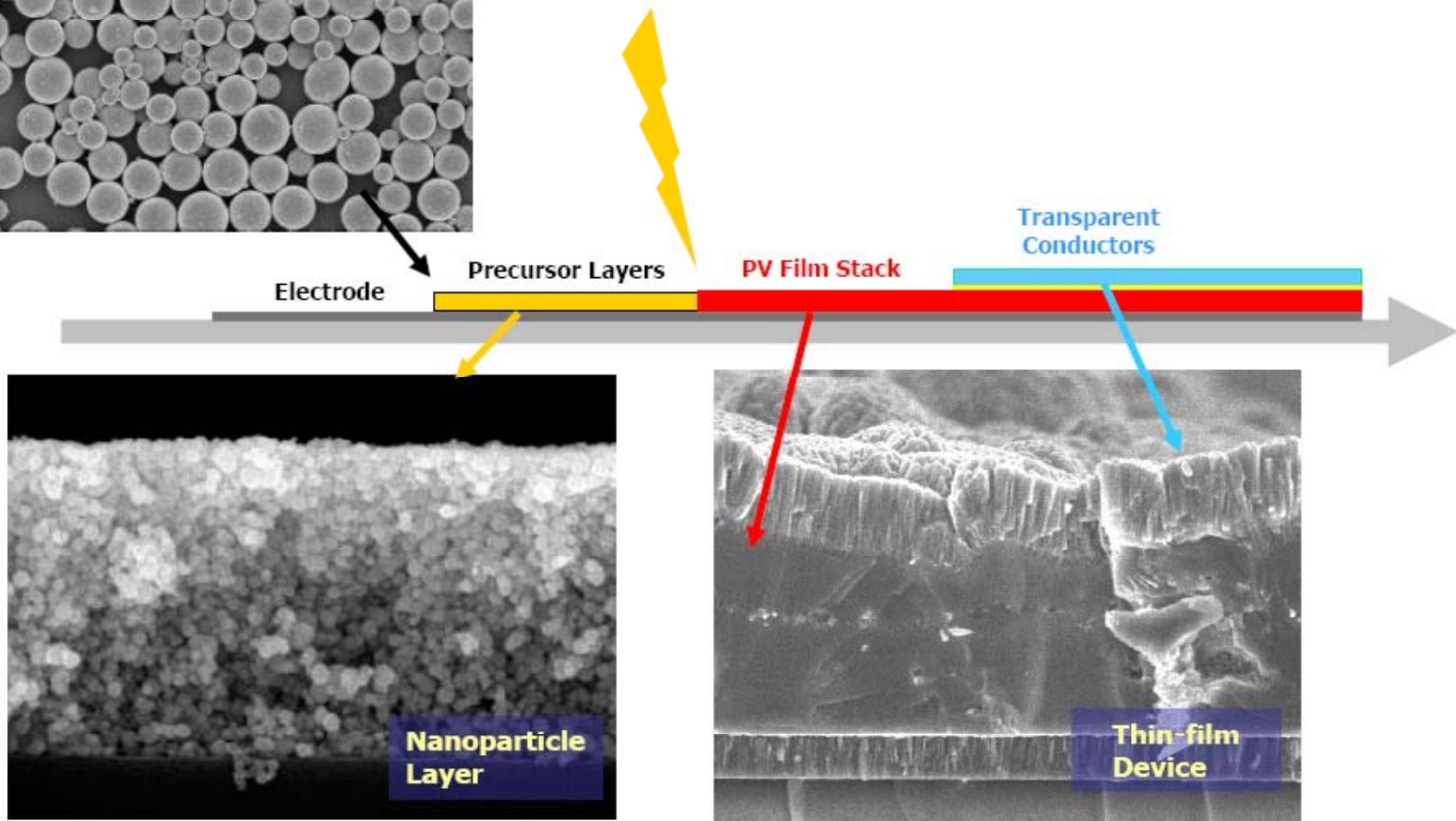
Martin Roscheisen explained the disadvantages of the Solyndra approach back in 2009. (<http://www.nanosolar.com/company/blog/tubular-pv>)



PRINTED SEMICONDUCTOR



Printed Semiconductor +
Rapid Thermal Processing (RTP)

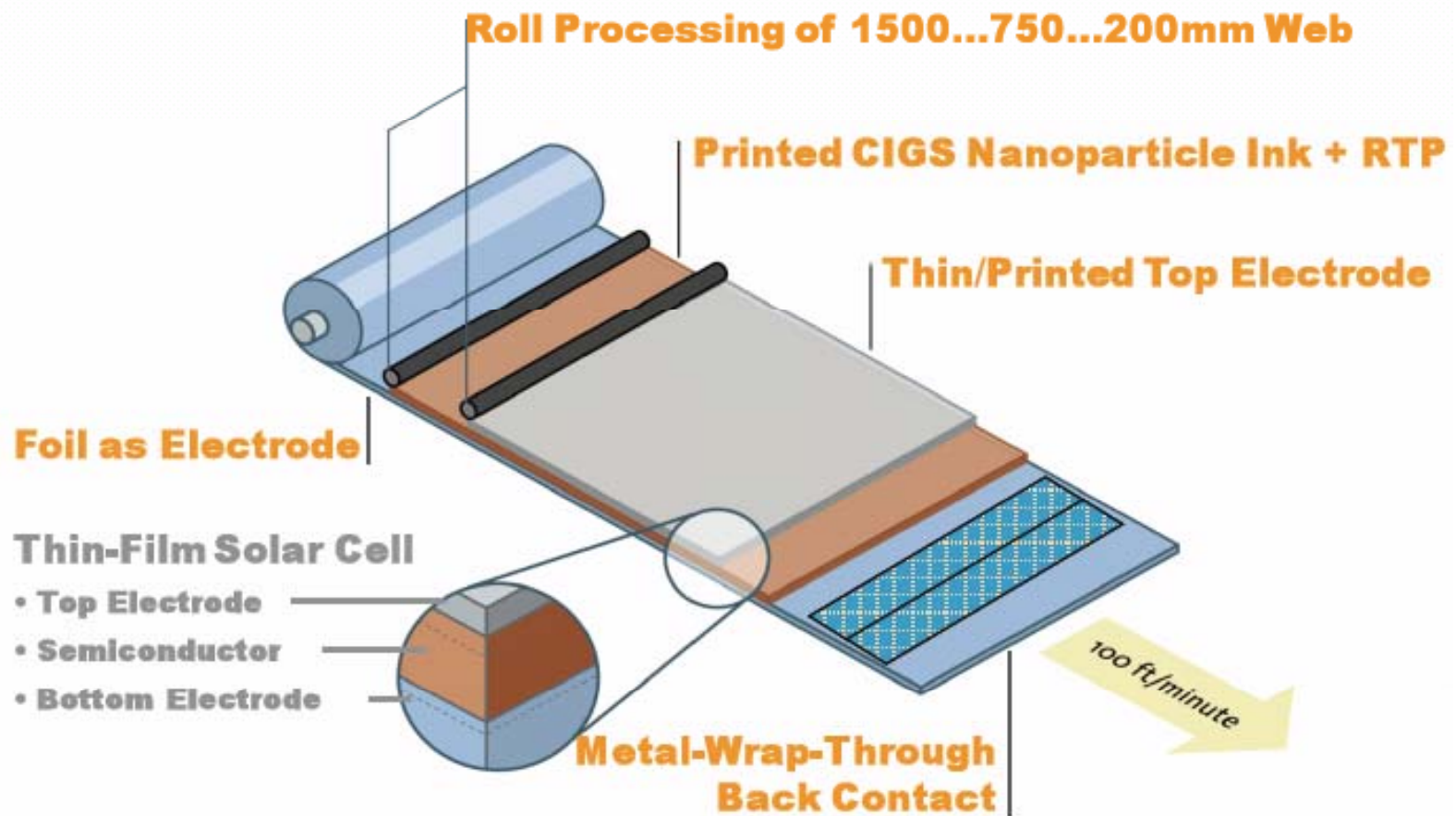


Nanosolar's Roll-to-Roll Coating



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 Cell and Module Design

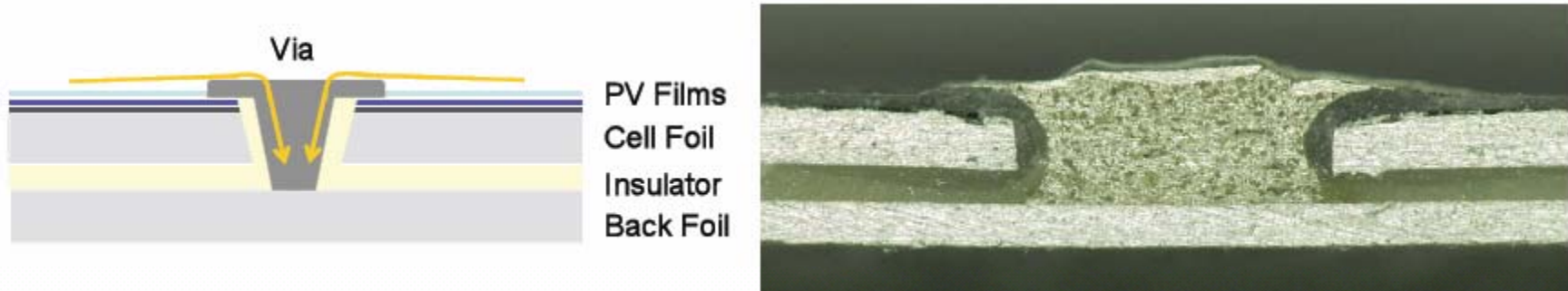


Figure 14: Nanosolar Back-Contact Cell Architecture: Two laminated aluminum foils with conductive vias.



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.

Miasolé

- Sputters CIGS on steel foil
- 15.7 % efficient modules verified by NREL
- Fully automated process for making modules
- Should be shipping ~13.5 % efficient modules at around \$0.8/W soon



Is there enough Te for CdTe?

The amount of Te in a cell is

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

2- μm thick cells require

$$(2 \mu\text{m})(5.7 \text{ g/cm}^3)(0.52) = 5.7 \text{ g/m}^2.$$

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

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

A very similar story can be told for the In needed in CIGS

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.

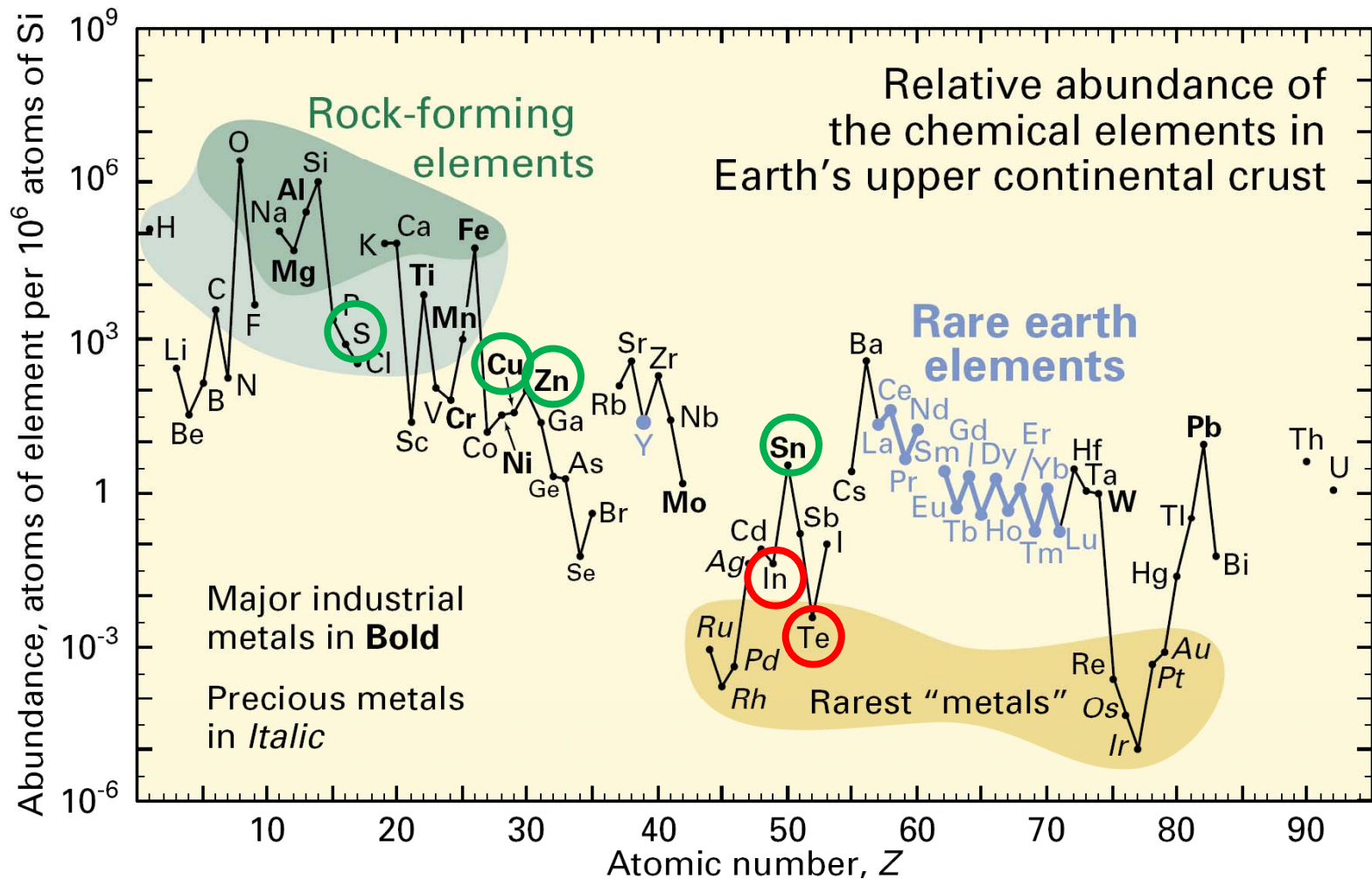
The cost of Te

- 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.

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)

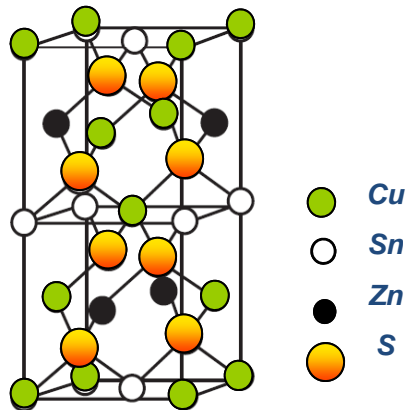
Searching for more abundant materials



U.S. Geological Survey Fact Sheet 087-02

Solar Cells Using *Non-Toxic Abundant* Materials

- CuInGaSe_2 – 20.4 % efficient – thin film architecture
- $\text{Cu}_2\text{ZnSnS}_4$ (CZTS) is similar to CuInGaSe_2 in many ways



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)

A newer thin film approach: organic solar cells

- Molecules can be sprayed onto plastic substrates rapidly, inexpensively and at low temperature.
- No rare or toxic elements are needed.
- Tandems can be made easily.

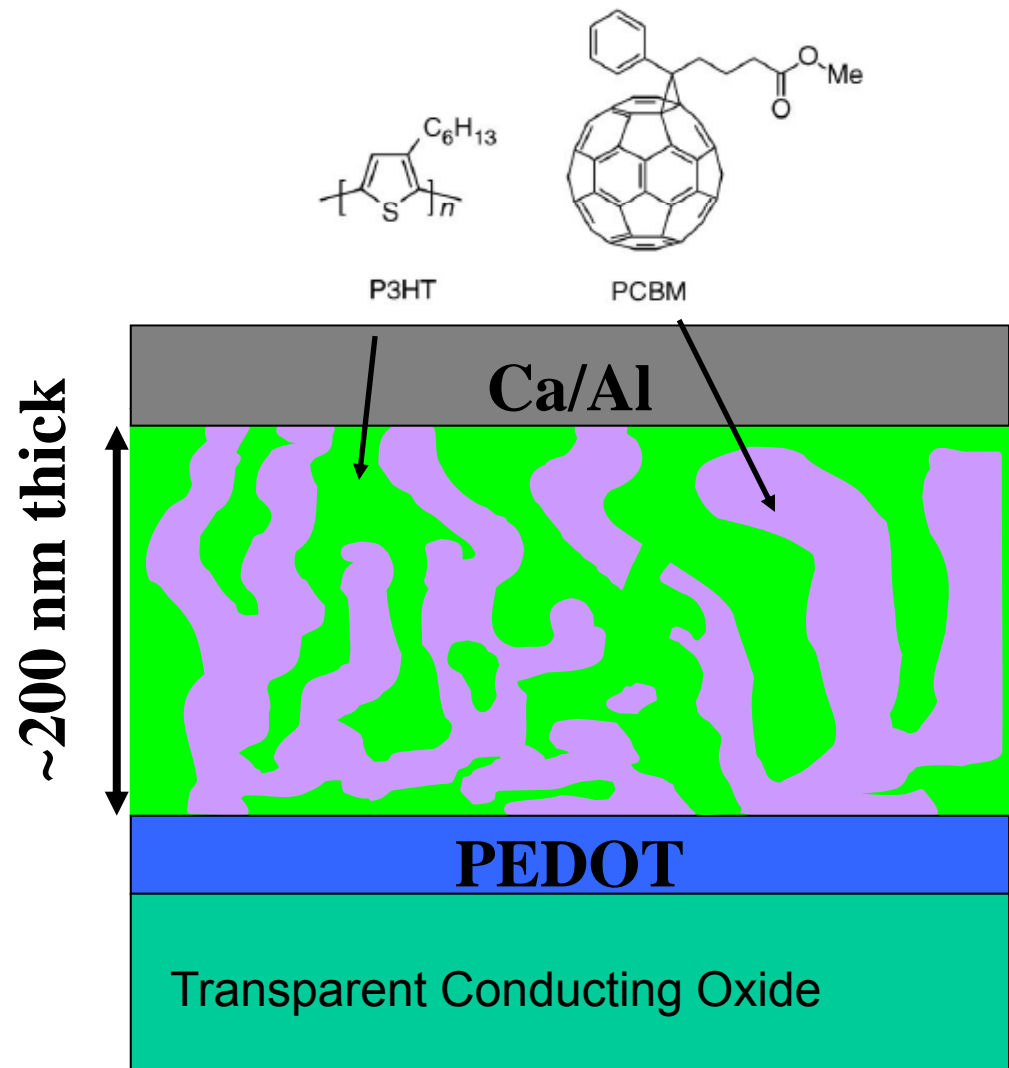


Konarka

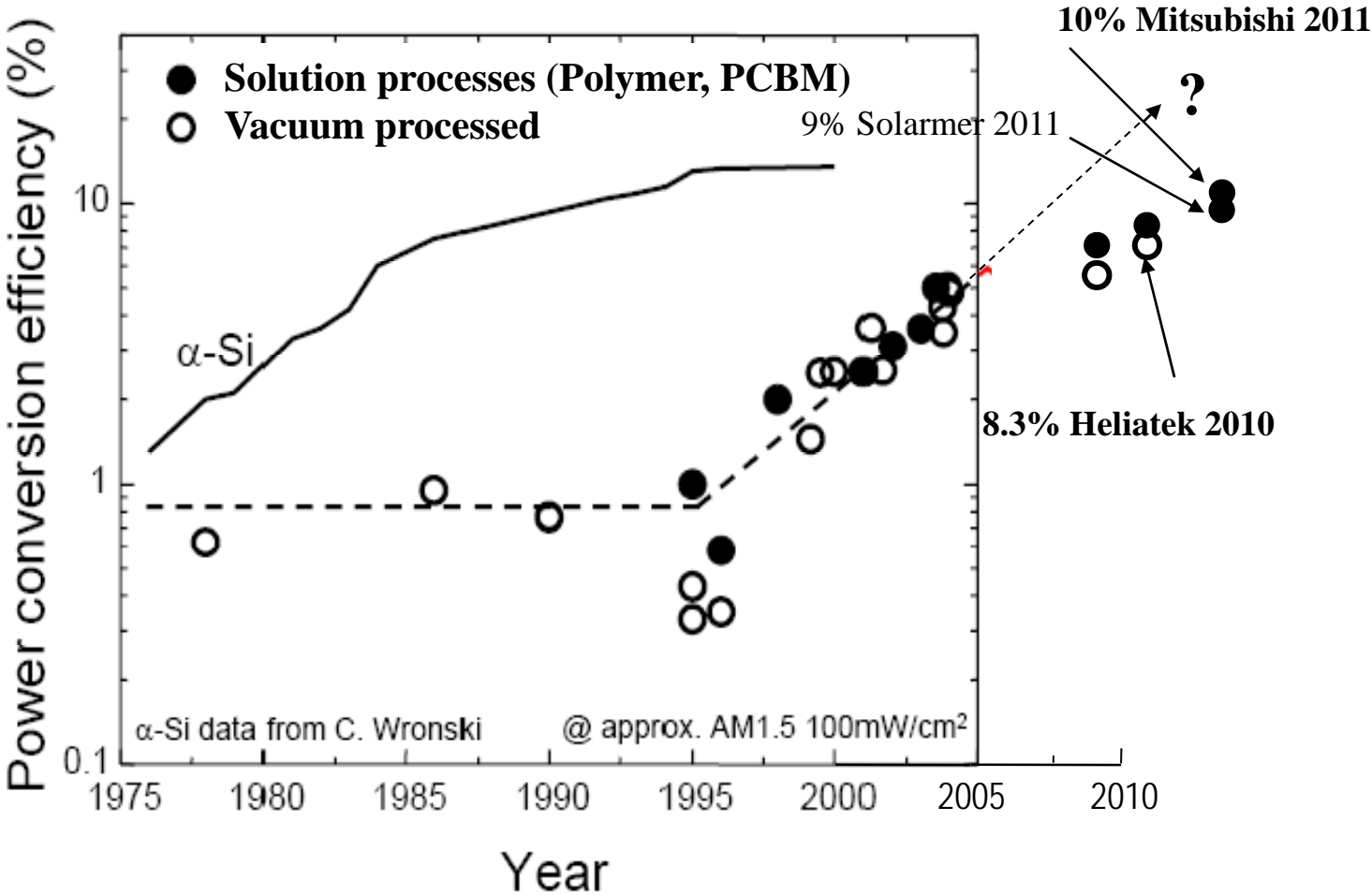
The hope is that we will some day be able to print 15 % efficient cells on flexible substrates at < \$50/m².

Polymer-Fullerene Bulk Heterojunction Cells

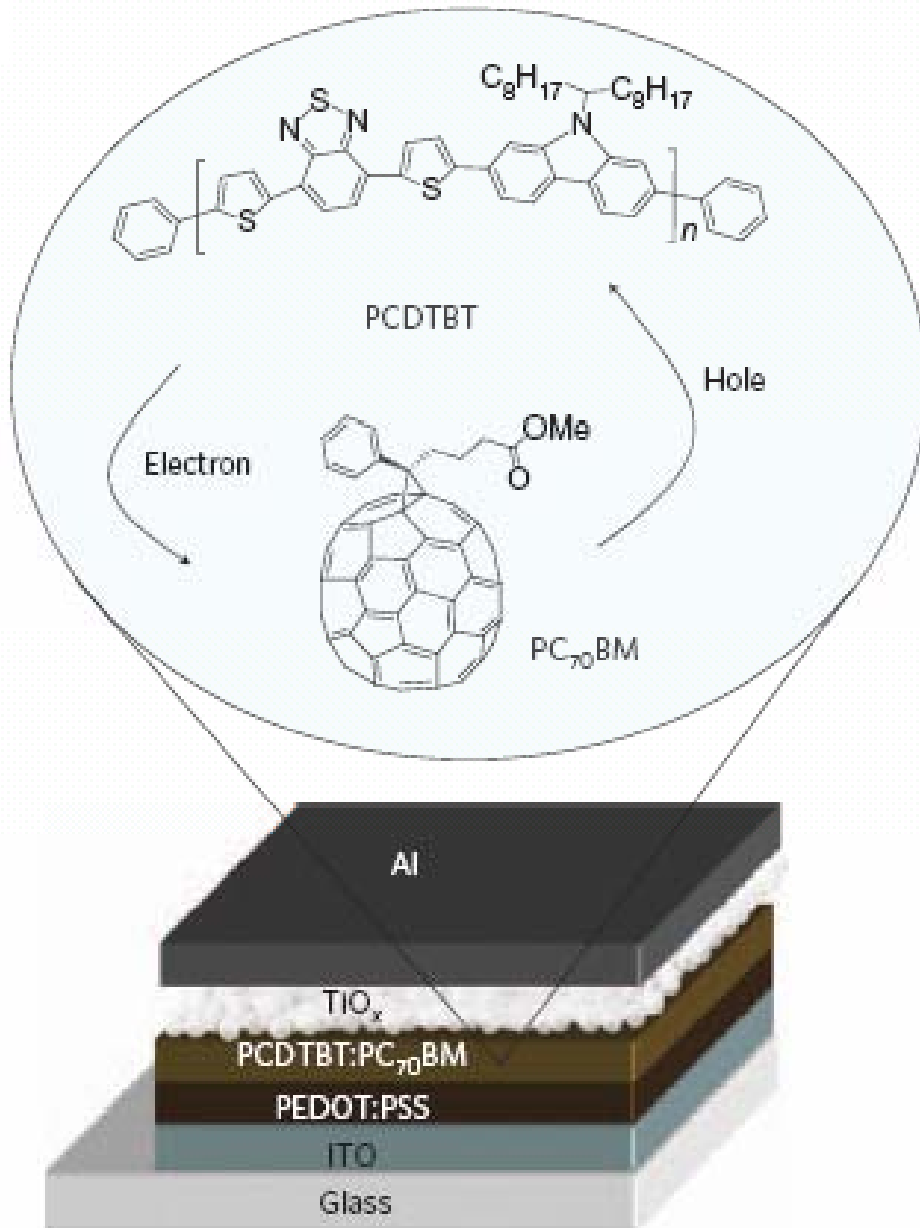
- Donor polymer (i.e. P3HT) absorbs light generating an exciton (i.e. bound electron hole pair).
- Exciton must diffuse to the Donor/Acceptor (e.g. PCBM) interface to split.
- Electrons travel to the back electrode.
- Holes travel to the front electrode.



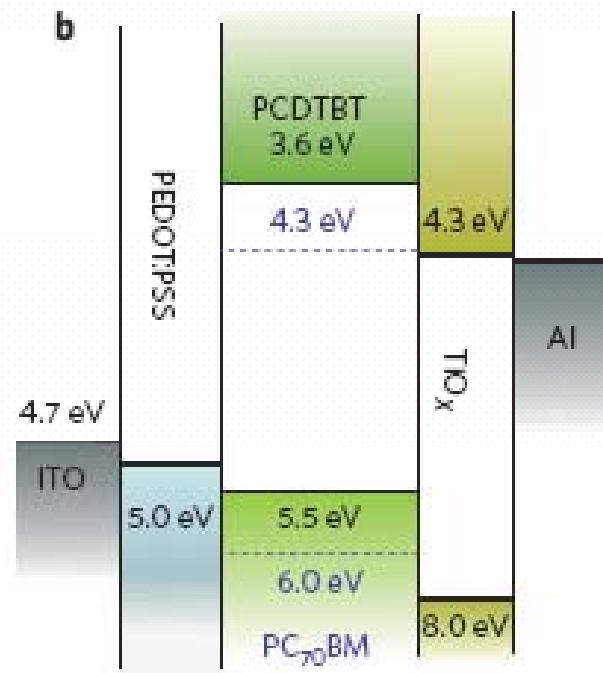
Organic Solar Cells are Rapidly Improving



The world record cell in June 2009: 6.1 %



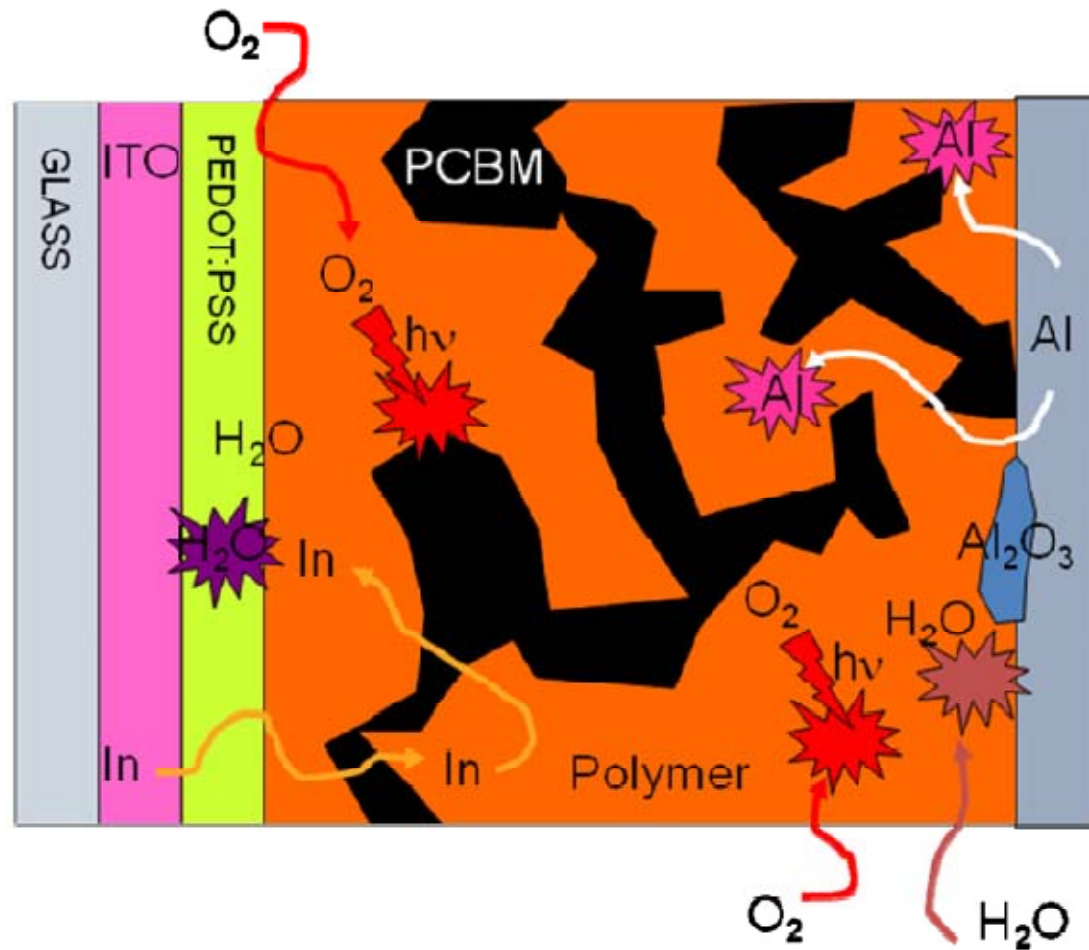
- The chemistry is being tuned to get the right energy levels.
- The morphology is being optimized to prevent recombination.



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

Reliability

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

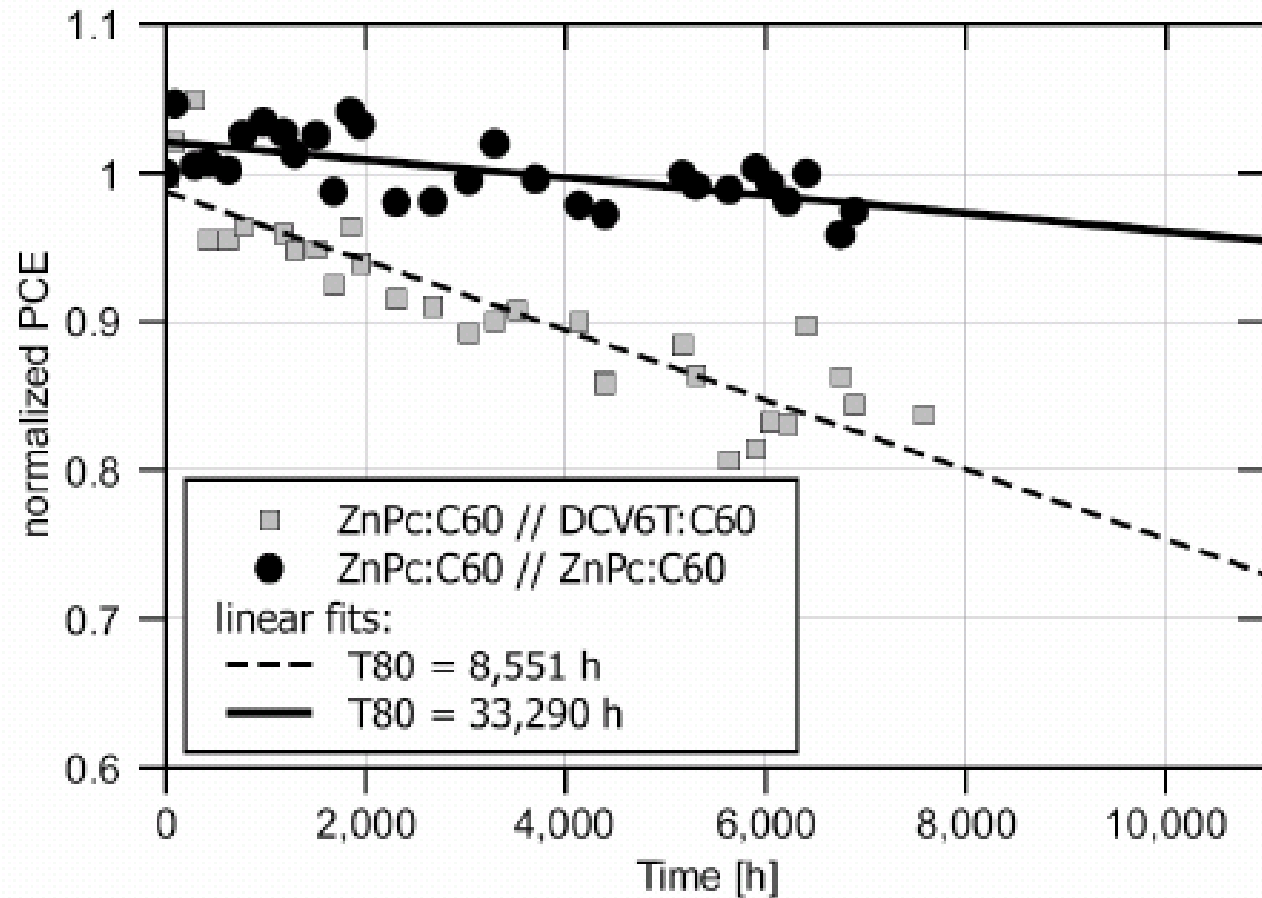


F.C. Krebs, et al., Solar Energy Materials (2008)

Heliatek Reliability Study

Light intensity
2.2 suns

Temperature
48 °C



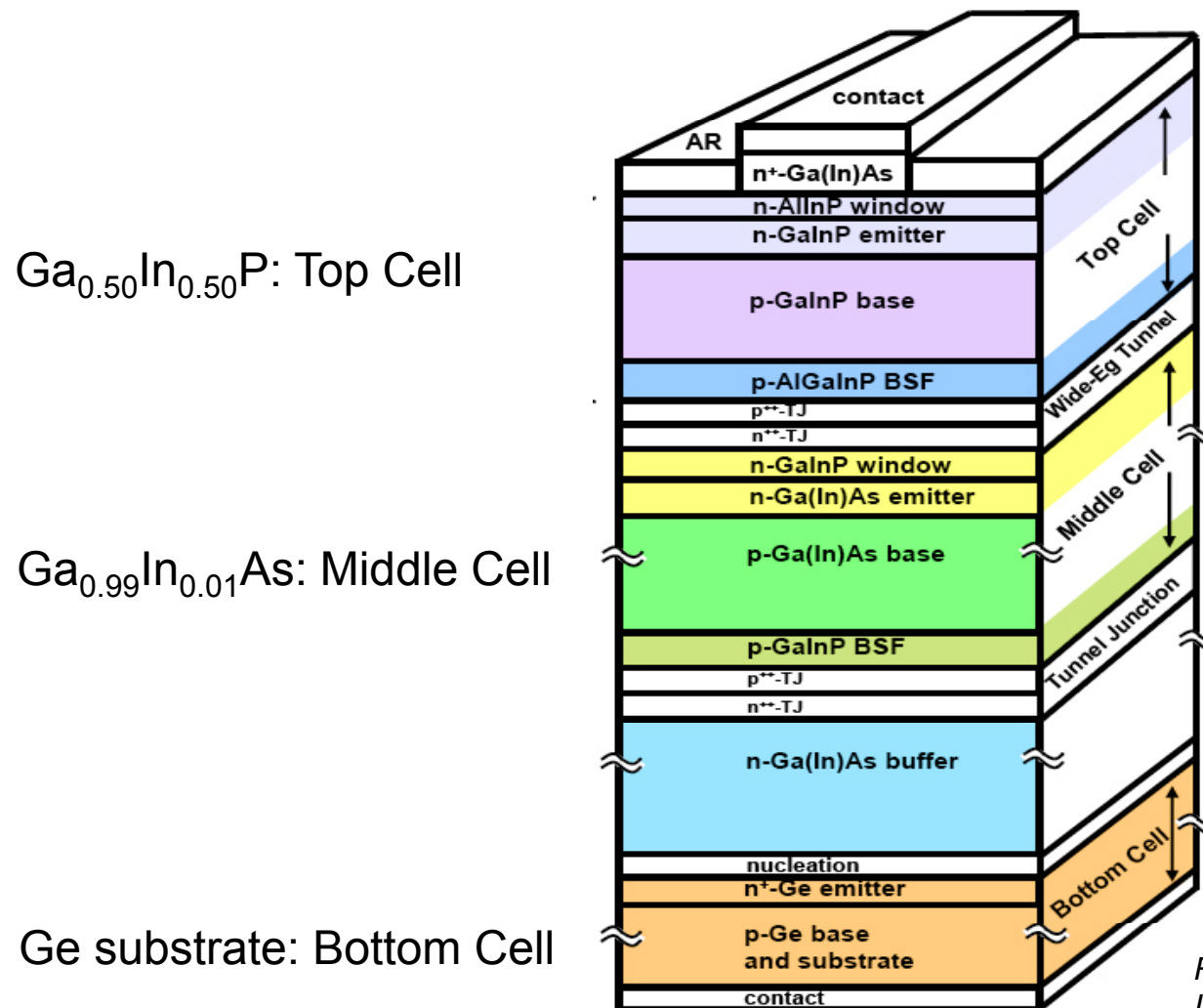
$(33,290 \text{ hrs})(2.2) = 73,000 \text{ hrs}$ or **8.4 years continuous use**

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

Recommended General Reading List

- C. Deibel and V. Dyakonov, **Polymer–fullerene bulk heterojunction solar cells**, *Rep. Prog. Phys.* **73** 096401 (2010)
- T. Ameri , G. Dennler , C. Lungenschmied and C. J. Brabec, **Organic tandem solar cells : A review**, *Energy Environ. Sci.*, **2**, 347-363 (2009)
- A.C. Mayer, S.R. Scully, B.E. Hardin, M.W. Rowell, M.D. McGehee, **Polymer-based solar cells**, *Materials Today*, **10**, 11 (2007)
- C. J. Brabec, S. Gowrisanker, J. J. M. Halls, D. Laird, S. Jia, S. P. William, **Polymer–Fullerene Bulk-Heterojunction Solar Cells**, *Adv. Mat.* **22**, 3839-3856 (2010)
- P. Peumans, A. Yakimov and S.R. Forrest, **Small molecular weight organic thin-film photodetectors and solar cells**, *J. Appl. Phys.* **93**, 3693, Apr 2003

Multijunction Cells are Very Expensive



- These complex structures are grown very slowly under high vacuum.

- 37 % cells can be purchased for \$50,000/m²

- Concentrating the light is essential.

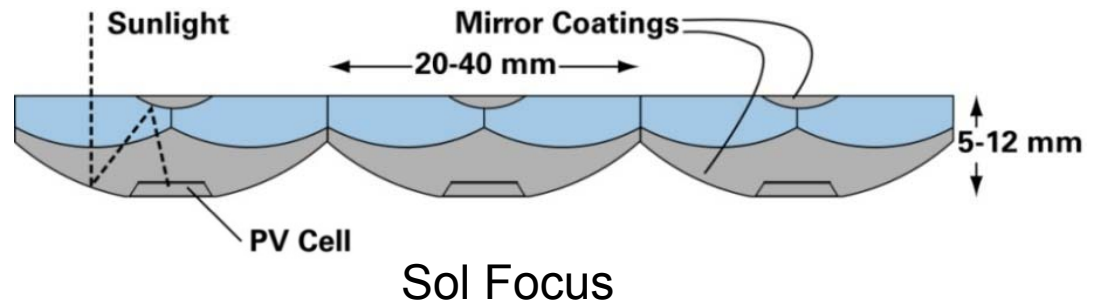
R.R. King; Spectrolab Inc., AVS 54th International Symposium, Seattle 2007

Concentrating Light

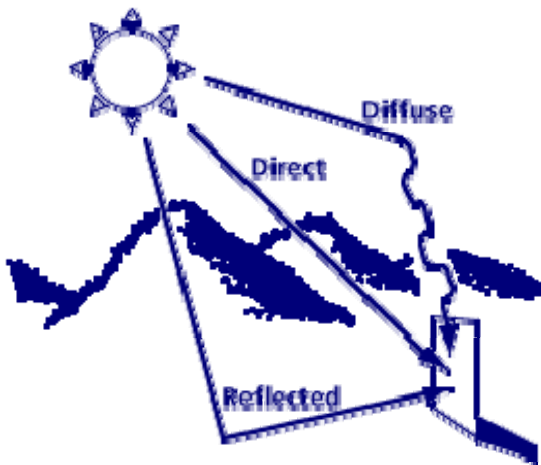
It is possible to track the sun and concentrate the light by 500X



Dish Shape



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-m ²]	
	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 of MJ Cells with Concentrators

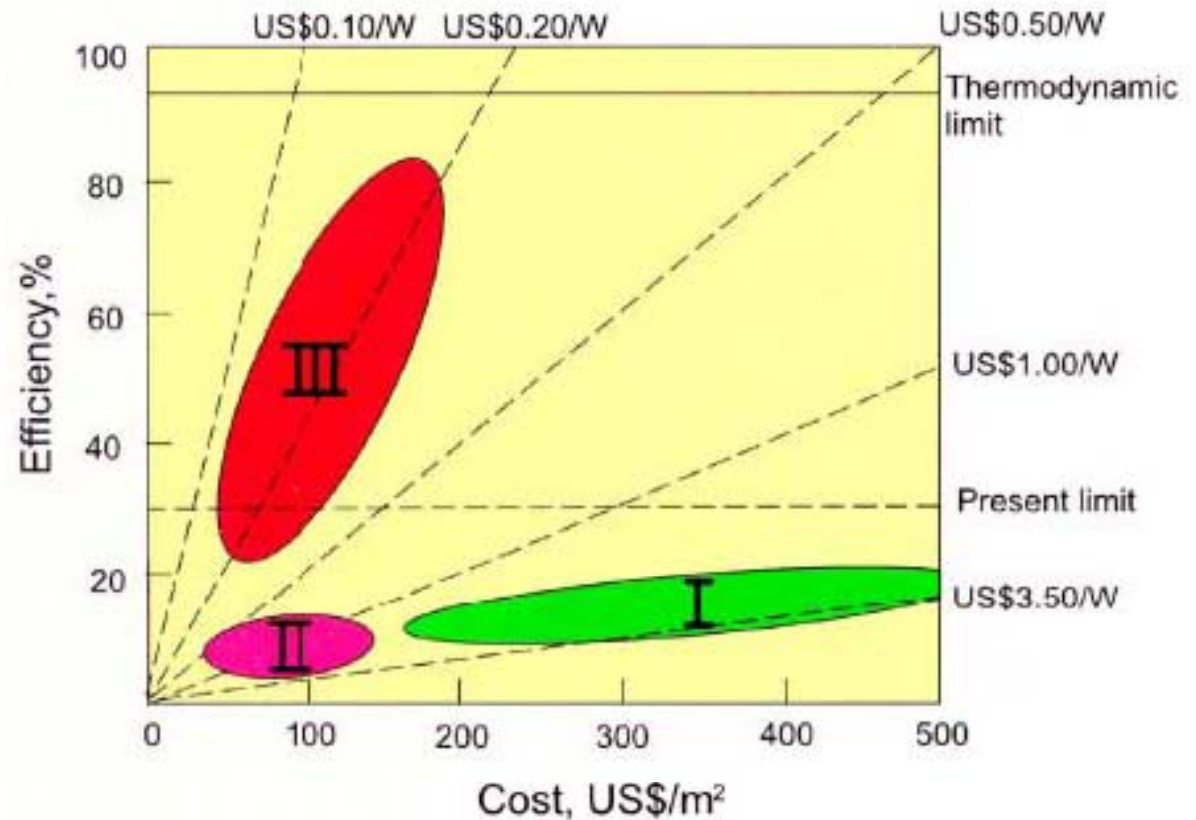
- The cost of multijunction solar cells is approximately \$50,000/m² (\$5/cm²). 500X concentration reduces this to \$100/m².
- Let's say the tracker and concentration cost \$200/m².
- The sun gives us 1000 W/m², but this is reduced to 850 W/m² direct sunlight.
- The best commercially available cells 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/m² of electrical power.
- At \$200/m² 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

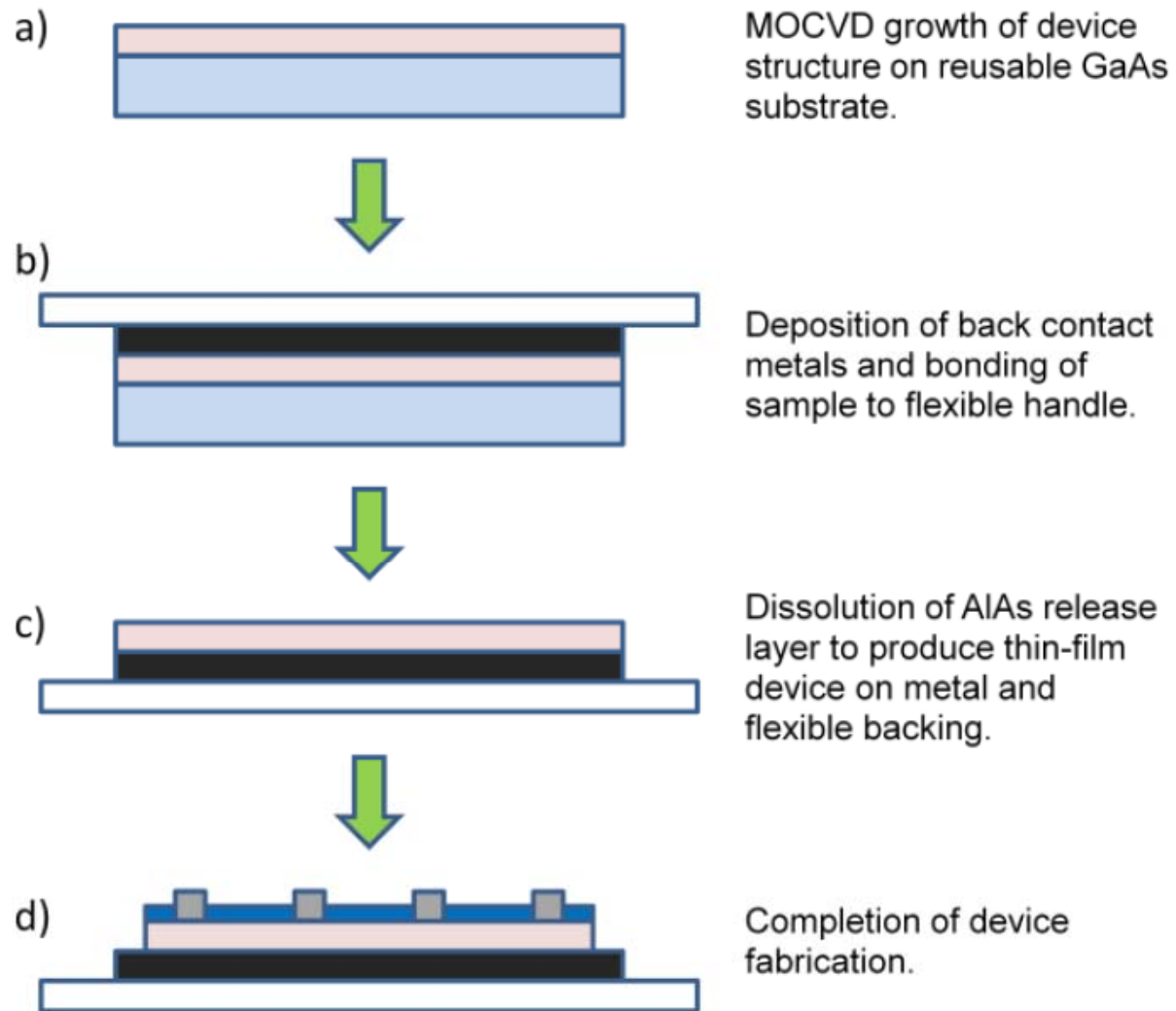
Martin Green's Generations of PV Technology

- Gen I: Single crystal
- Gen II: Thin Film
- Gen III: Beats Shockly-Queisser limit



This extremely popular plot was generated at least 8 years ago and often used to justify Gen III PV. Gen I and II are already much better than shown here. Generation III is not even remotely close to being as good as shown by the red region.

Alta Devices 28.2% efficient thin-film GaAs cell



Source: B. Kayes, IEEE PVSC, June 2011

Alta Devices' New Record

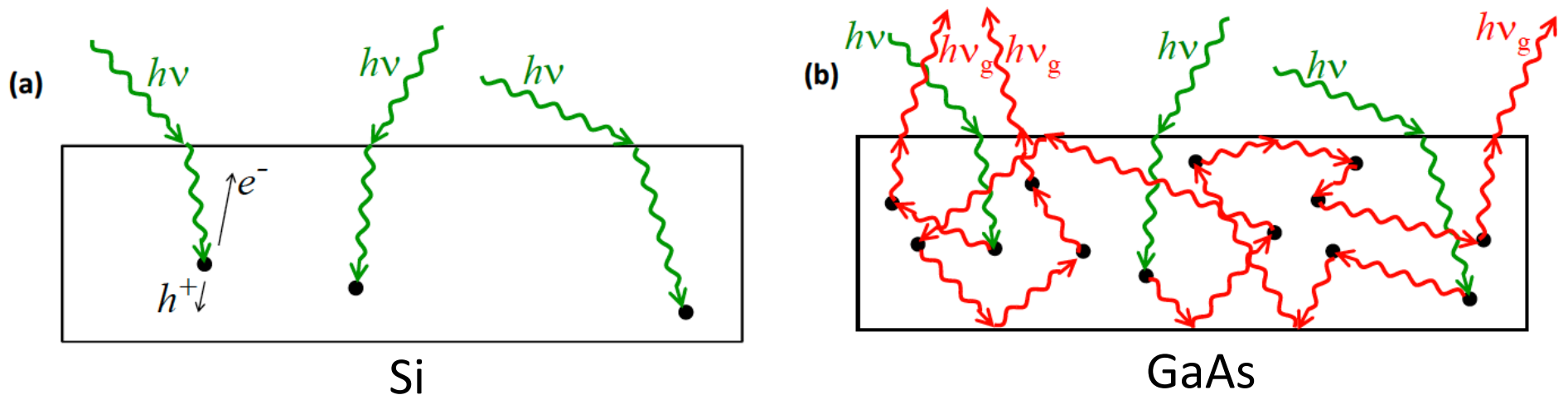
A world record for single junction solar cells

	Wafer record (NREL)	Alta Devices
Efficiency	25.1%	27.6%
Jsc (mA/cm ²)	28.2	29.6
Voc (V)	1.022	1.107
FF	0.871	0.841
Area (cm ²)	3.91	1.0

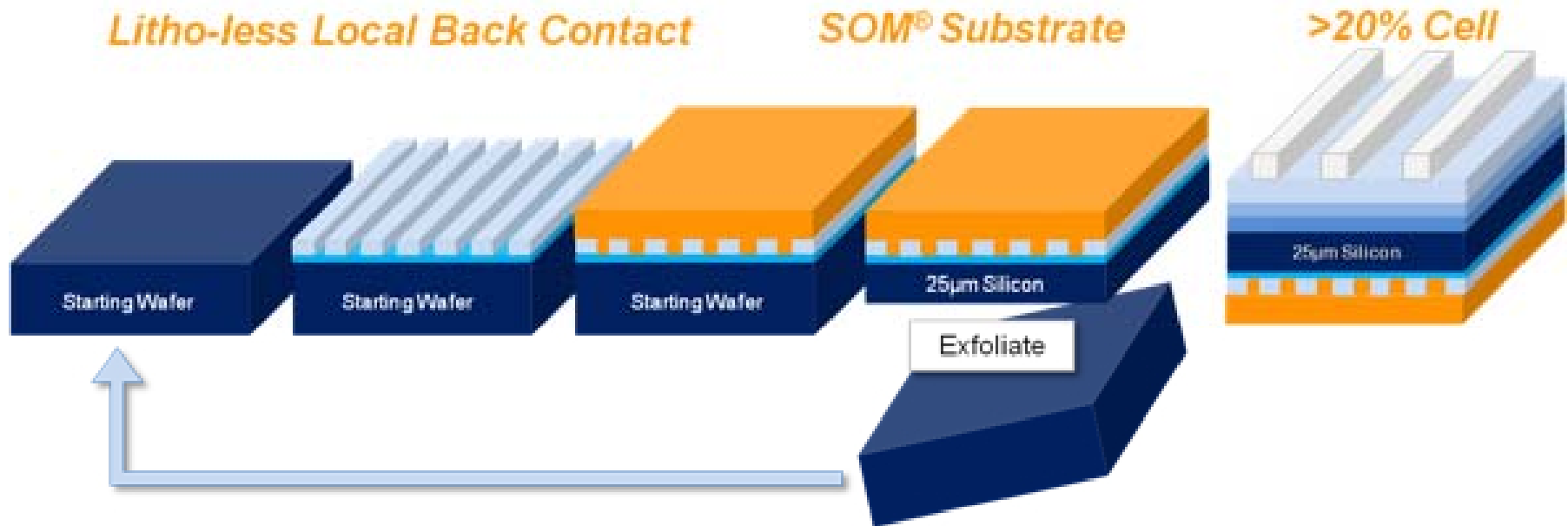
- As of June 2011, Alta had reached 28.2%
- Size of a 4" wafer
- They are flexible

Photon recycling in thin film GaAs

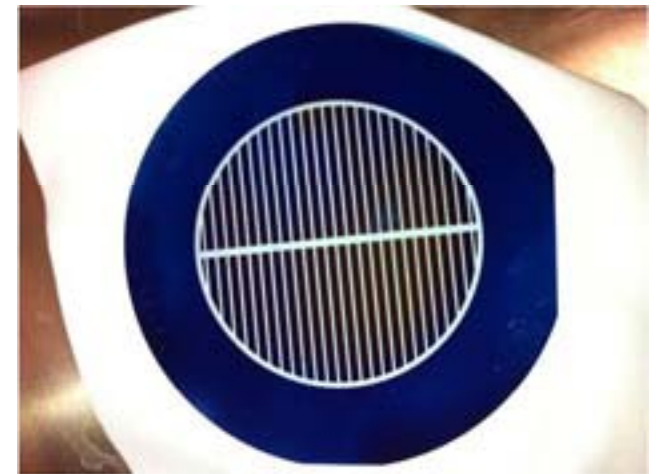
If the radiative lifetime is short, a photon can be absorbed and re-emitted $>$ 50 times before the free carriers are collected.



Silicon can be peeled off too



- Astrowatt claims Si PV efficiency >20% efficiency.
- Twin Creeks is based on ion implanting hydrogen into Si and having hydrogen bubbles pop off a thin film.



Is peeling cells from single crystal wafers the way to go?

The approach is very exciting, but quite challenging.

It is not clear that

- high quality μm -thick films of GaAs can be deposited at a reasonable price
- there is a reliable way to peel off silicon
- peeling can be incorporated into a high-throughput factory
- a wafer can be reused >1000 times as Alta hopes

Conclusions

- Solar is really taking off
- Si is in the lead, but many technologies may still have their day

