Photovoltaics: status, issues and promise

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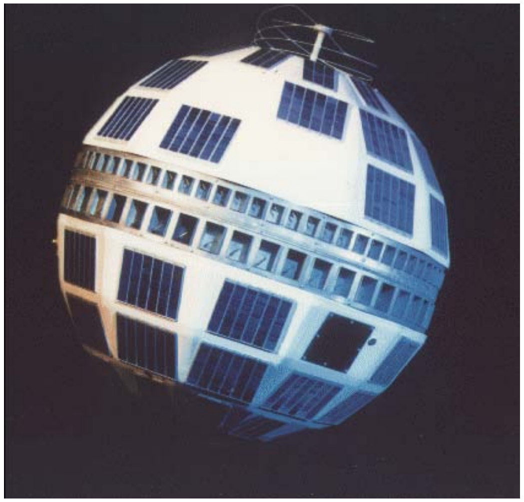
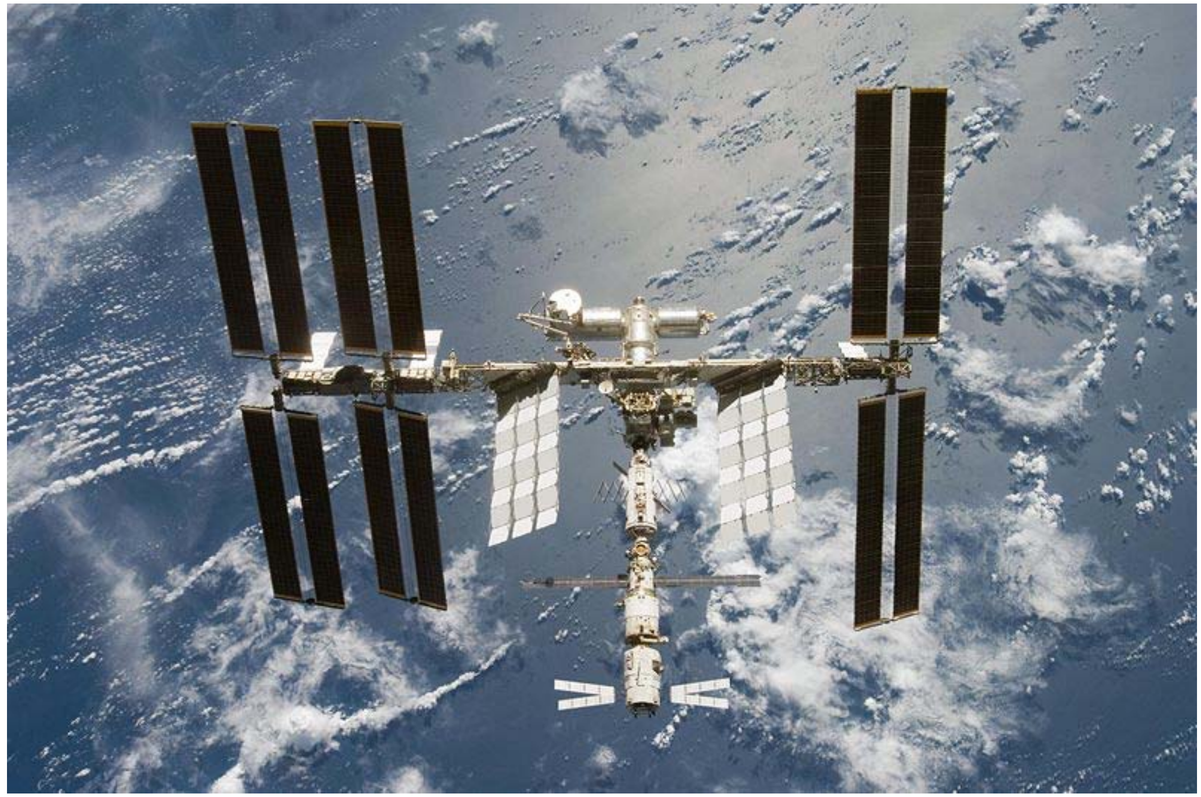
Outline

- PV background
  - How solar cells work
  - Technology today
- The role of efficiency
  - Limits
  - Paths for improvement
- Market dynamics
  - Pricing
  - Other issues

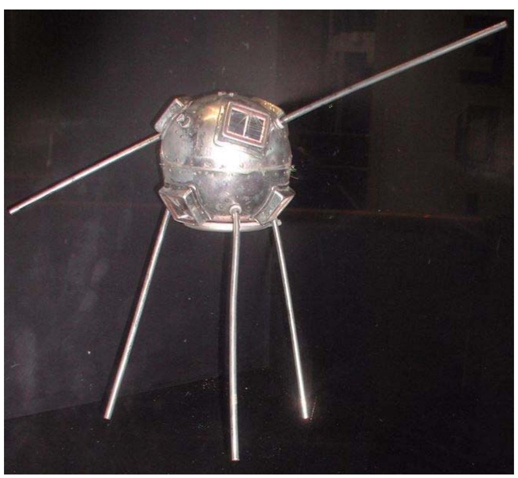
Satellites, the ultimate off-grid application, came first



Telstar (1962) – first communications satellite

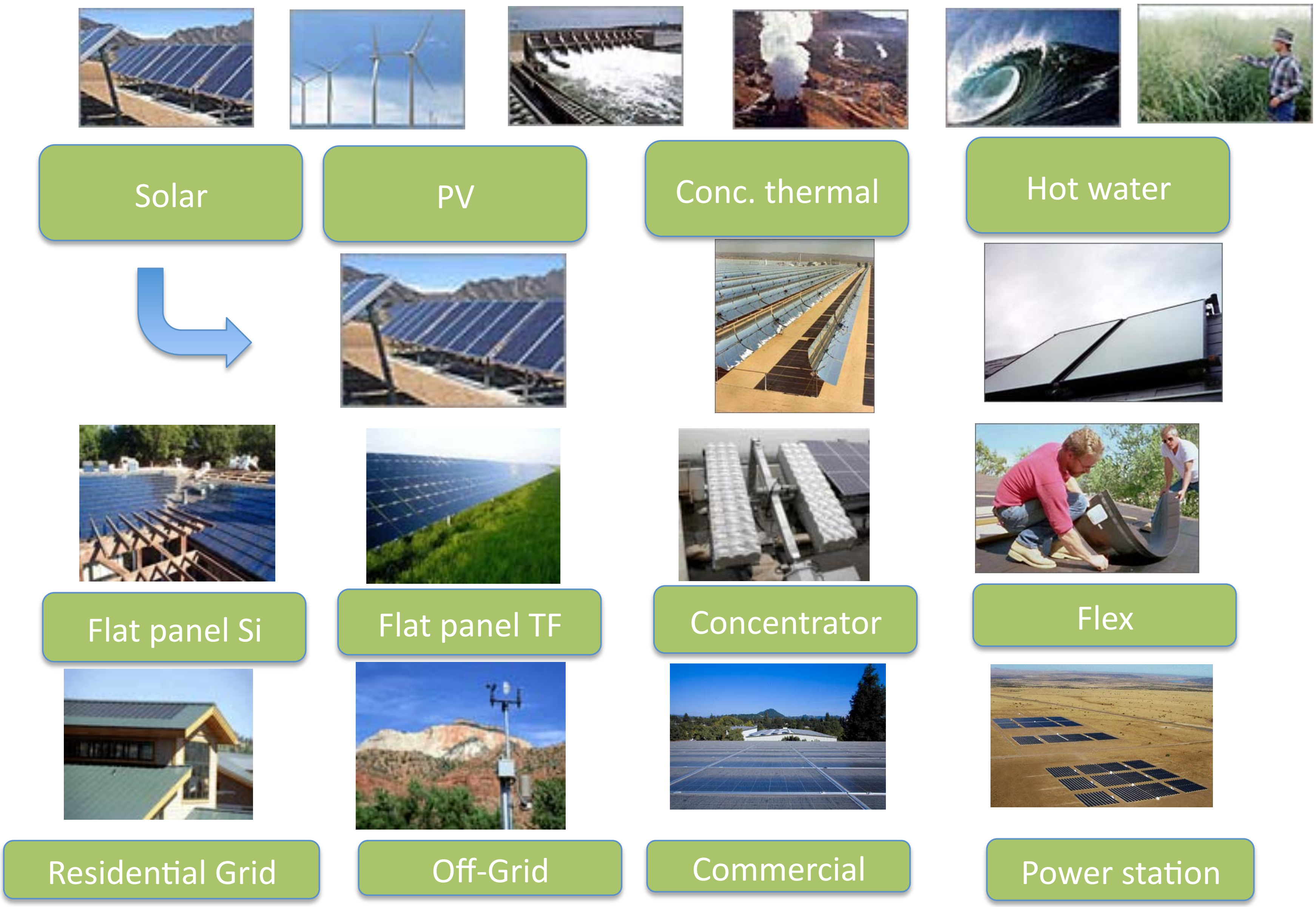


International Space Station (today)

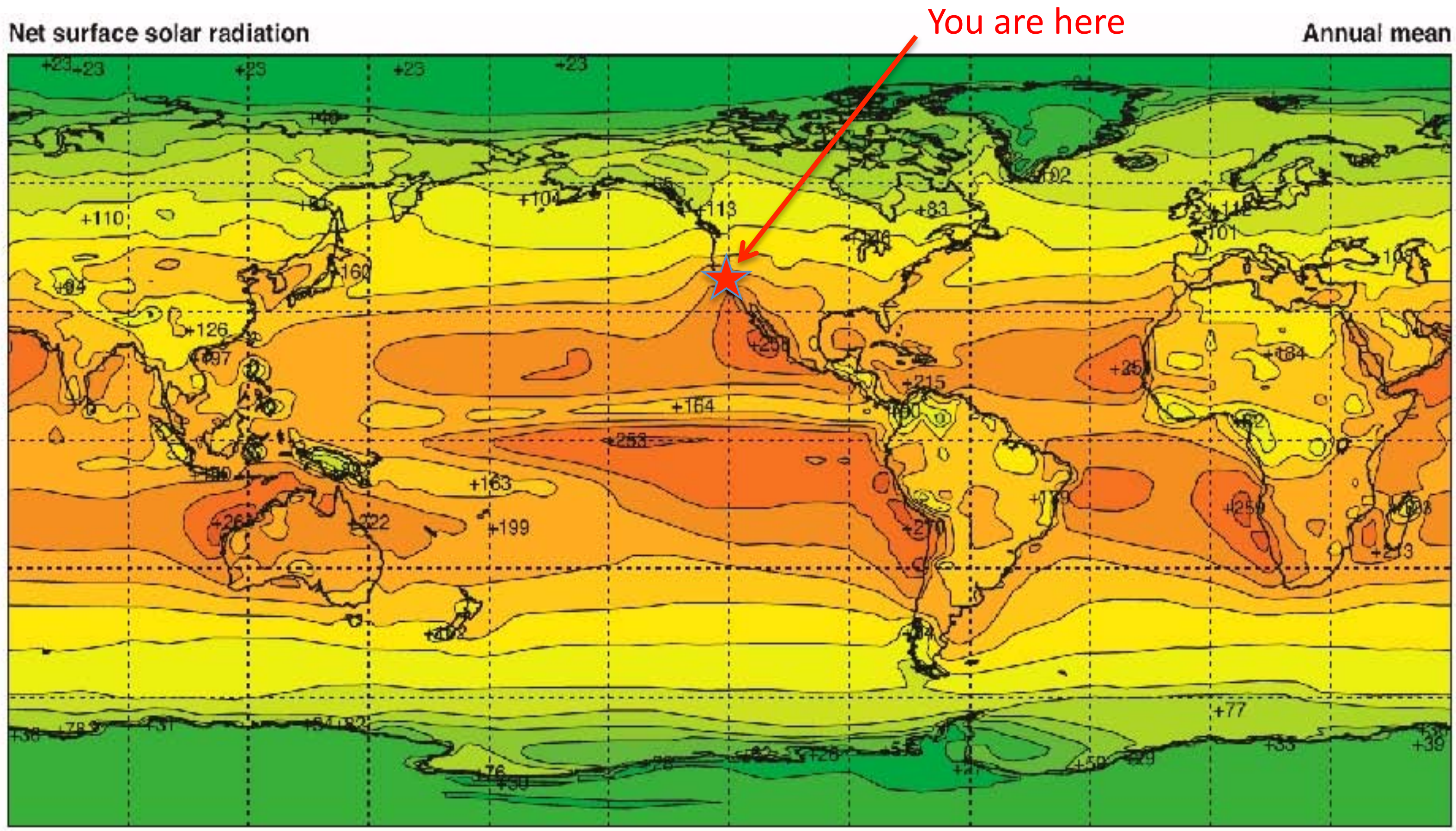


Vanguard (1958) – first satellite with solar cells

Renewable energy sources – the family tree



Solar insolation around the world

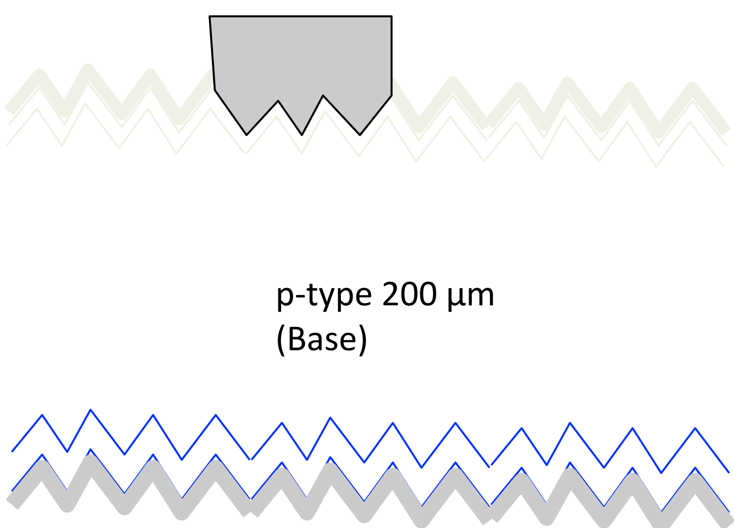


W/ m^2	KWhr/ m^2
500	4380
300	2628
275	2409
250	2190
225	1971
200	1752
175	1533
150	1314
125	1095
100	876
80	701
60	526
50	438
40	350
30	263
20	175
10	88

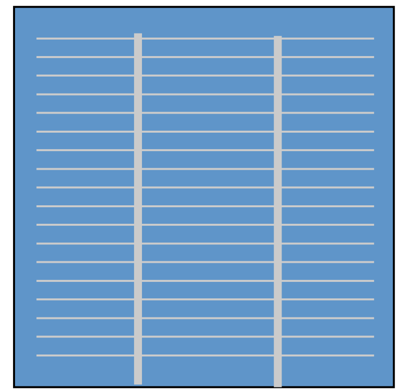
The Bay Area receives annual average 180 W/m^2, or 1550 $KWhr/m^2$.

- Panels are rated at 1 kW/m^2 (a 14% efficient, 1.4 m^2 panel is about 200W)
- An array in the Bay area generates 1550 KWhr/KW (eg 3 KW = 4650 KWhr/yr)

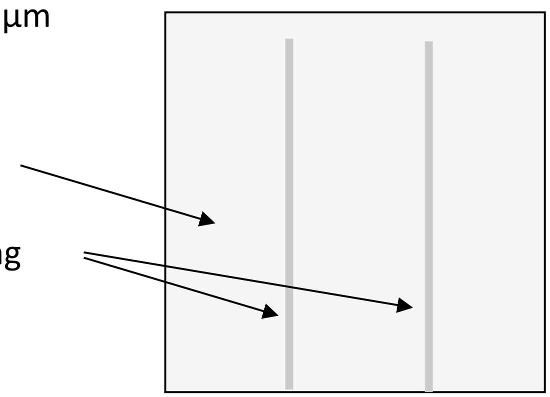
Key parts of a solar cell



Front



125 – 156 mm square

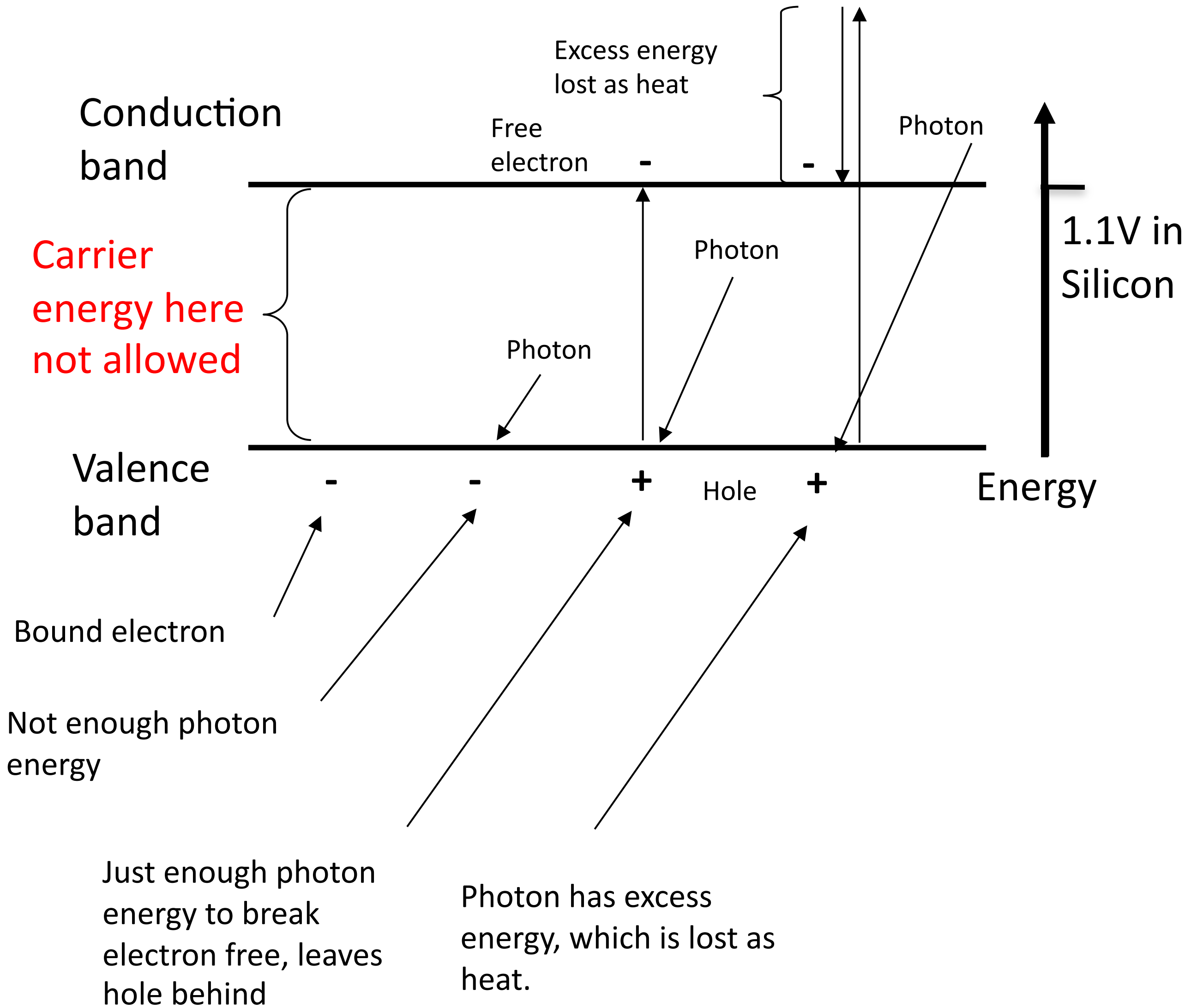


Back

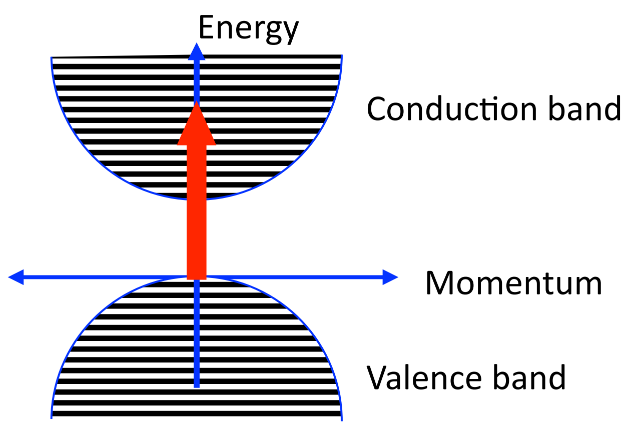
This is the basic design made today; many other designs exist

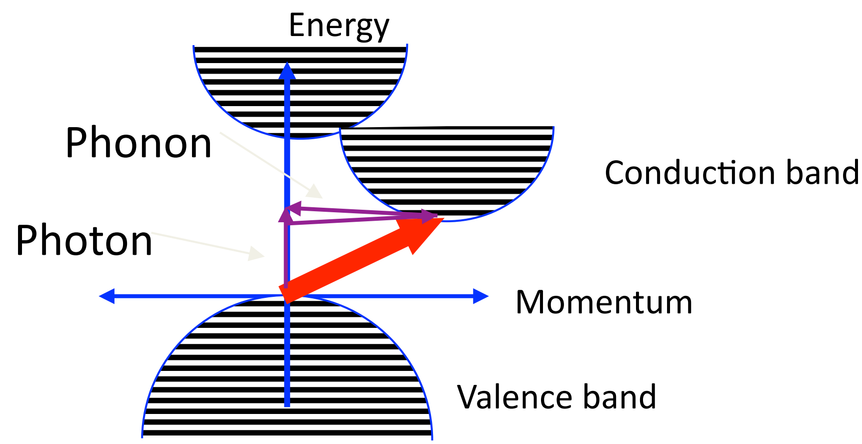
How a solar cell works – light absorption

- Semiconductors have a “Bandgap” energy. Carriers need to absorb at least this much energy to become free to conduct electricity.
- Excess energy is lost as heat. At peak of solar spectrum, 2.5 eV (green), about 60% of energy lost as heat.



Photon absorption





A **direct gap** semiconductor (GaAs)

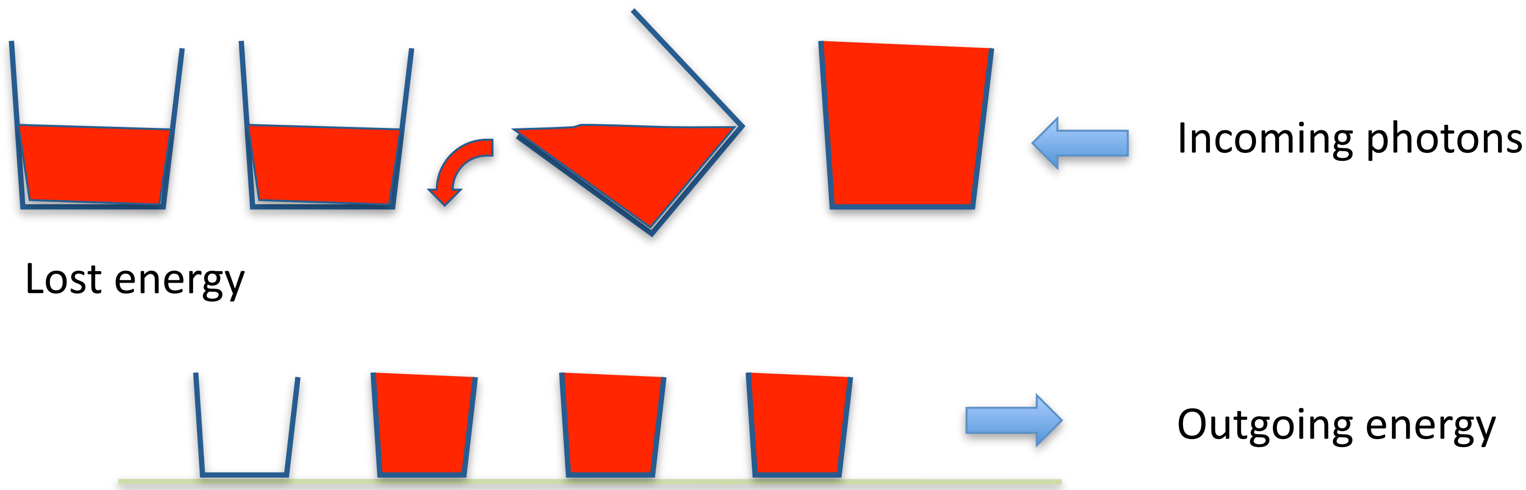
- Conduction and valence bands line up over one another.
- Absorption is an efficient process, and the absorption depth is shallow

An **indirect gap** semiconductor (Silicon)

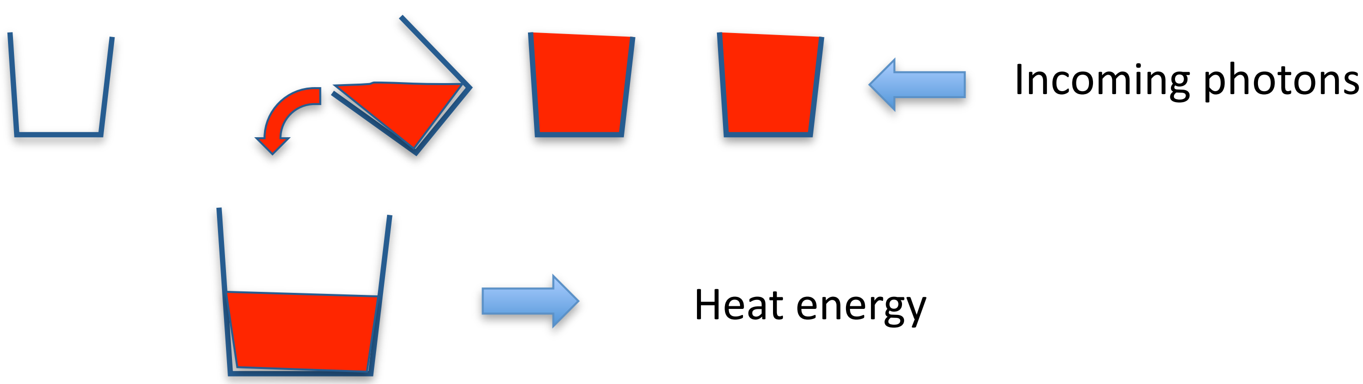
- Conduction band minimum and valence band maximum are offset
- Absorption requires a photon and a phonon (a lattice vibration, which can be absorbed or emitted)
- Absorption is an in-efficient process, and the absorption depth is deep
- Silicon has a direct gap at high energy.

Why photon energy is important

PV has fixed size buckets and can only claim part of the photon energy. Red photons, with less excess energy, convert more efficiently than blue.



Thermal conversion does not have this problem, but needs high temperature to be efficient.



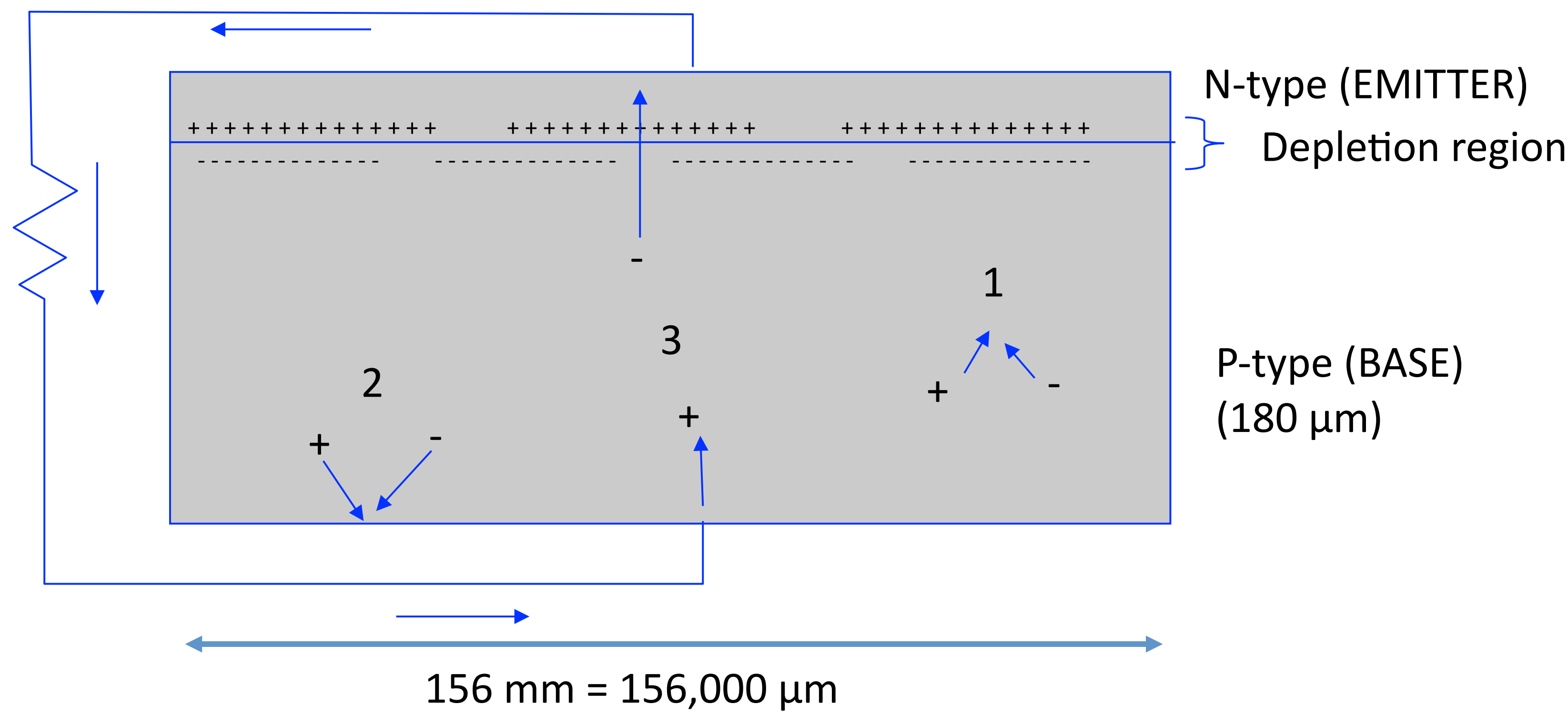
How a solar cell works – collection of carriers

Carriers can do three things:

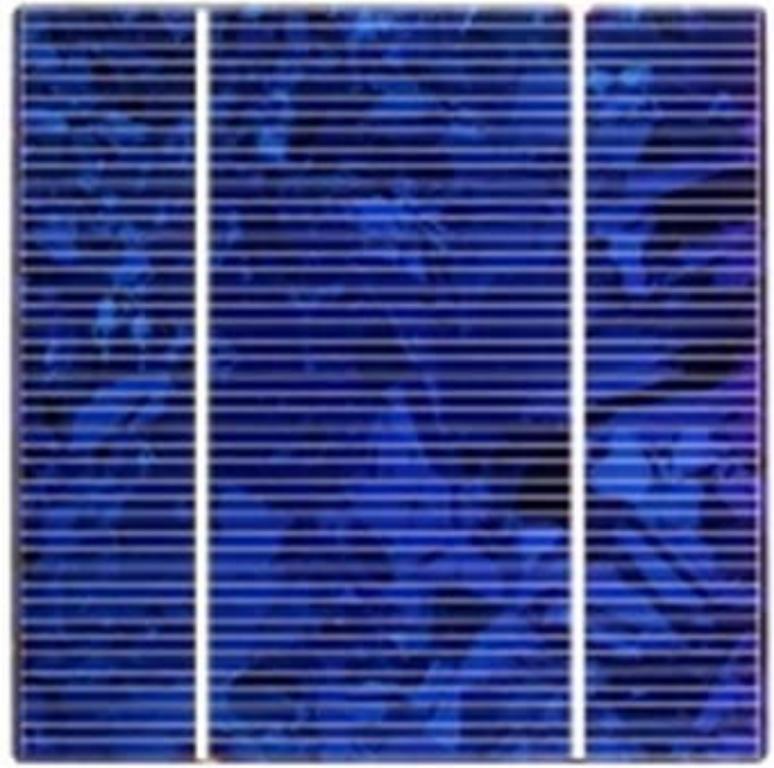
1. Recombine in the bulk
2. Recombine on the surface
3. Get swept across the junction, do work in a load.

Bad – carriers lost

Good – energy does work



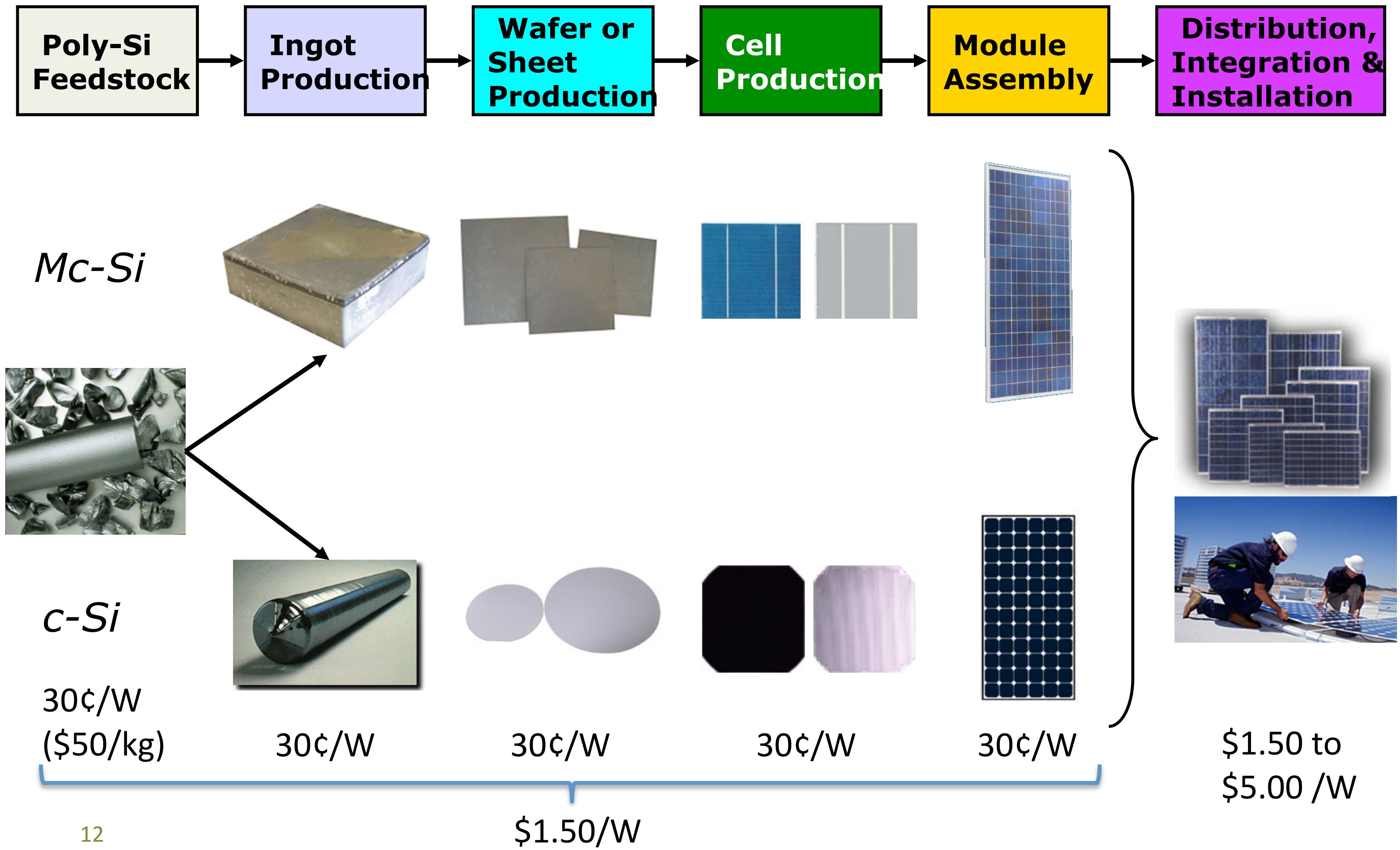
A silicon solar cell



Single crystal

Multi-crystal

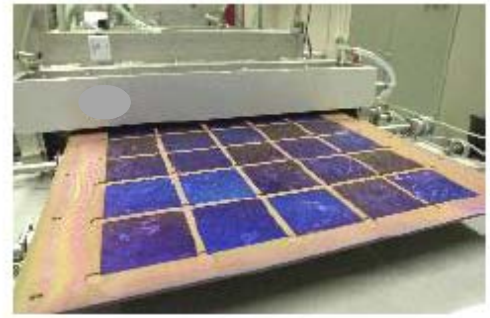
Solar PV Module Value Chain



From Wafer to Solar Cell

chemical etch

pn-junction diffusion



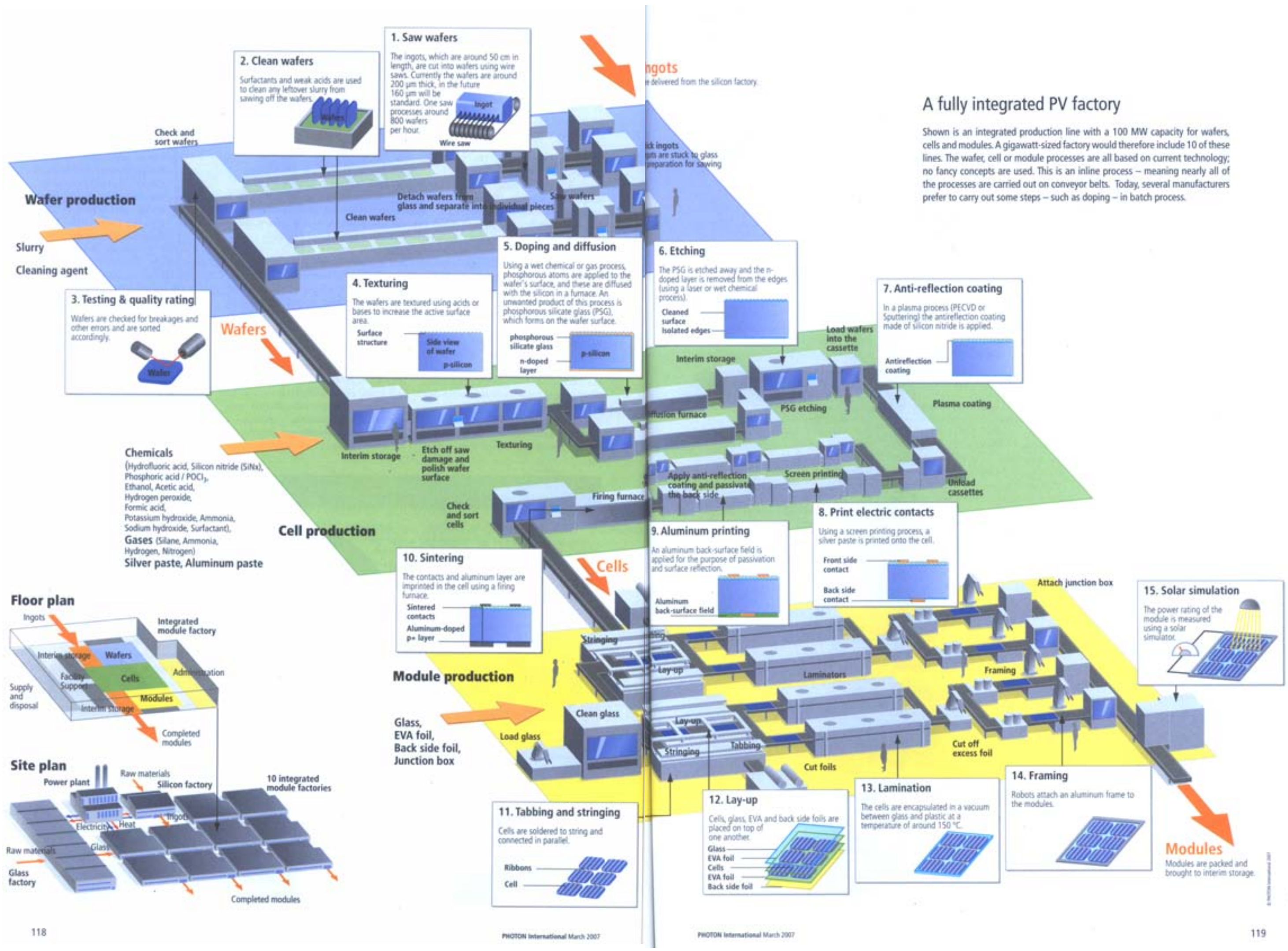
anti-reflection coating

screen printed metallisation

metallisation sintering

solar cell

Wafer-based module production line



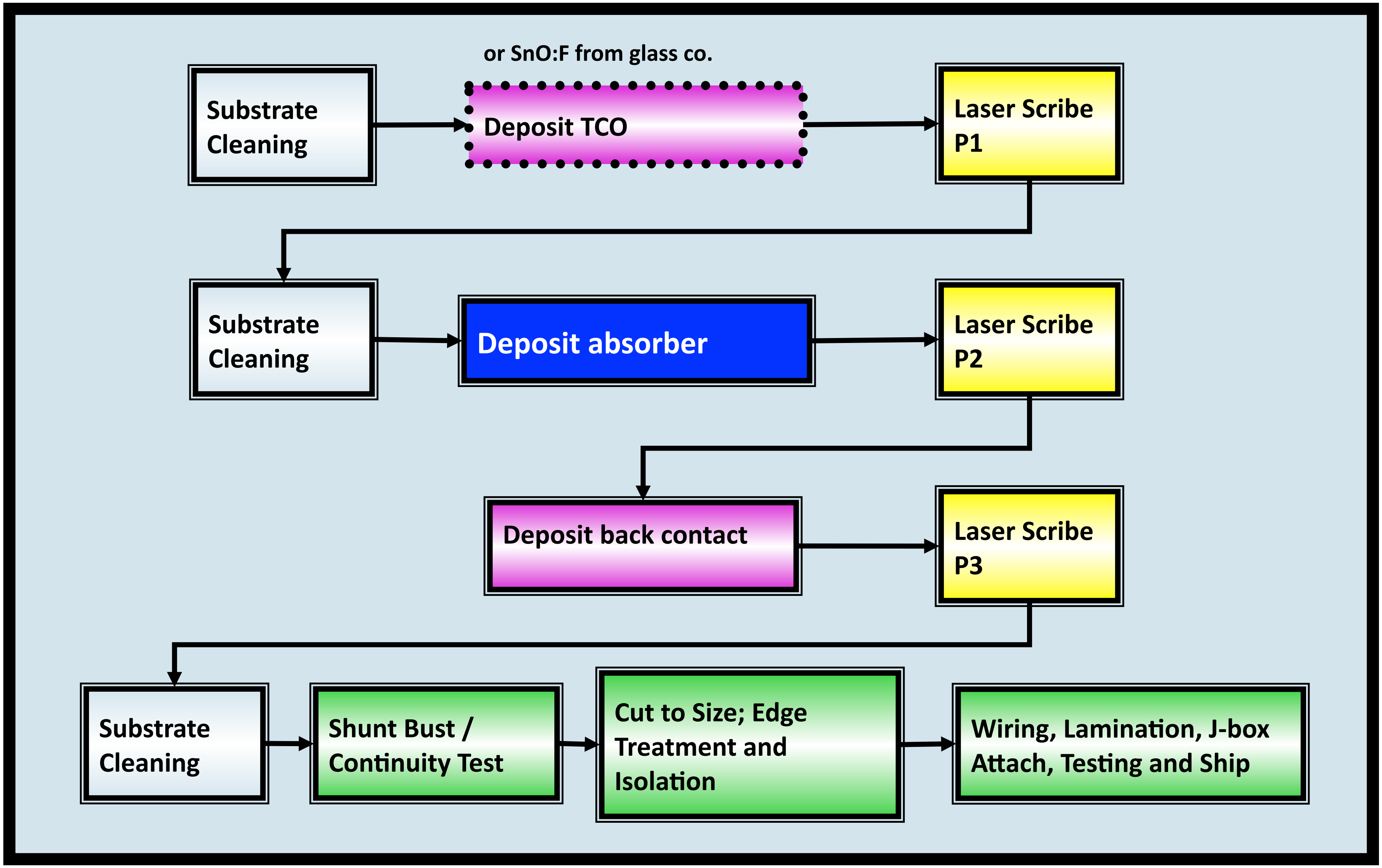
Thin Film technologies

Technology	Best efficiency (cells, R&D)	Module efficiency (Production)	Issues to resolve
Amorphous Si	9%	6.4%	Efficiency
Micromorph (a:Si over uc:Si)	15%	8.5%	Efficiency, deposition rate
CdTe	16.5%	10.8%	Efficiency
CIGS	20.1%	10.8%	Module efficiency, yield, throughput
Organic	6.7%	2-3%	Cost, eff., stability
Third generation	Low	n/a	Many

To compete with silicon, thin film modules need

- efficiencies in the 12-15% range and
- reliability history to become generally accepted in the supply chain.

Thin film factory process flow



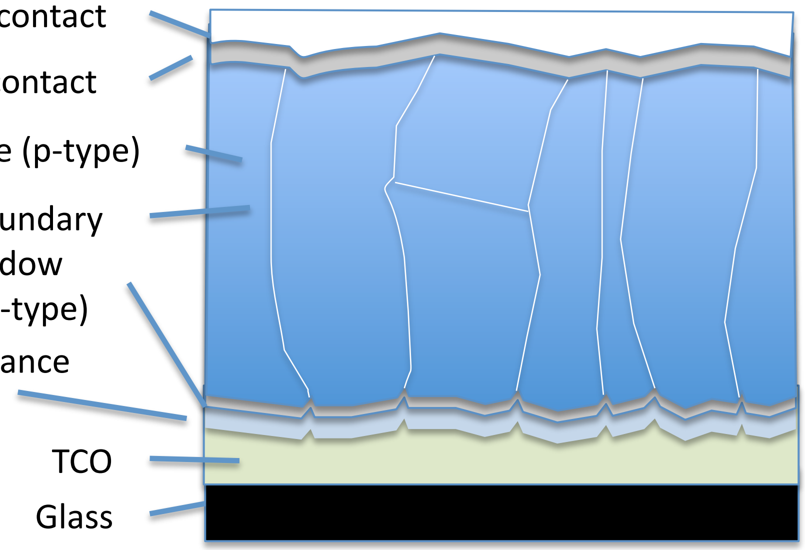
Mainstream technology comparison

	Silicon	Thin film
Efficiency (module)	12-19.5%	6-11%
Stable field performance	>30 years	~15 years
Market share (2009)	85%	15%
Module cost ($/Wp)	~ $1.20/W$_p$	$0.80/W$_p$ (CdTe)
CapEx cost	$2.00/W$_p$	$2.00/W$_p$
Improvement strategy	Lower cost, higher efficiency	Higher efficiency and manufacturing volume
Target markets	All	Large systems, architectural, 3rd world

- Today's largest market is residential rooftop, where silicon's efficiency and reliability is an advantage.
- Customers in larger potential markets, such as utilities and industrial rooftops, are conservative. Driven more by pure cost of energy, demand proven reliability.
- As TF field performance is proven, these markets will open, increasing the TF market share. Increased volume will bring down TF costs.

CdTe cell structure

The CdTe cell uses a hetero-junction between p-type CdTe and n-type CdS. The best lab efficiency is 16.1% (NREL), and commercial modules have efficiency in the mid-10% range. The high efficiency for a thin film cell comes from the columnar grain structure, high mobility, and short absorption length. Special features include a CdCl treatment to create p-type doping and increase grain size, special anneals to get a good junction and back contact, and the high resistance TCO to reduce shunting through the thin CdS layer.



Some material properties:

Band gap 1.5 eV

Electron affinity 4.28 eV

Absorption coef 6×10^{4}/cm@600 nm

Index of refraction 3

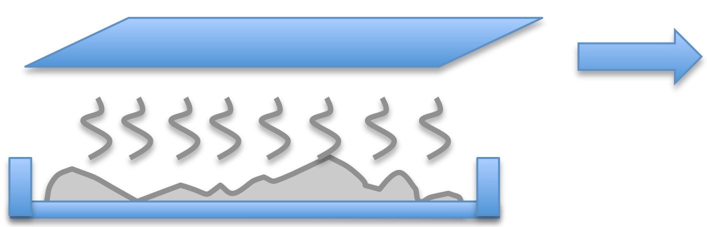
Mobility (electron) 500-1000 cm^{2}/V-sec

Mobility (hole)50-80 cm^{2}/V-sec

CdTe deposition

CdTe can be deposited by a number of processes, including sputtering, evaporation, screen printing, and spraying. The most successful commercial process is Close Space Sublimation. The glass substrate is heated to 600°C and brought close to a bed of CdTe heated to 650-750°C at a pressure of about 10 Torr. Layer thickness is about 4 μm, deposited at a rate of 1-5 μm/min.

Substrate at 600°C



CdTe at 650-750°C

This process is simple and yields the stochiometry and grain structure for best efficiency, which is why CdTe today offers the lowest $/W of any commercial product.

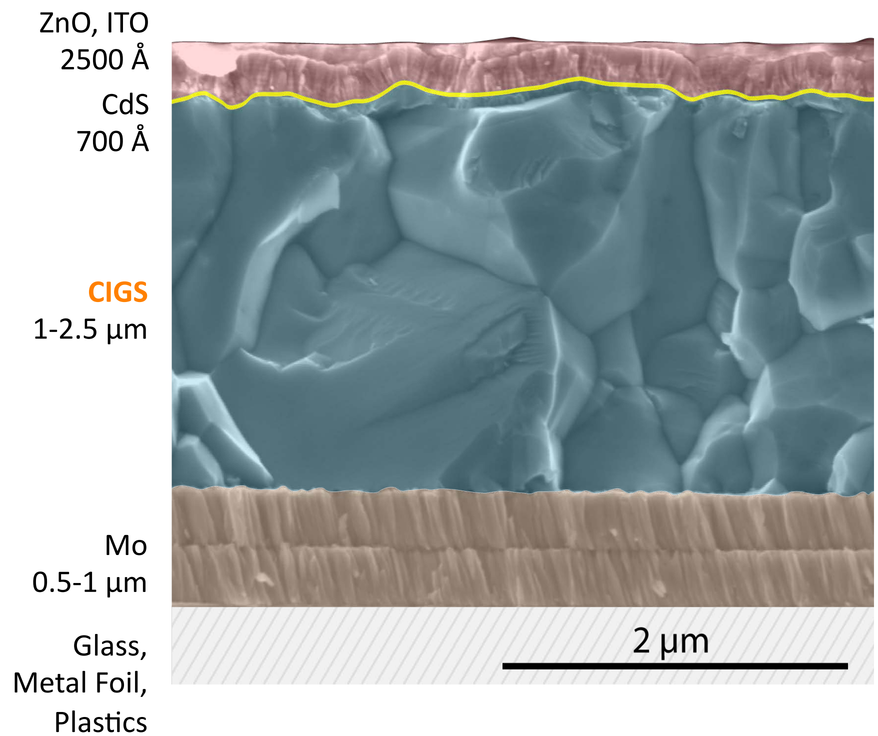
Issues include small module size, because glass softens at 600°C, and cleaning of excess CdTe in the chamber.

CIGS structure

CIGS has the highest efficiency of any thin film cell – 20.1%. It uses a hetero-junction between p-type CIGS and n-type CdS. The CdS is often plated in a wet bath following deposition.

A back contact is formed with a two-layer Mo deposition, the paired layers used to reduce stress.

Unlike other thin film cells, the light is incident from the top (as opposed to through the substrate).



R. Noufi, 4th WCPEC, 2006

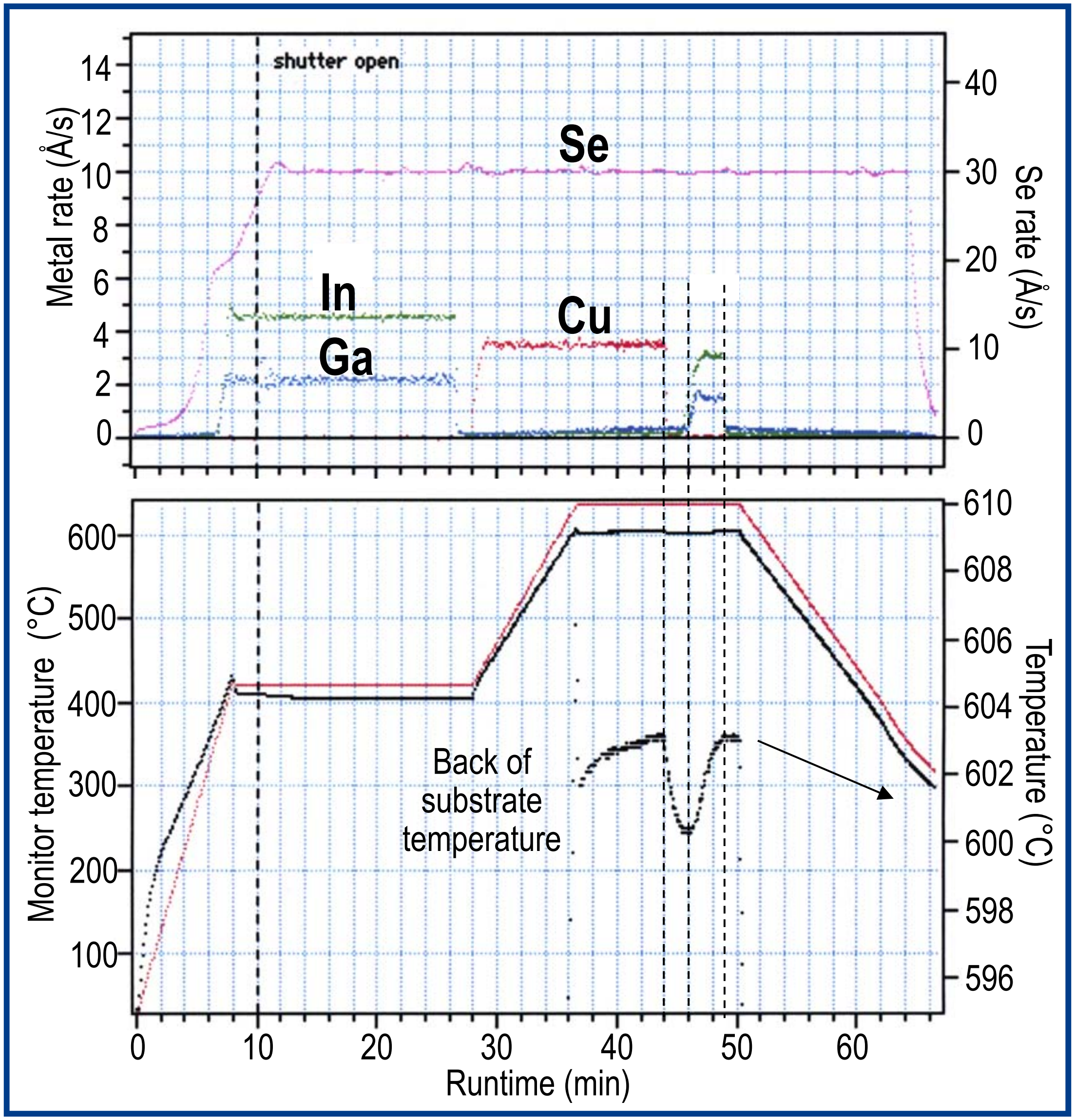
$$\frac{Cu}{(In+Ga)} = 0.82 - 0.95$$

$$\frac{Ga}{(In+Ga)} = 0.26 - 0.31$$

Deposition

CIGS is formed using a variety of processes. The highest efficiency was obtained with co-sputtering of In, Ga and Cu in a Se background, following the deposition rate and temperature profile shown to the right. This yields the optimum stochiometry and grain structure.

The composition will sometimes be graded to create a drift field from back to front. In some cases, it is found that Na can improve performance, coming either from the glass substrate or the deposition.

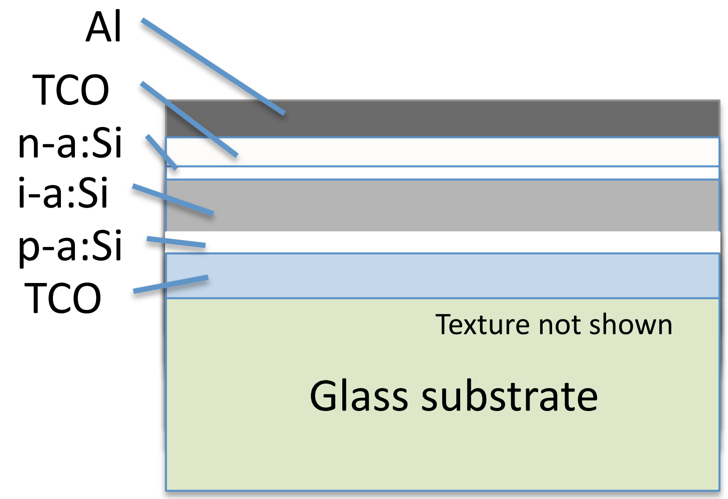


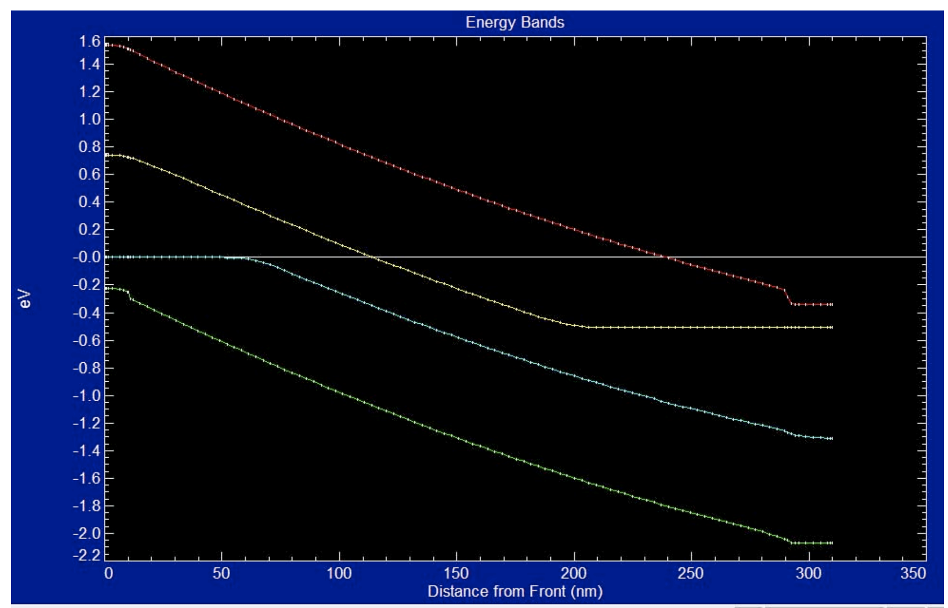
Amorphous silicon cell structure and process

Amorphous silicon is one of the oldest thin film technologies. It offers a low cost cell, with efficiencies in the 5-6.5% range.

The active region is typically 3-500 nm thick. It is undoped, forming a drift field to accelerate carriers across the cell (see band diagram below right). This is needed because of the very short diffusion length due to the poor lifetime.

The bandgap ranges from about 1.75 to 1.9 eV, depending on the deposition process.





Amorphous silicon band gap

A purely amorphous material would not be photo-active. However, short-range order leads to a density of states with a minimum, thereby creating a bandgap. The band edges are not sharply defined, but have tails, as shown below. A high density of states in the gap leads to the short lifetime.

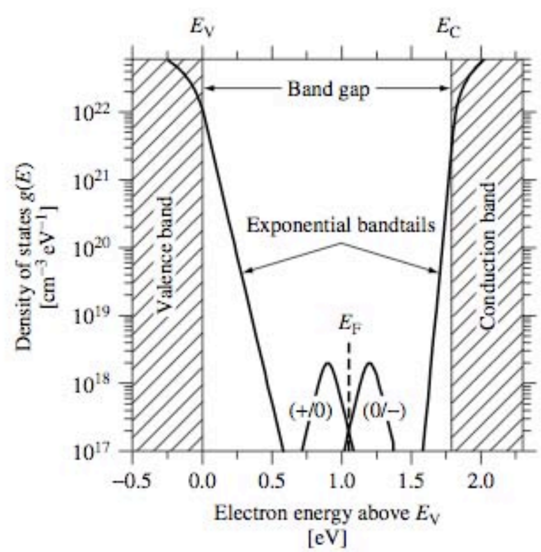
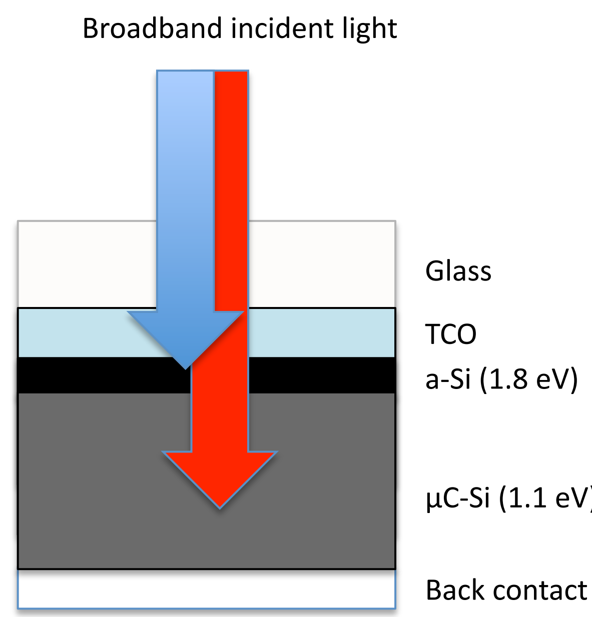


Figure 12.9 Density of electronic states $g(E)$ in hydrogenated amorphous silicon. The shaded areas indicate delocalized states in the bands; these bands themselves have tails of localized states with an exponential distribution. Midway between the bands are levels belonging to gross defects such as dangling Si bonds indicated by the two peaked bands around E_F

Handbook of Photovoltaic Science and Engineering, Luque and Hegedus Ed.

Micromorph cells

Higher efficiency can be obtained using stacked cells with multiple bandgaps. A 1.8 eV bandgap a-Si cell absorbs shorter wavelength light, passing the longer wavelength light to a µC-Si cell with a bandgap of 1.1 eV. More sophisticated designs add a third Si-Ge cell to obtain laboratory efficiencies > 13%.



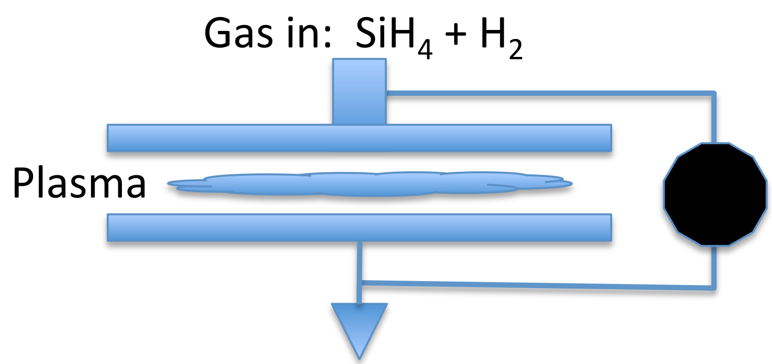
This configuration adds some issues:

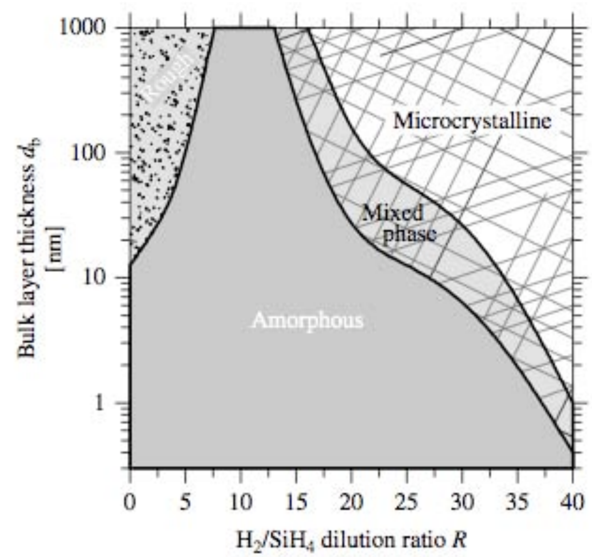
- The µC-Si cell is 1-2 µm thick, and requires a long deposition time,
- The cells must use a low resistance tunnel junction interconnect, and
- Cell currents must match, which makes the cell spectrally sensitive.

Thin film silicon deposition processes

The most common deposition process is plasma-enhanced chemical vapor deposition (PE-CVD), although other methods such as hot wire CVD have been used. Deposition rates are on the order of 0.5-3 nm/sec, with lower rates providing better efficiency. Higher rf frequencies are sometimes used to improve the deposition rate, although this leads to more complex reactor designs because of standing waves.

The hydrogen dilution can control whether amorphous or micro-crystal silicon is deposited (see graph to the right. High dilution ratios are best for µC-Si.





Handbook of Photovoltaic Science and Engineering, Luque and Hegedus, Ed.

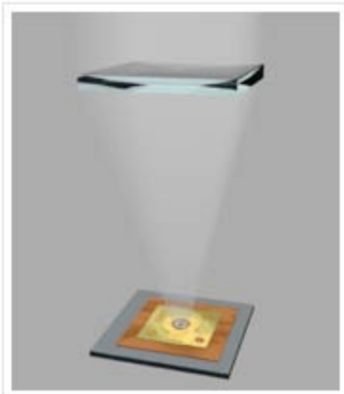
Concentrators

- Concentrators replace expensive cell area with low cost optics such as mirrors or fresnel lenses.

- Advantages include
  - Among lowest cost/watt potential
  - High output for longer fraction of the day

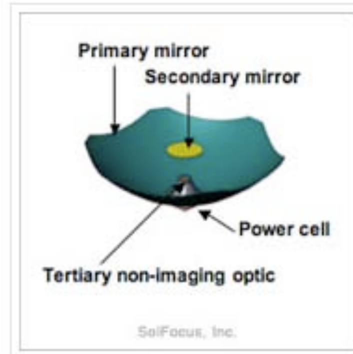
- Drawbacks include
  - Greater reliability concerns
  - Spectral sensitivity when using multi-junction cells
  - Tracker limits market to industry and utilities, with the latter having steep reliability requirements
  - Far behind the cost curve

Basic concentrator approaches



FLATCON CPV cell

FLATCON solar module



SolFocus Gen1 Mini-dish

SolFocus Gen1 solar module prototype

A fresnel lens focuses light onto a small high efficiency solar cell. The module consists of an array of lenses and cells

A mirror concentrates light onto a small high efficiency solar cell. Secondary optics can fold the optical path to reduce the size.

An important trade-off is tracking accuracy vs. concentration

- Low concentration (few tens of suns) have high tracking error margi, and low tracker cost, but less gain from using high efficiency, high cost cells.
- High concentration (>100 suns) requires better tracker, but can use better cells

Flexible solar cells

Plusses

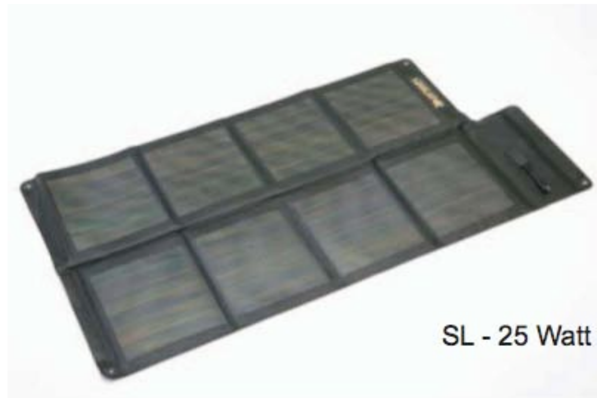
- Flexible
- Light weight

Issues

- Low efficiency
- Reliability

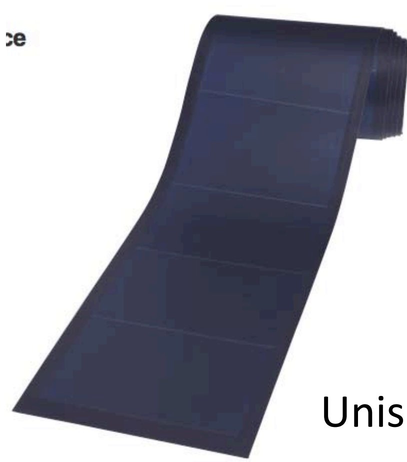
Applications

- Portable devices
- BIPV
- Chargers



Global Solar (CIGS)

Fuji Electric (a-Si)

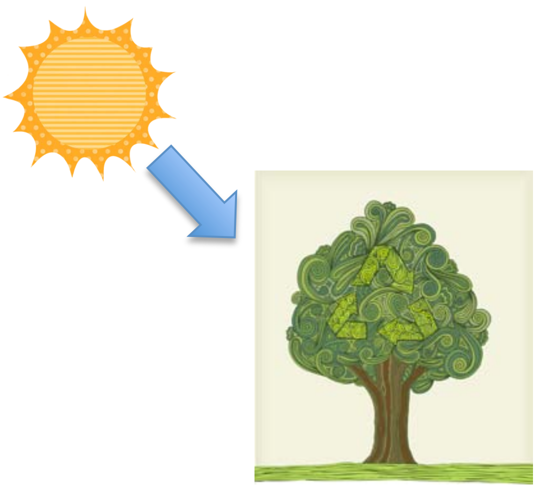


Unisolar (a-Si/a-SiGe)

The meaning of efficiency

Conversion efficiency is a relative number (if the sun were 2X brighter, half the efficiency would be just as good).

Compare to the efficiency of a well known solar converter: a tree



1.5×10^{13} joules in:

- 10 m diameter, 10 m high
- 25 years AM1.5 for 6 hrs/day

3.9×10^{10} joules out:

- 1 m diameter base, 500 kg/m^3
- 10^7 J/kg yield (70% efficient)

Tree is 0.25% efficient
Best PV cell is 41.6% (164 x tree)
Best PV panel is 20% (80 x tree)

Note: Algae and some plants may be
1-2% efficient.

Ideal efficiency limits – one junction

Original calculation by Schockley and Queisser (J. Appl. Phys. 32, 510-519, 1961). Assumes only radiative recombination in an ideal semiconductor cell. Predicts ≈31% for silicon, 32.8% for GaAs @ 1 sun.

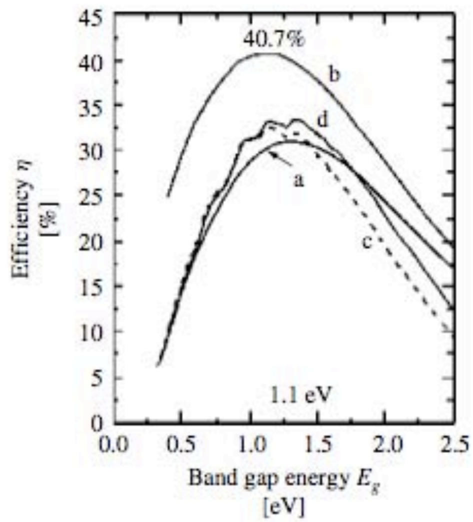


Figure 4.3 SQ efficiency limit for an ideal solar cell versus band gap energy for unconcentrated black body illumination, for full concentrated illumination and for illumination under the terrestrial sun spectrum: (a) unconcentrated 6000 K black body radiation (1595.9 Wm^{-2}); (b) full concentrated 6000 K black body radiation (7349.0×10^4 Wm^{-2}); (c) unconcentrated AM1.5-Direct [18] (767.2 Wm^{-2}) and (d) AM1.5 Global [18] (962.5 Wm^{-2})

The optimum bandgap for one junction is 1.4 eV, close to GaAs, but Si is nearly optimum.

Handbook of Photovoltaics, Luque and Hegedus

Efficiency at low and high concentration

- At low concentration (left), the peak efficiency is about 29% for ideal light trapping.
- At high concentration (right), the peak efficiency increases with acceptance angle because normal-incident rays are more readily trapped, although cells are impractically thin.

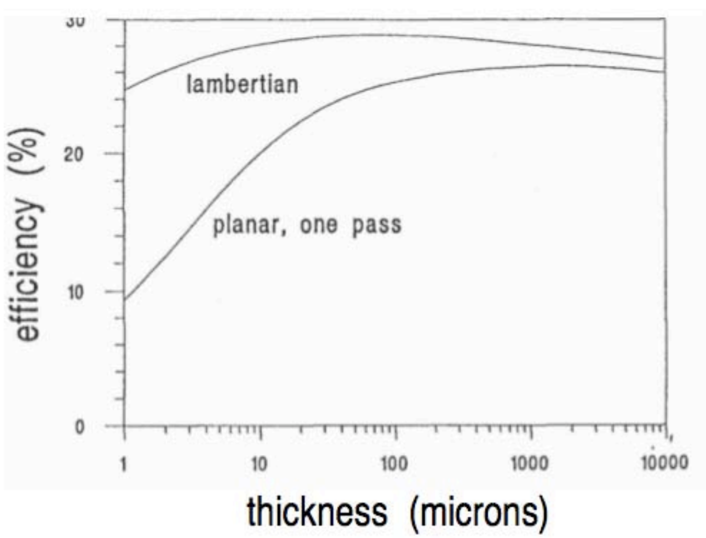
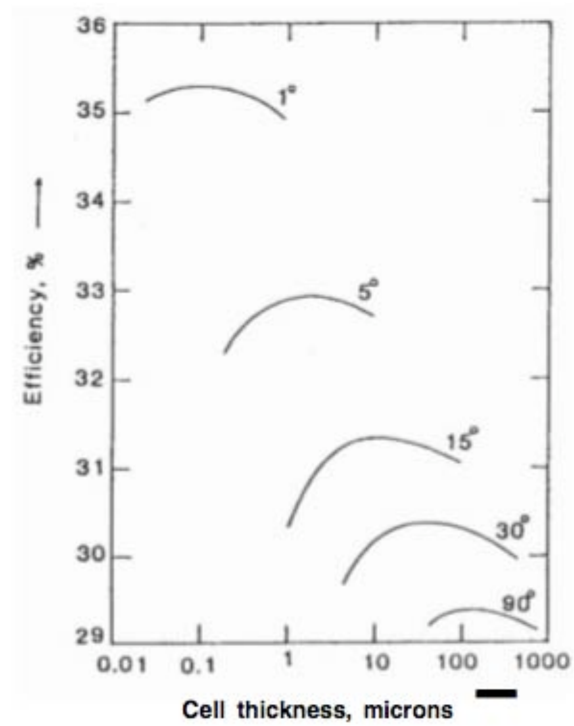


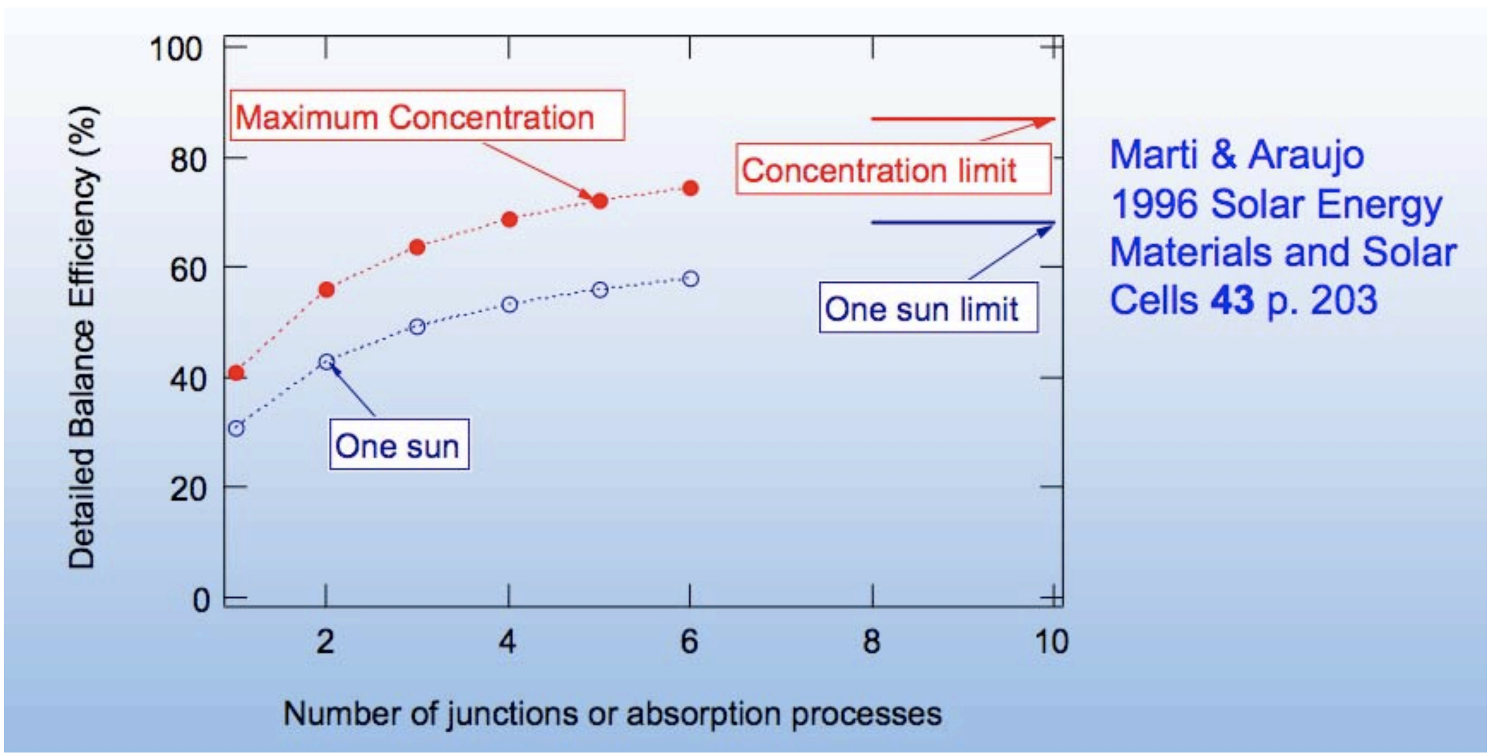
Figure 7.6: Limiting efficiency of a silicon solar cell with and without Lambertian light trapping (Global AM1.5 spectrum, 100 mW/cm^2, 25°C).

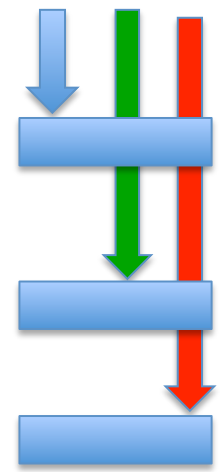


From Green, "Silicon Solar Cells: Advanced Principles & Practice, UNSW Press

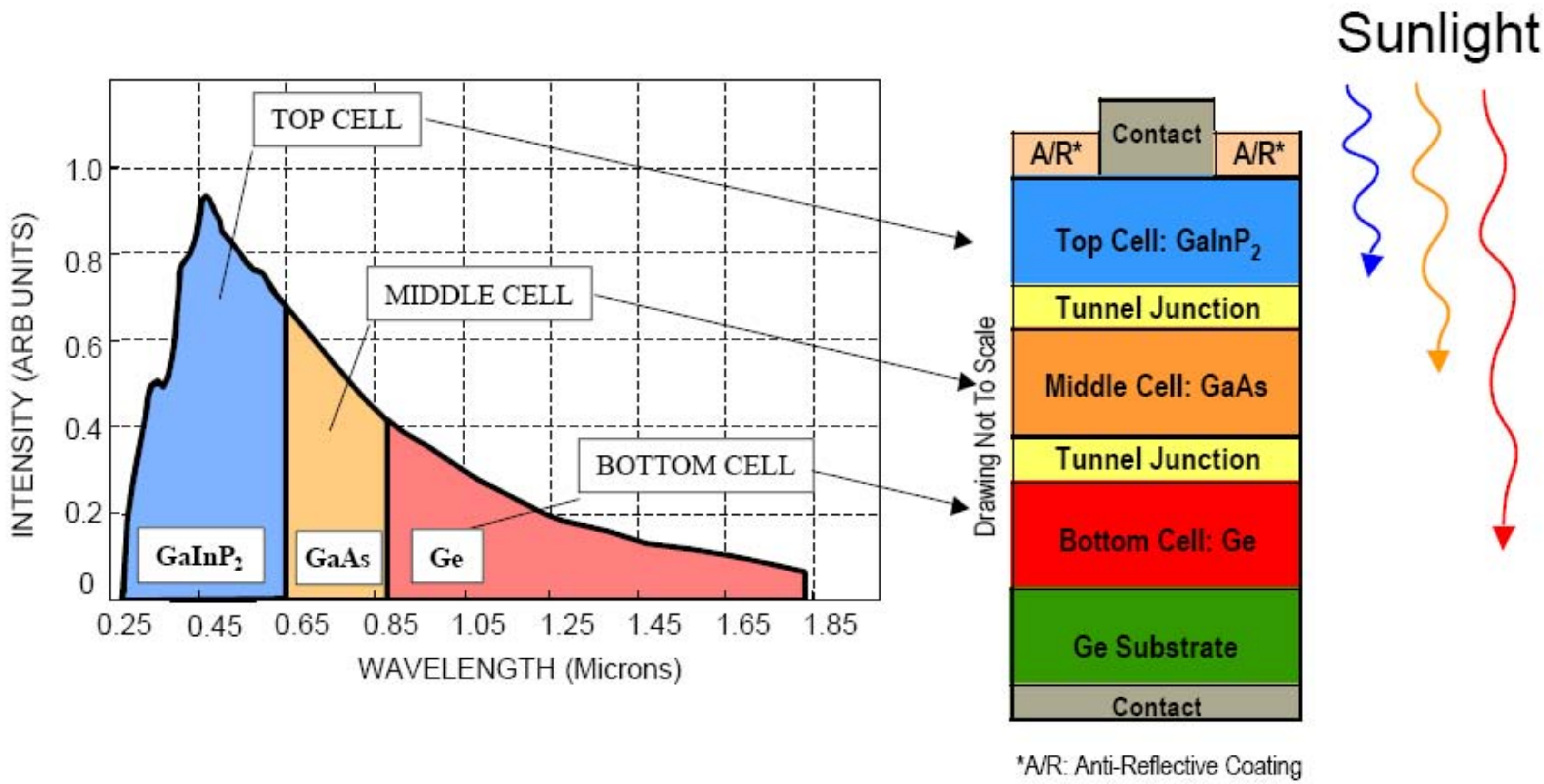
Multiple junctions can do even better

≈70% at 1 sun and ≈86% at maximum concentration, but requires infinite stacked junctions.





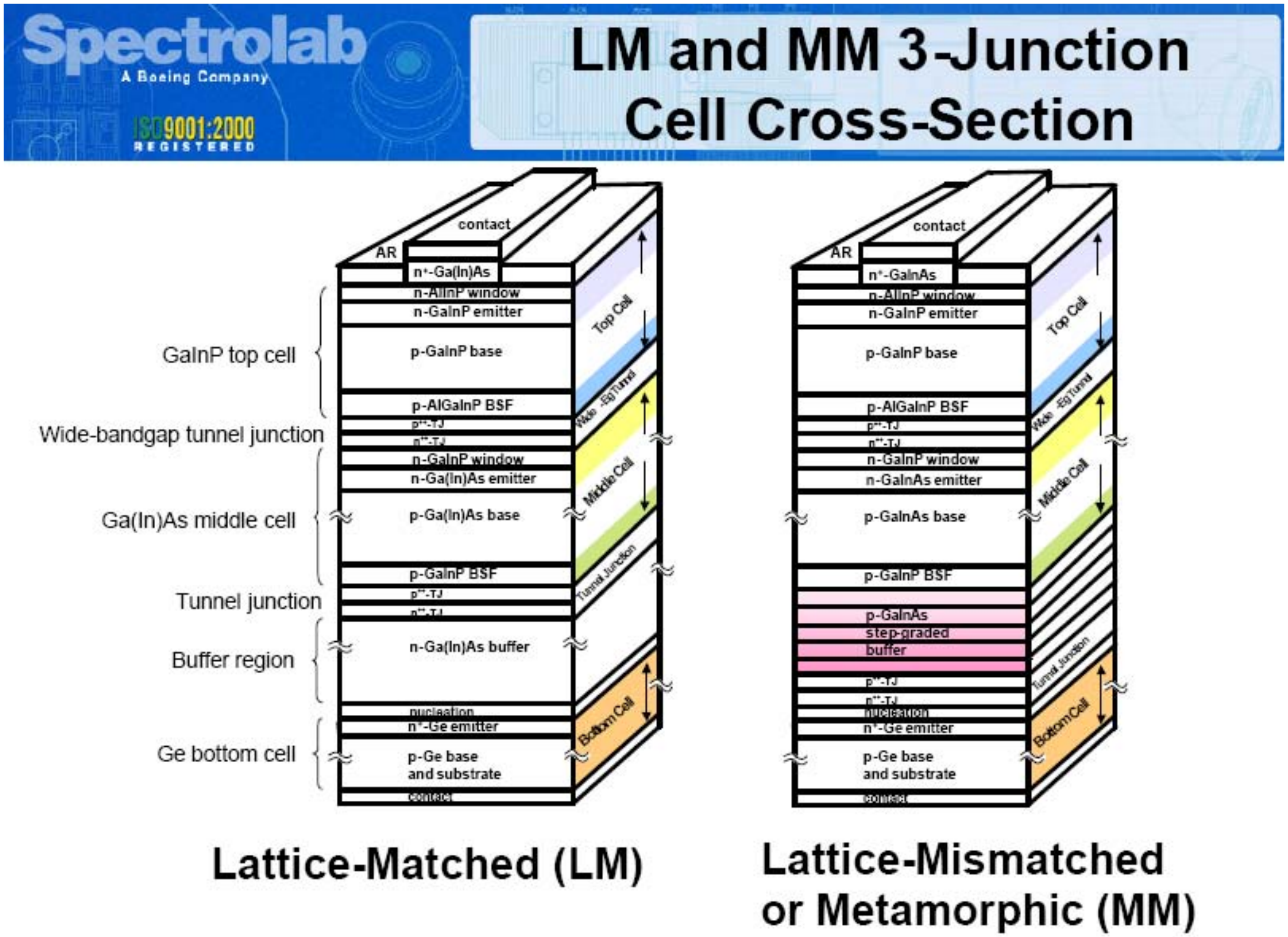
41.6% concentrator cell designed for W/gm, not $/W



- Typical cell contains >20 layers;
- Designed for space, adapted for concentrators

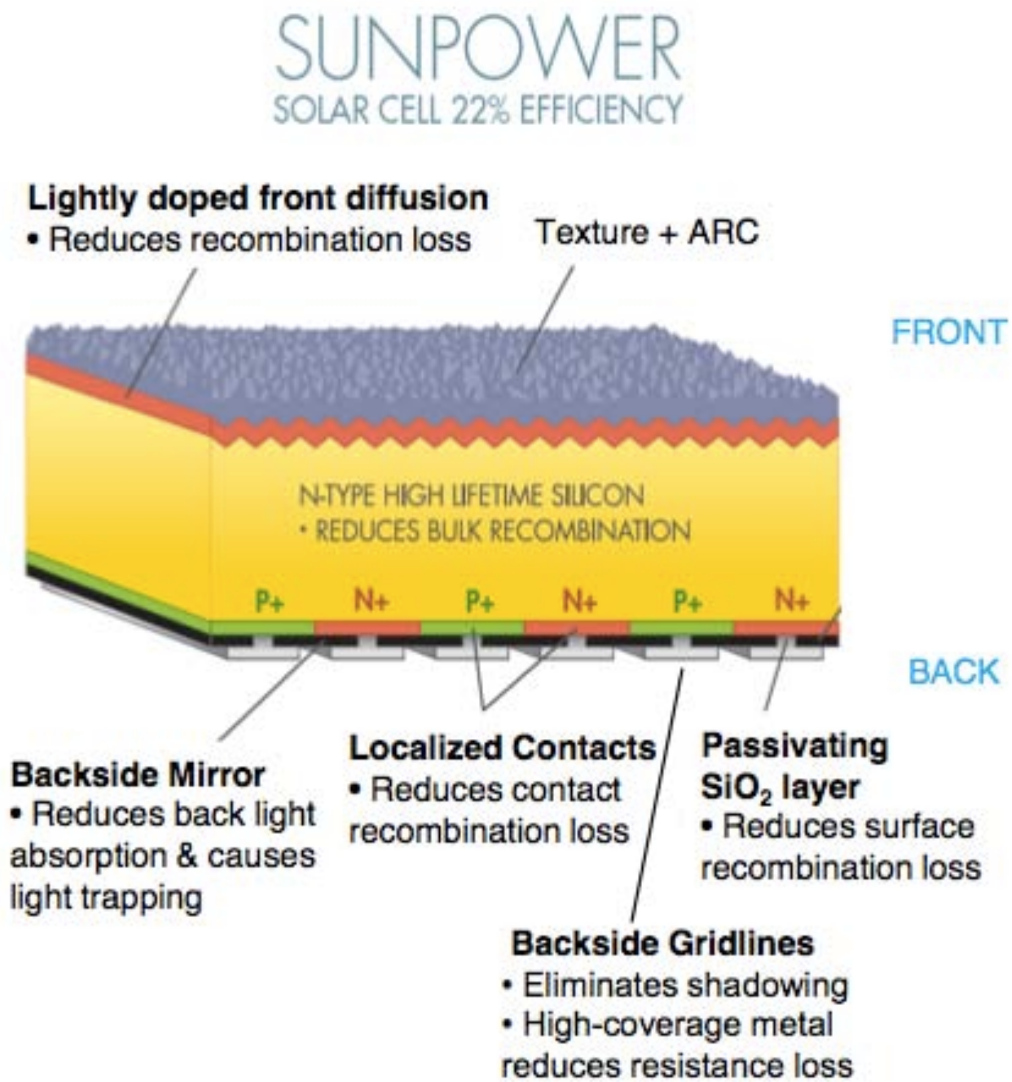
Source: Spectrolab

Detailed structure of high efficiency concentrator cell



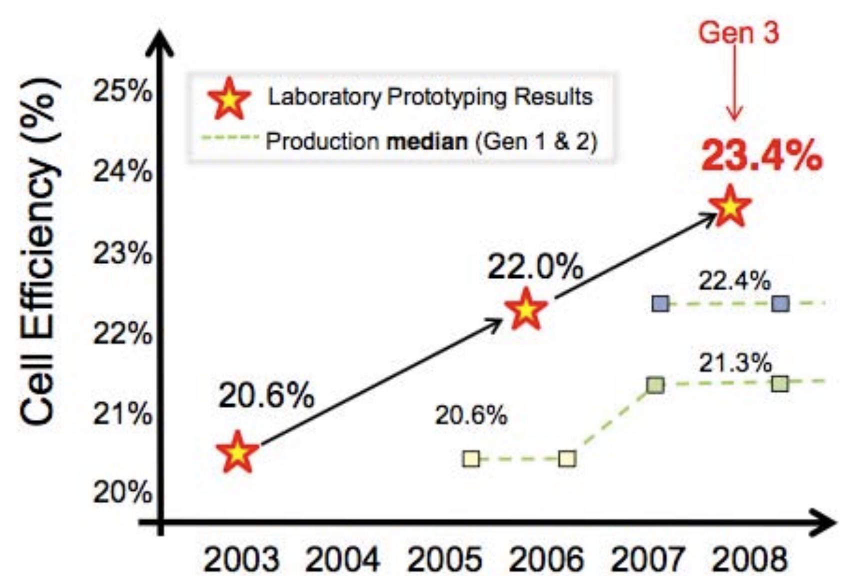
Expensive cell, but small area makes it practical for concentrators.

SunPower cells



These are the highest efficiency cells made today. They use localized back contacts with a back reflector, and have no front grid.

D. Rose, SunPower Corporation



Suntech's Pluto Cell

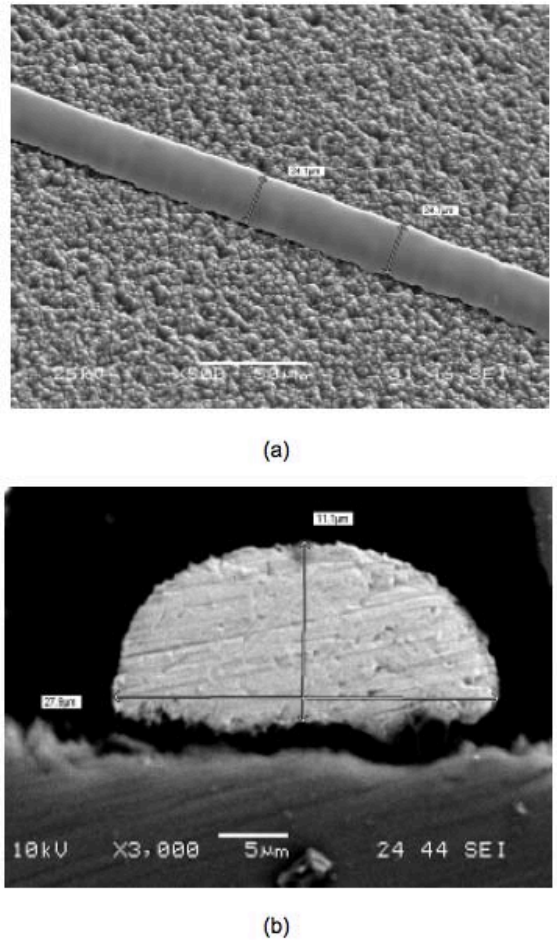


Figure 3: (a) Typical metal finger for the PLUTO cell demonstrating line width, height and aspect ratio the same as routinely achieved by the PERL cell using photolithographic and masking techniques. (b) Shows the cross-section of a typical PLUTO metal line.

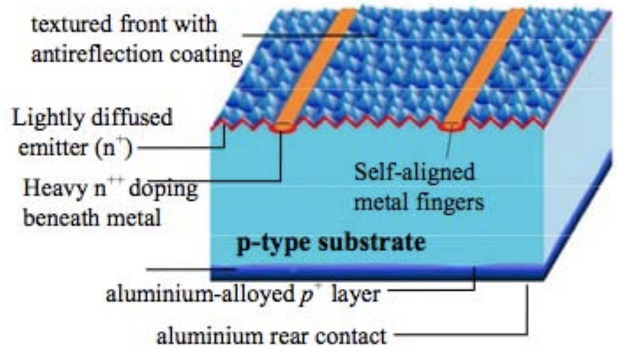


Figure 5: Schematic of the simplified PLUTO solar cell with screen-printed and fired rear aluminium contact and front metal lines only 20-25 microns wide.

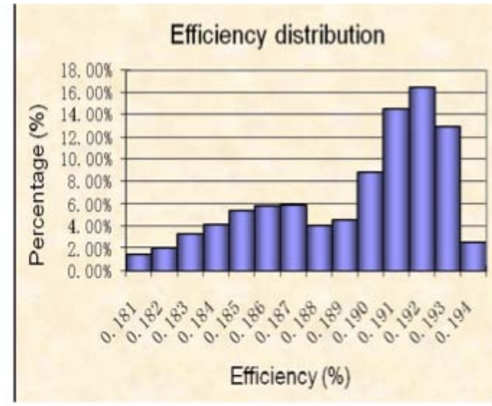


Figure 6: Typical efficiency distribution for a single-day's production of the 34MW PLUTO production line following 6 months of operation. The bi-modal distribution has been shown to be caused by wafers fitting into two distinct categories based on quality.

Process features

- Selective emitter
- Fine grid lines with high aspect ratio (enabling close spacing to minimize ohmic losses with selective emitter)
- Relatively little added cost over conventional process
- 1-2% absolute efficiency gain

From Shi, Wenham and Ji, 2009 IEEE PVSEC, Philadelphia

Tracking flat panel – a hybrid solution with >20% gain

Nellis Air Force Base - 14 MW - Nevada, USA

Bavaria Solar Park - 10 MW - Bavaria, Germany

Applied Materials Sunnyvale – 1 MW

SunPower trackers and field applications

Tracking flat panel option with high efficiency

High efficiency, as available with many silicon flat panels, makes tracking economical. This is viable for power station and some commercial applications, resulting in significant gains. Polar tracking is found to be nearly as good as two axis tracking.

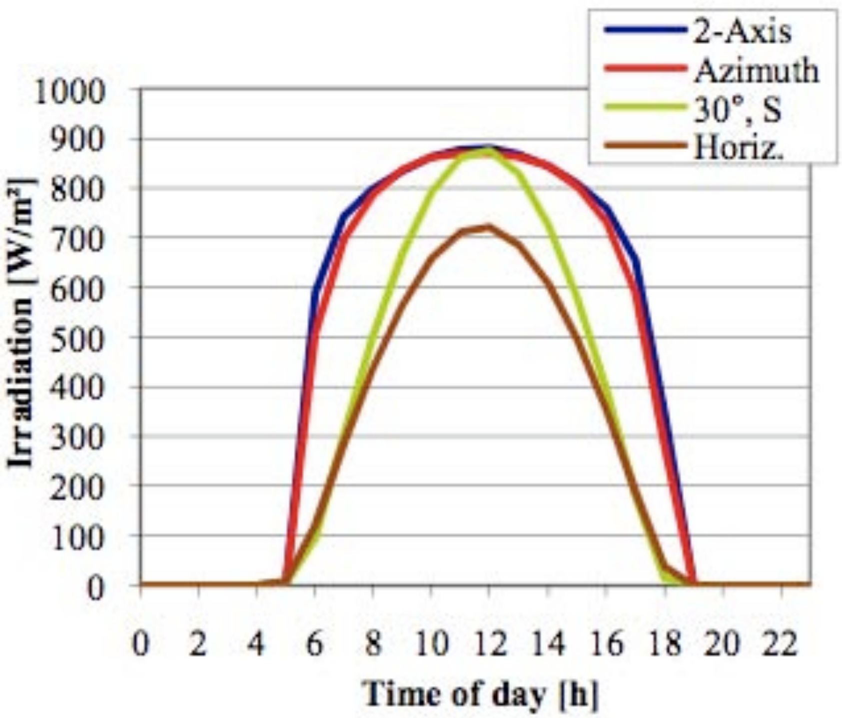


Fig. 7: Daily profile of the irradiance for September, 1st

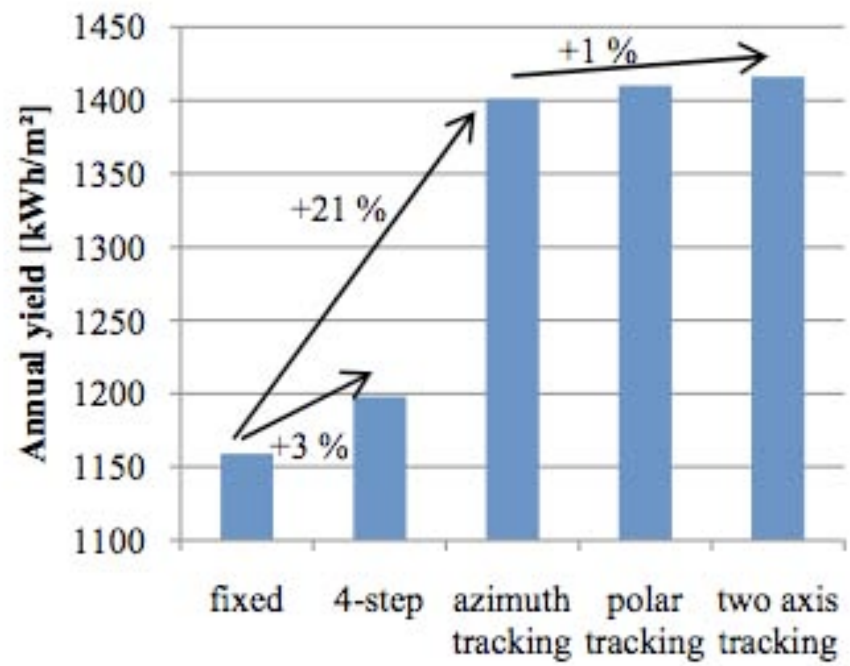
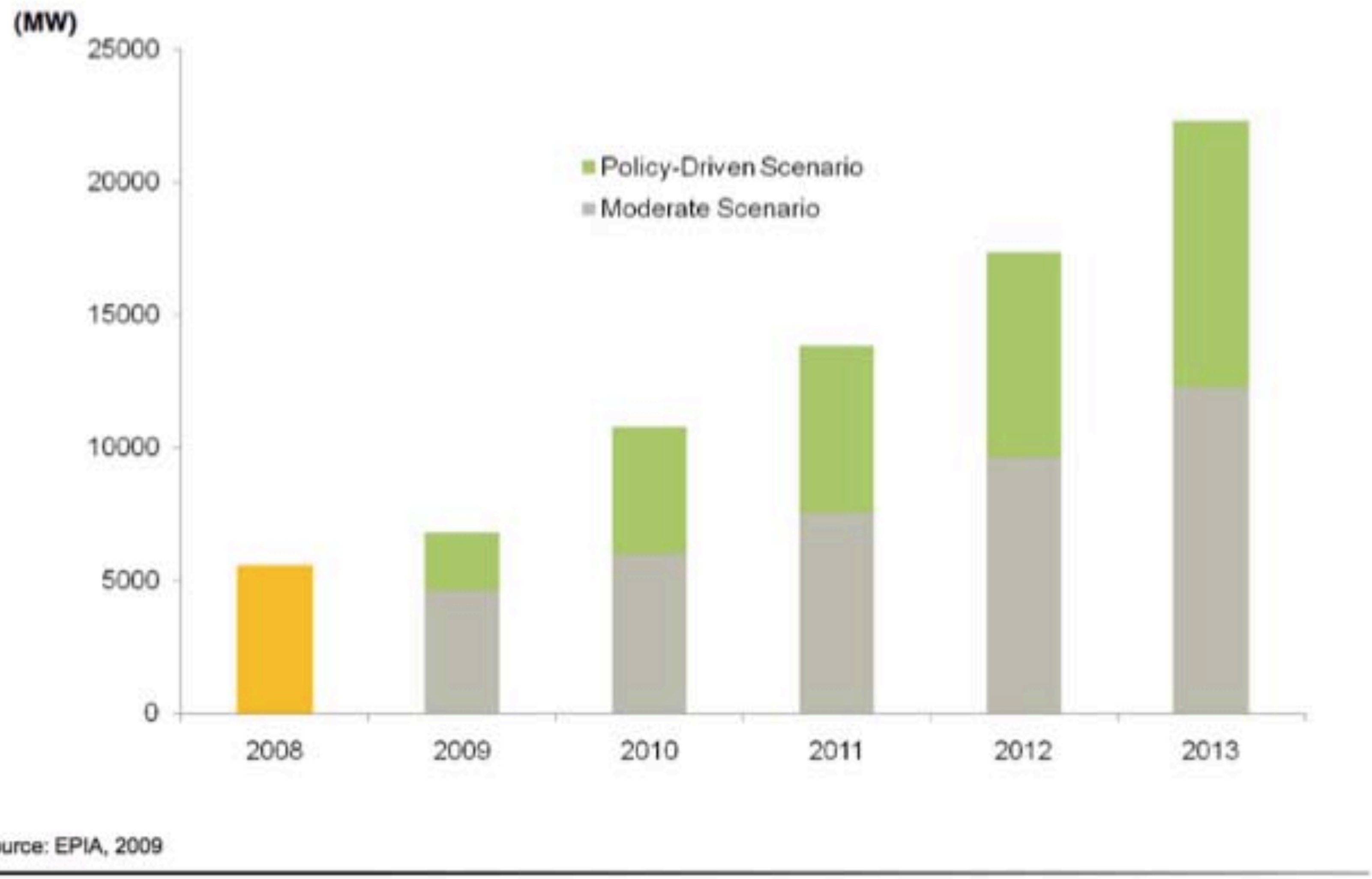


Fig. 5: Comparison of the different tracking modes

Hoffmann et. Al., 2008 European PVSEC, Valencia

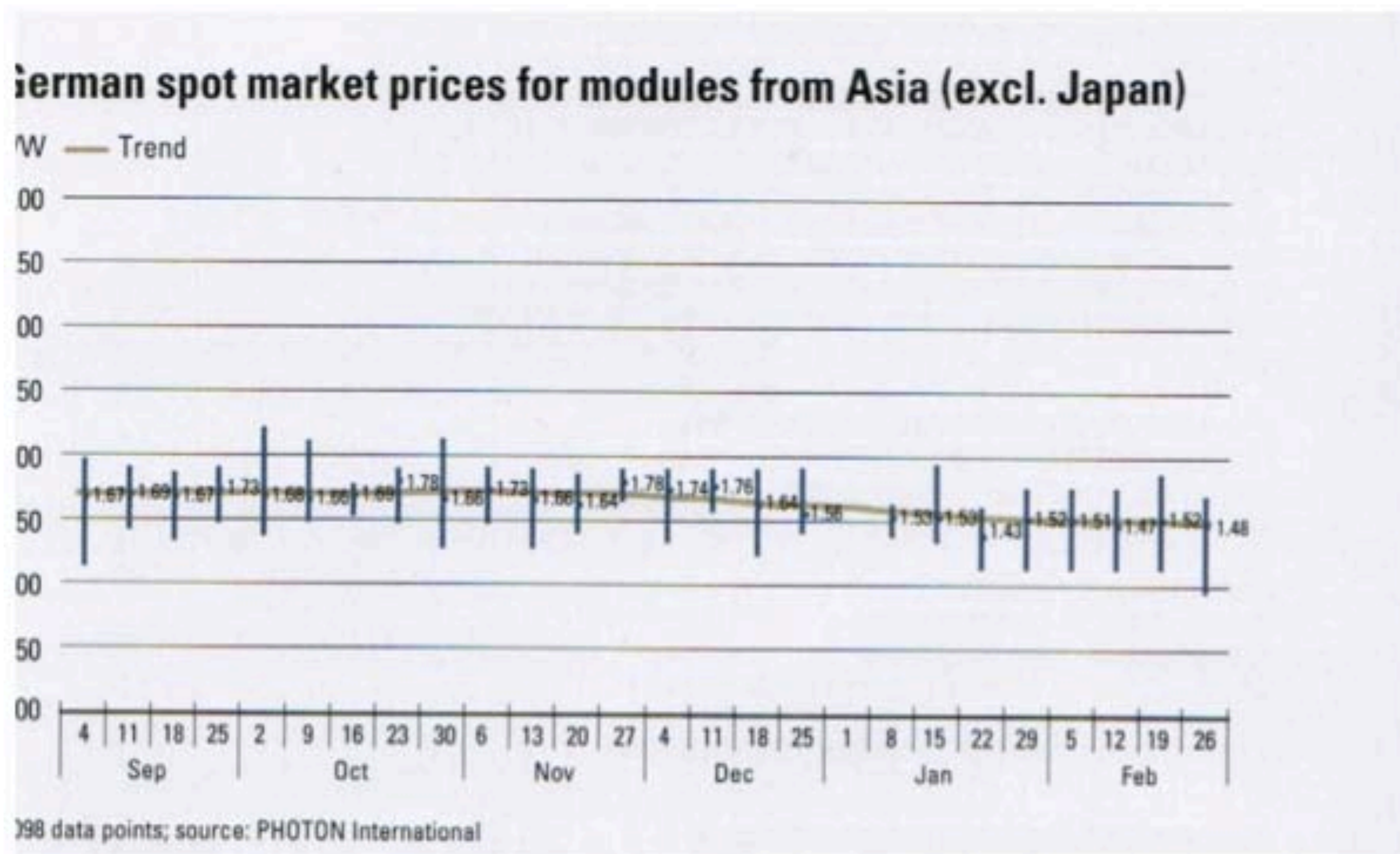
Market size



Source: D. Rose, SunPower, EPIA 2009

Prices of silicon modules from China

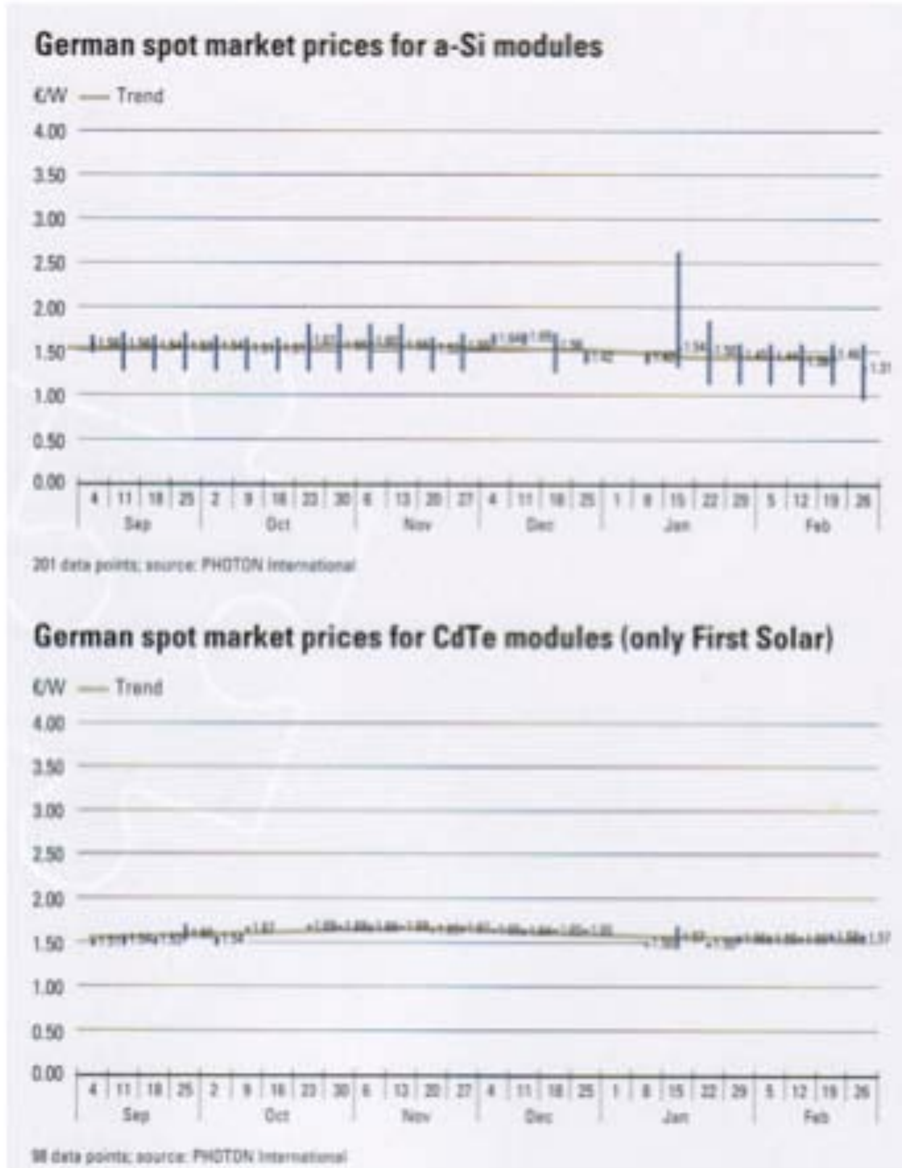
Wafer-based silicon modules from China are putting pressure on thin film technologies that trade efficiency for low production cost



Photon International, May 2010

Thin film module prices (€/watt)

Low prices create a difficult environment for smaller-scale suppliers to survive, and challenging for start-ups to prove reliability and performance and grow to a cost competitive scale.



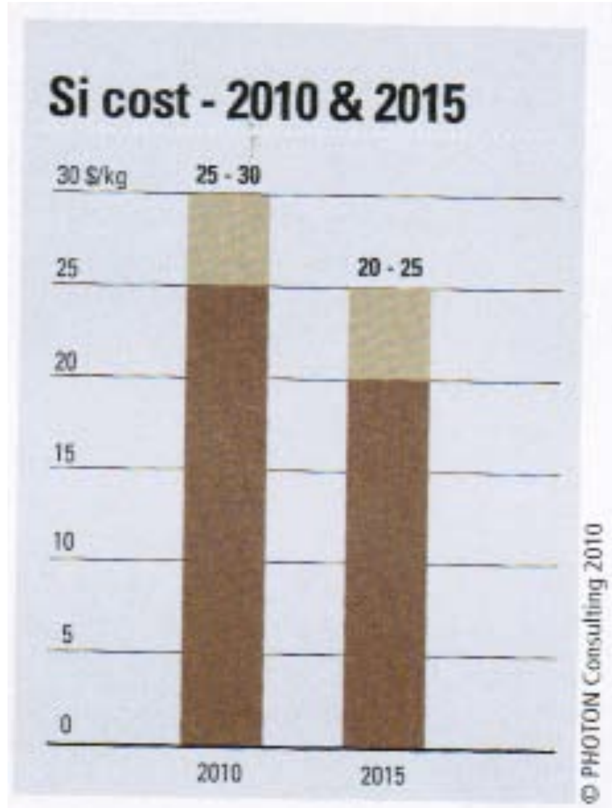
€1.31/W

€1.57/W

Photon International, May 2010

Polysilicon prices continue to decline

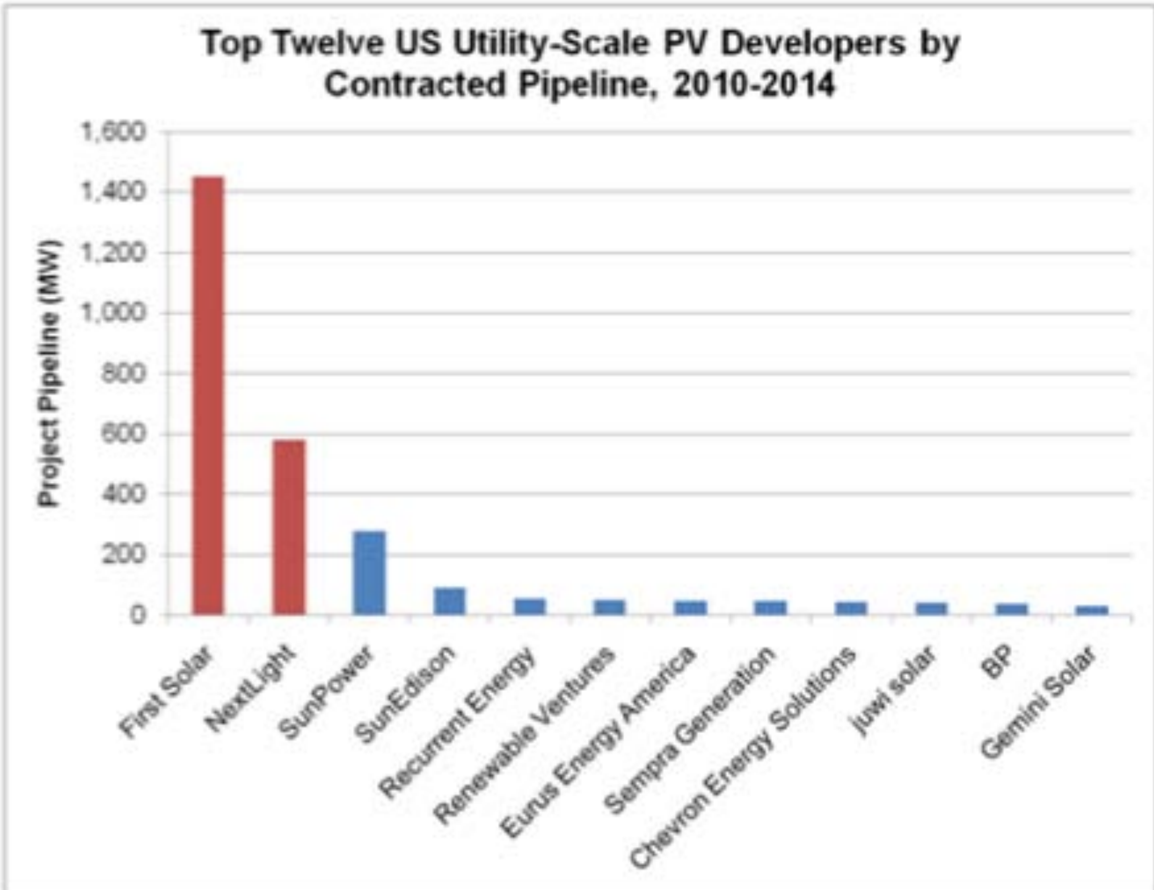
- Current spot prices are $50-60/kg, down 10X from the peak
- Process improvements provide margin for further declines
- This puts pressure on technologies based on trading substrate cost for efficiency



▲ Best practice: PHOTON Consulting's analysis indicates that leading silicon producers have the potential to achieve fully loaded production costs of $20 to $25 per kg within the next 5 years.

Photon International, May 2010

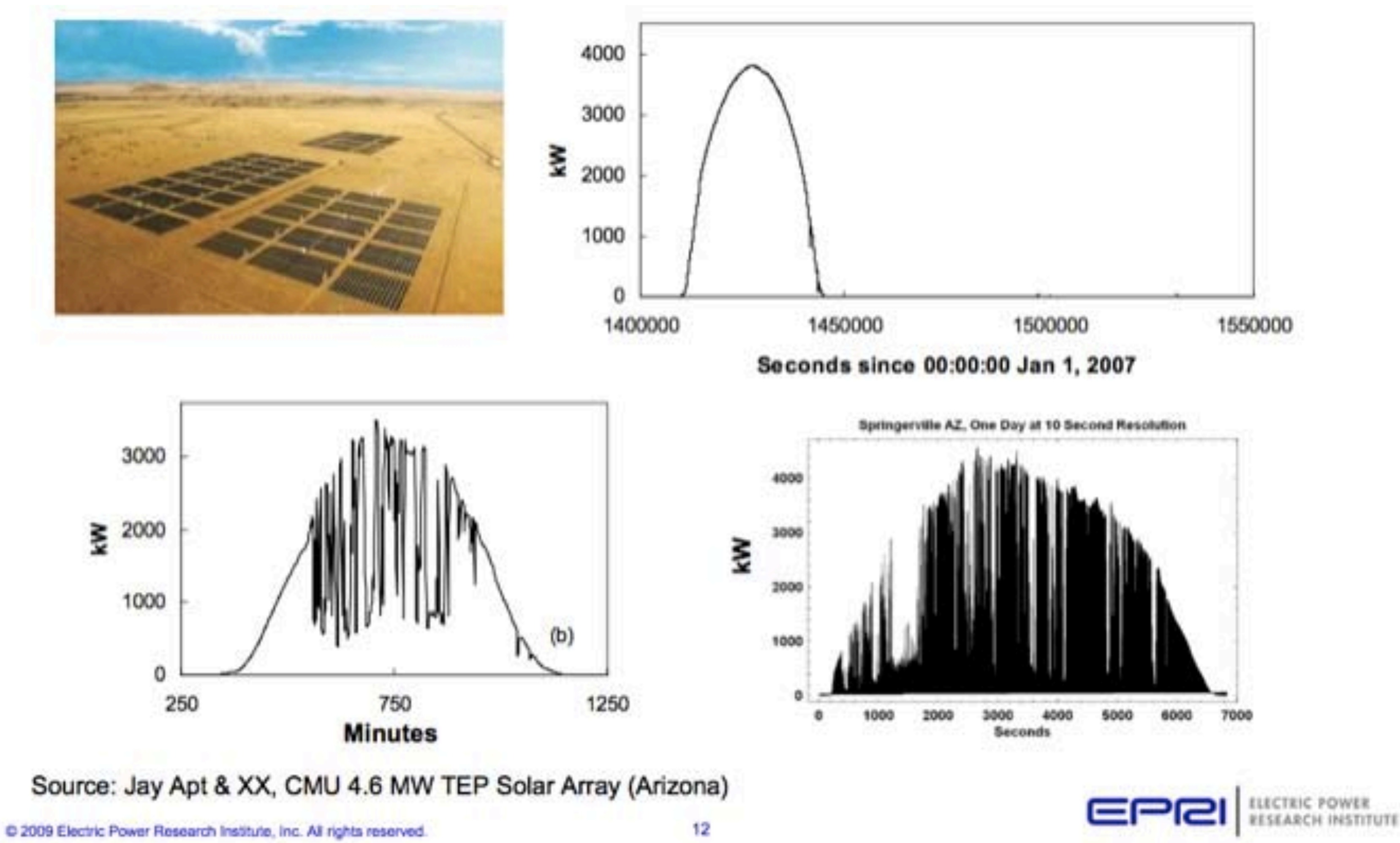
PV makers are providing large-scale systems



Source: GTM Research

Insulates from technology competition and creates a barrier to entry for smaller suppliers

Lack of storage is an issue for large systems



Clouds cause sharp fluctuations in output, which is hard for the grid to handle with utility-scale PV systems

Conclusion

- PV is one of a suite of renewable energy technologies
- The advantages include a match to grid load, low maintenance, simplicity, and a wide range of applications, from small remote systems to utility scale fields.
- Disadvantages include higher cost than other renewable options and lack of storage.
- Wafer based silicon, with its higher efficiency and rapidly dropping cost, continues to lead the market. CdTe supplier First Solar became the largest manufacturer last year. Other technologies have a small market share.