NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

CPV 101: Intro to CPV Technology, Opportunities and Challenges

NREL

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Outline

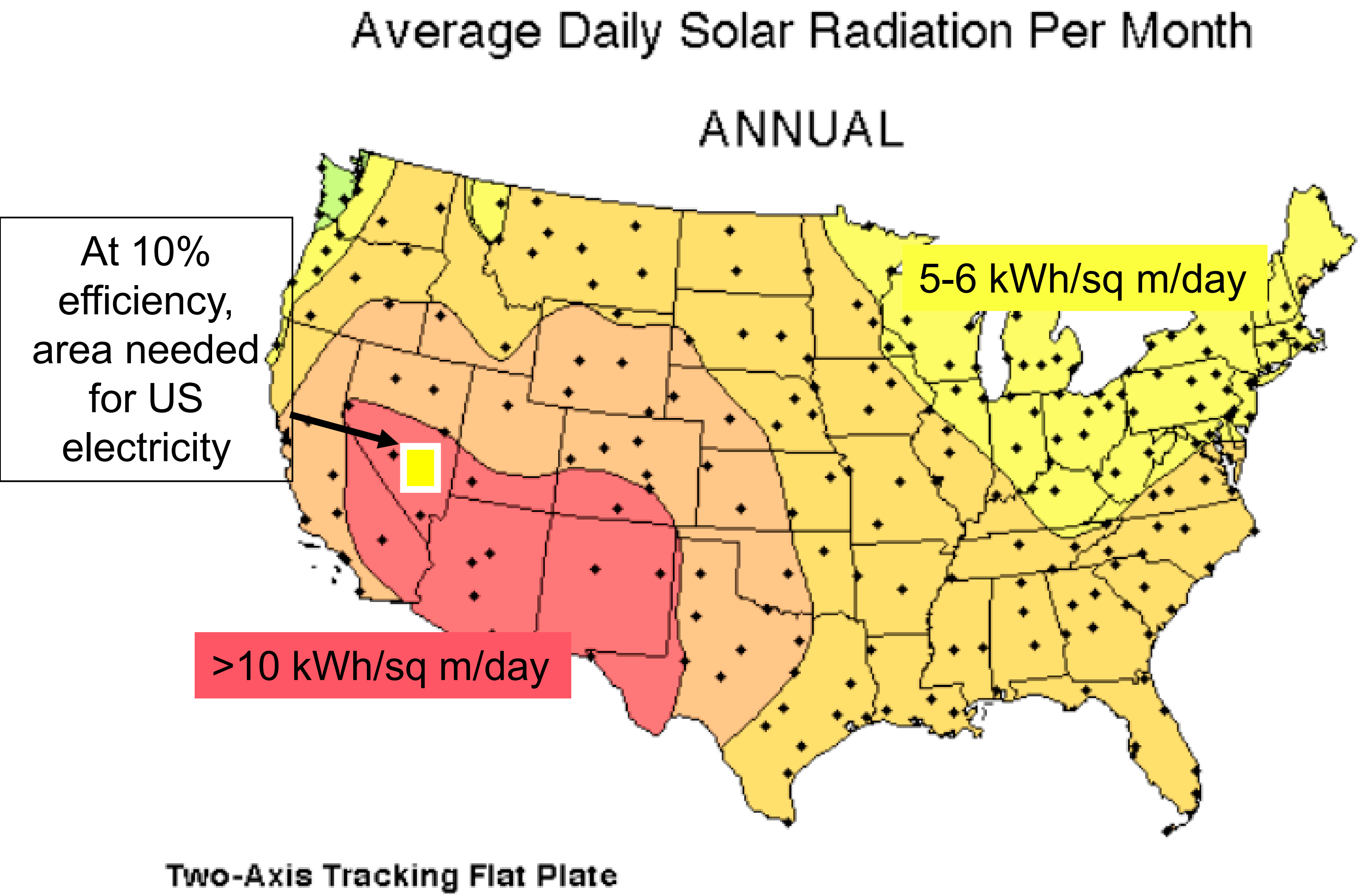
- Overview of PV – Opportunity for CPV
- Fundamentals of concentrating PV
  - Why CPV?
- Design considerations
  - Bird's eye view
- Sorting it out
  - Worm's eye view
- Status of industry
  - Standards
  - Many companies
  - Is it a turning point?

Outline

- Overview of PV – Opportunity for CPV
- Fundamentals of concentrating PV
  - Advantages
  - Primary approaches (High & low concentration)
  - Designing from the system perspective
- Design considerations
  - Thermodynamic limit of concentration
  - Refractive vs reflective optics
  - Concentration ratio, f number, etc.
  - Thermal considerations
  - Keeping it clean and dry
  - Cells

Solar energy is abundant

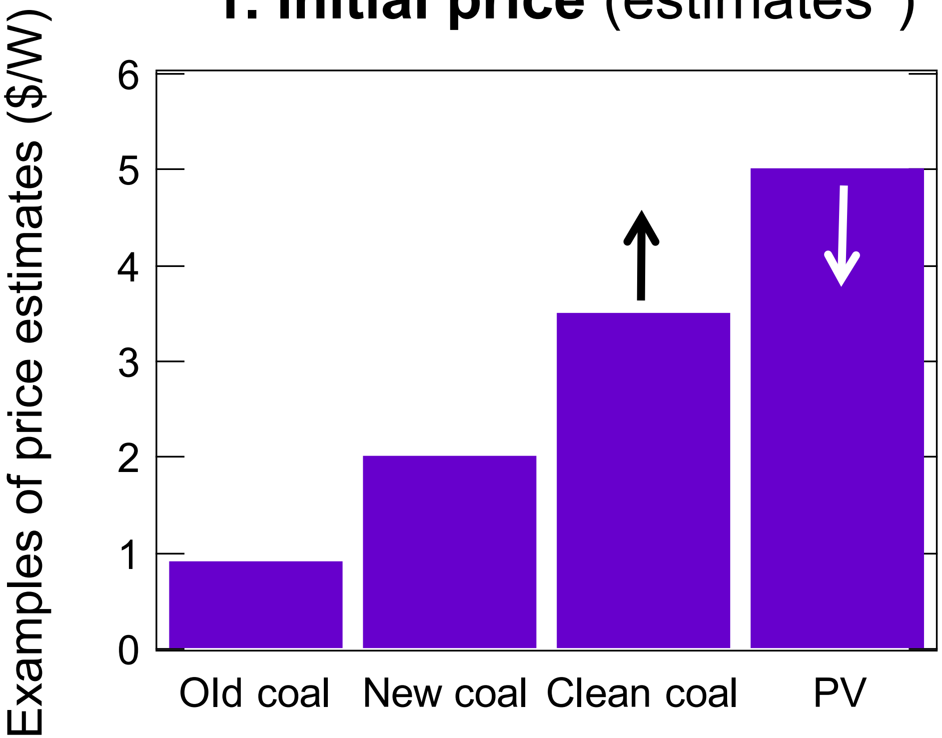
Convenient truth: small area can supply our energy needs



Sunlight reaching earth in 1 hour is enough to power the world for 1 year

Cost of electricity: two or three parts

1. Initial price (estimates*)



*Fortnightly's SPARK, p. 10, May 2008

2. Operation and maintenance

- Fuel cost (Coal✗ PV✓)
- Operation (Coal✗ PV✓)
- Maintenance (Coal✗ PV✓?)

PV is already competitive for peak power in some locations

3. Total electricity generated

- Capacity factor (Coal✓ PV✗)
 (Coal ~100%; PV ~ 25%)
- Life of plant (Coal✓ PV?)

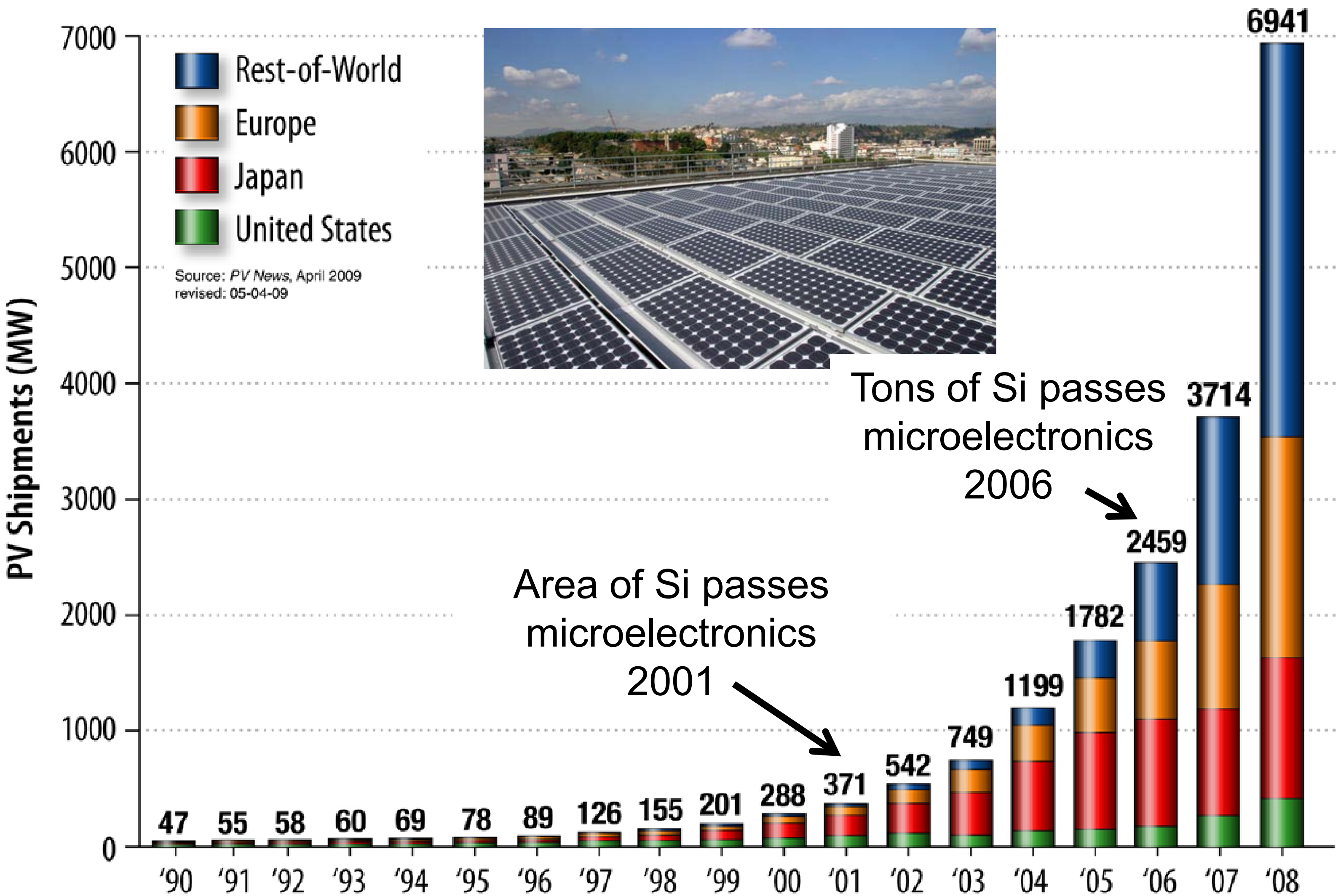
Upfront costs for PV and coal plants are converging

Ongoing costs are less for PV

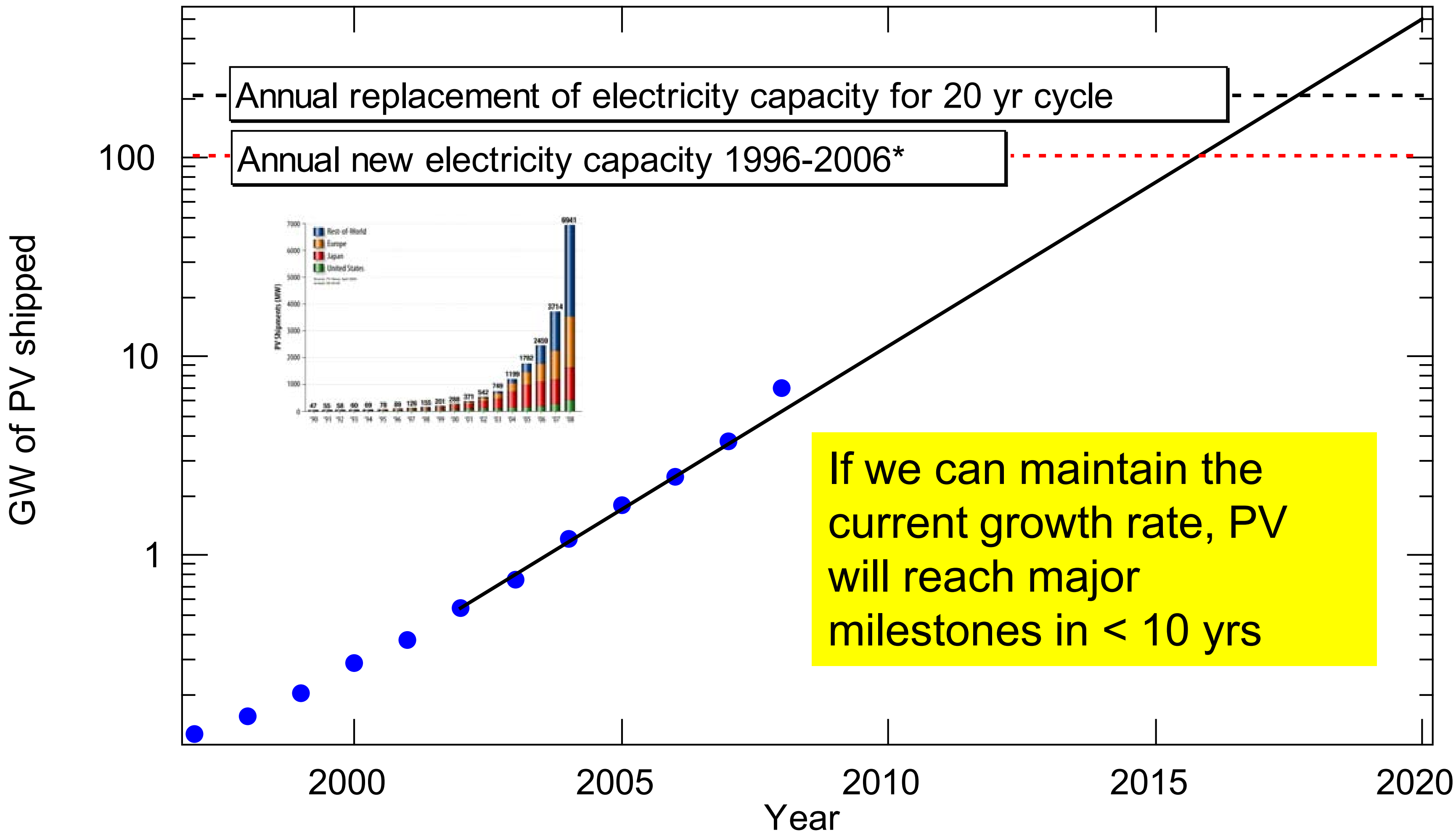
Operation only during daylight hours increases cost by ~X4 (flat plate)

Lifetime is critical

Growth of photovoltaic (PV) industry



Growth of PV industry - opportunity



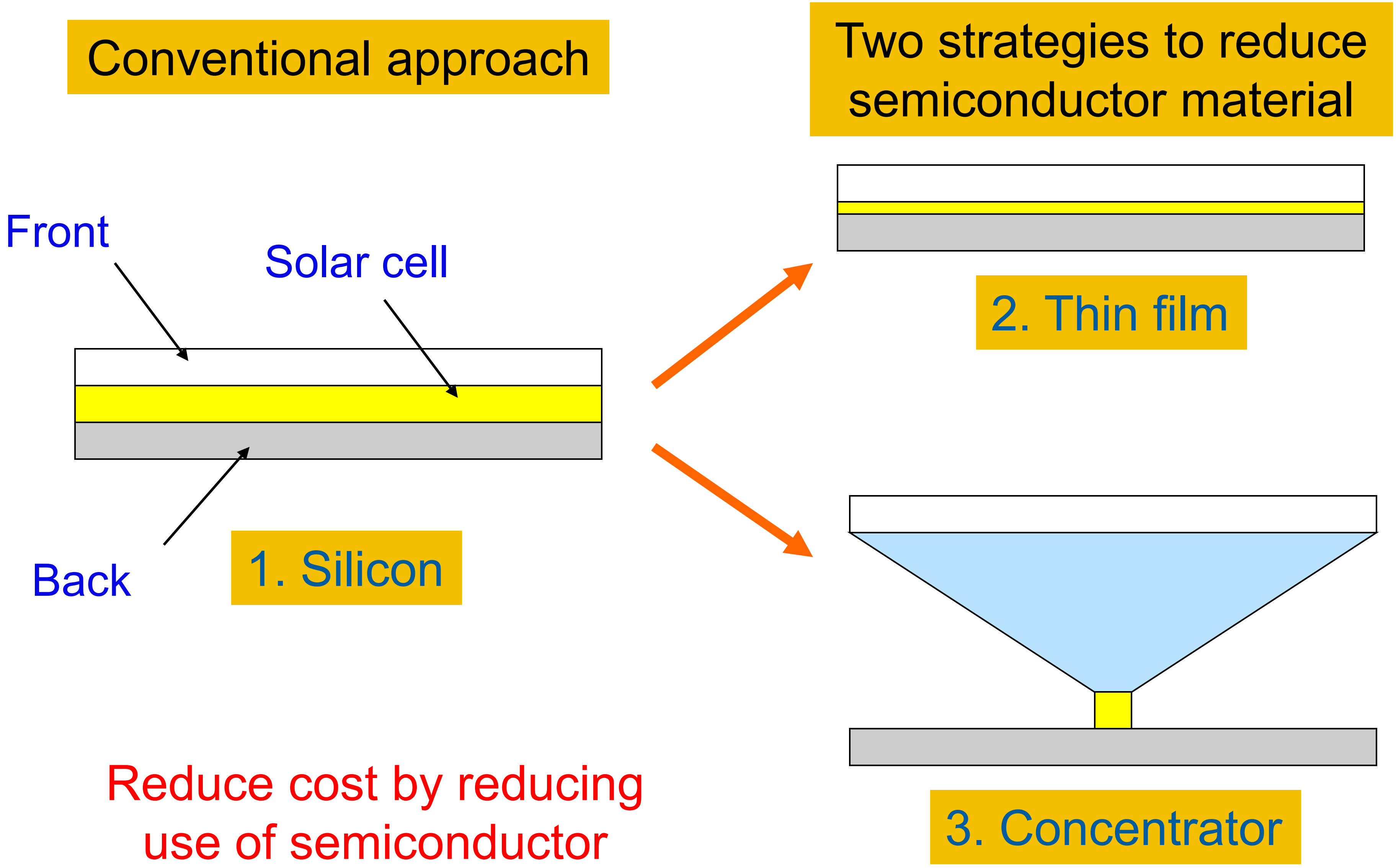
*www.eia.doe.gov/emeu/international/electricitycapacity.html (4012-2981 GW)/10 yr

(These milestones do not consider low capacity factor nor growth of electricity demand)

Opportunity – what's needed?

1. Low cost
   - Reduce use of semiconductor material
   - Higher efficiency can reduce area costs (installation, land, & BOS costs)
   - Long lifetime reduces cost of electricity
2. Scalability
   - CapEx costs
   - Time to ramp production

Three key approaches to photovoltaic (PV) panels

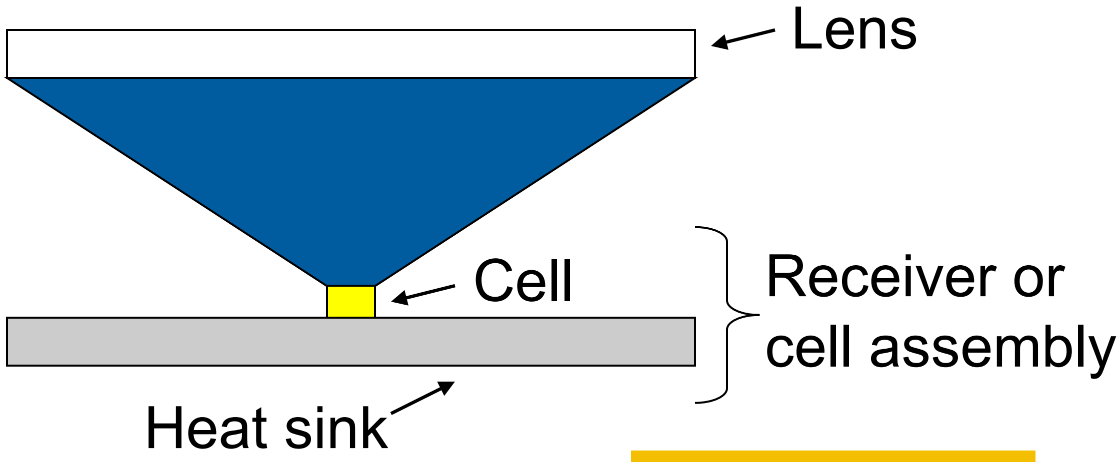


Concentrating Photovoltaic Systems: CPV

Dish: requires active cooling

Microdishes can be passively cooled

Fresnel lenses focus light on small cells: Passive cooling



Many designs

Concentrating PV (CPV) vs Concentrating solar power (CSP)

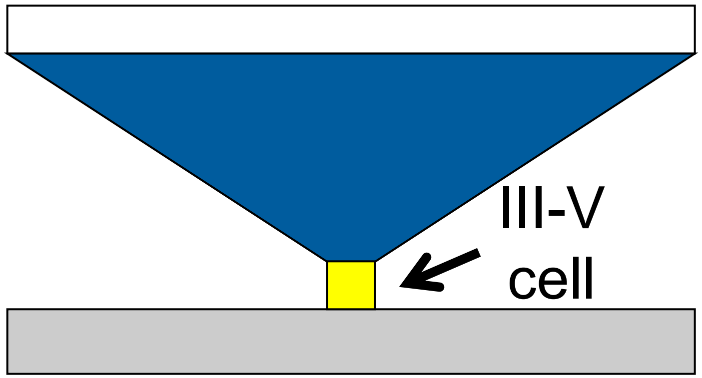
CPV

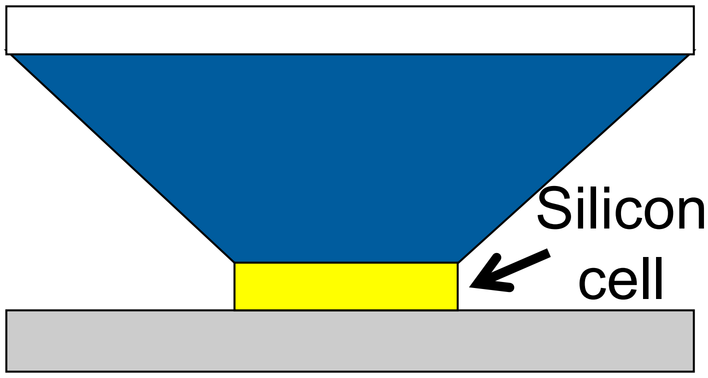
- Appropriate for > 50 kW
- Usually requires no water
- Low maintenance
- Good match to load profile (better than fixed PV; not as good as CSP)

CSP

- Appropriate for > 100 MW
- Heat generates steam to run conventional power plant
- Possibility of storage – run into the evening
- Supplement fuel for conventional plant

Scope of this presentation – high & low X





High concentration ~ 500X

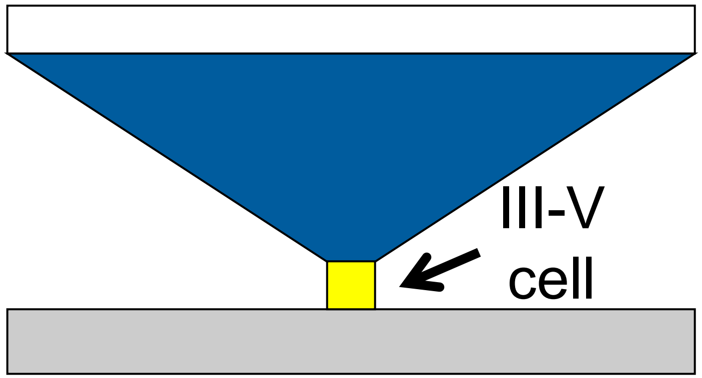
Multijunction cells ~ 40%
(cells are ~ $4/cm^2)

Low concentration: 1.5 - 200X

Silicon cells 15-25%
(may use 1-sun silicon)

Both approaches are aggressively pursued today
Both will be discussed throughout presentation

Reduce semiconductor material



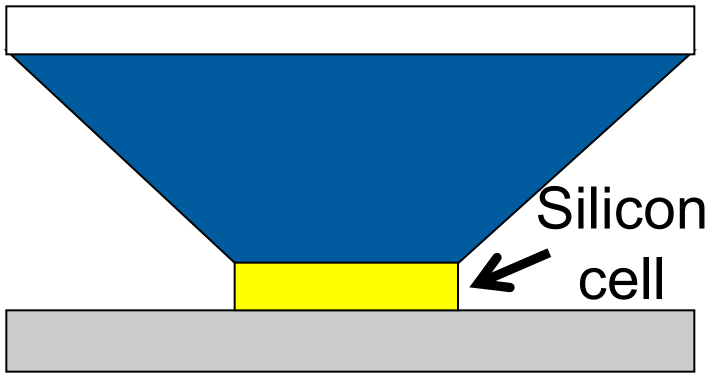
500X – GaInP/GaAs/Ge

0.007 g/W

500X – GaInP/GaAs/GaInAs
(reuse wafer)

0.001 g/W

Assumptions:
150 µm Ge X 1 cm2 X 5.3 g/cc = 0.08 g
25 mW X 500 X 0.85 /cm2 = 10.6 W
0.08 g/10.6 W = 0.007 g/W
10 µm of epi X 1 cm2 X 5.3 g/cc = 0.0053 g



1-sun Si – as low as 5 g/W

2-sun Si – 2.5 g/W

20-sun Si – 0.25 g/W

For comparison:

1 µm CdTe @ 12%

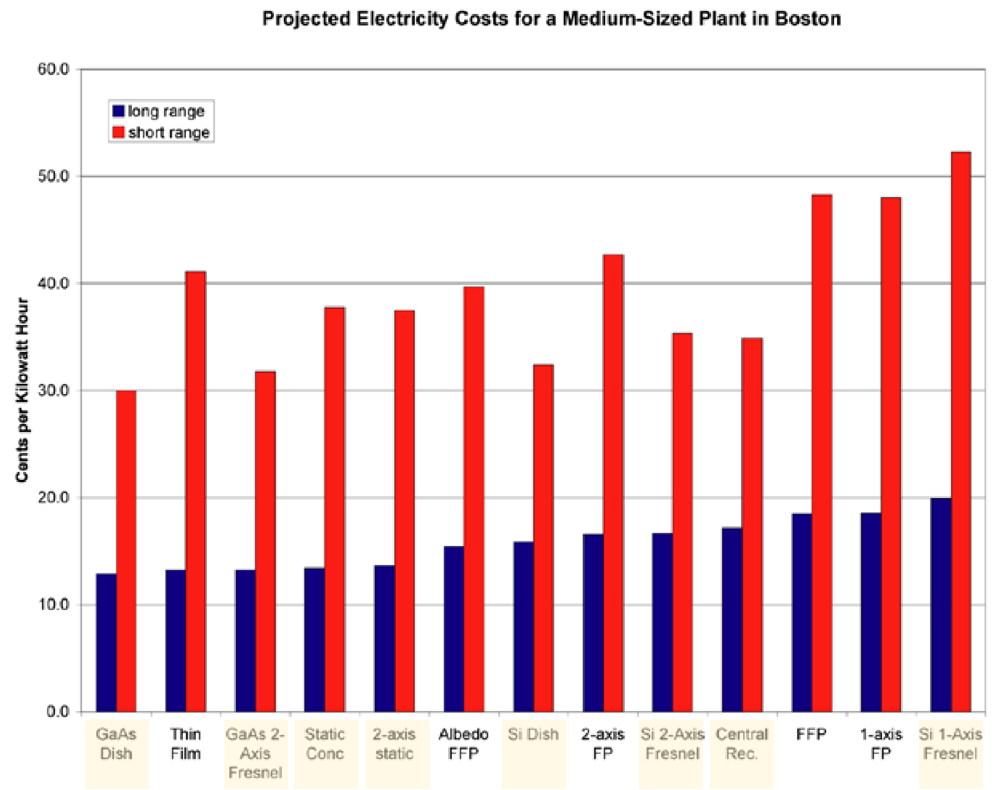
0.05 g/W

1 µm X 1 cm2 X 5.9 g/cc = 0.00059 g
12 mW/cm2 implies 0.00059 g/ 0.012 W = 0.05 g/W

Less semiconductor can mean lower cost; better scalability

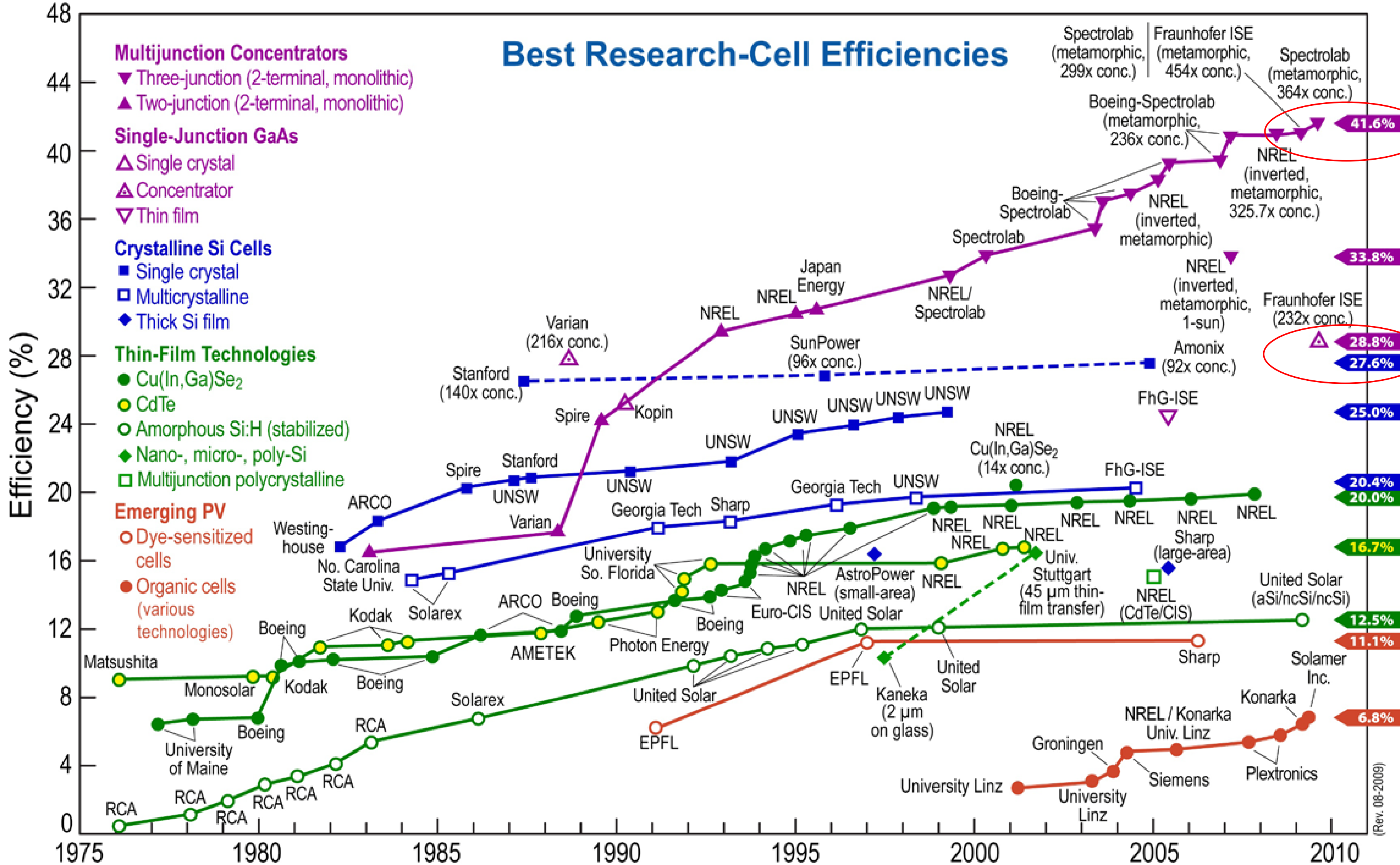
Potential for low cost

- CPV is estimated to have similar or lower costs than other technologies
- Uncertainty is larger than the difference between the technologies
- Must be at large-volume production before costs become apparent
- World benefits from exploring multiple options



Swanson, "The Promise of Concentrators," Prog. PV. **8**, 93 (2000)

Smallness enables use of highest efficiency cells



One "winner" or many technologies?

Alkaline

Nickel cadmium

Nickel metal hydride

CPV markets

- Sunny locations
- Large systems
- Area constrained

CPV advantages

- Scaleable
- Better match to demand
- High efficiency
- Low T coefficient (good kWh/kW)

Lead acid

Lithium ion

Lithium

Different technologies for different applications

Scalability

1. Is expected
   - Easier to scale up production volume for mirrors or lenses
   - Semiconductor use is small
2. Demonstration is yet to come
   - First Solar has demonstrated for thin film
   - Still needs to be demonstrated for CPV
3. Most companies are developing or demonstrating reliable product – are we close to a company being ready to ramp?

Be careful not to be confused

1. High efficiency can translate to higher electricity production but not always
   - CPV uses direct beam; diffuse light may not be focused – so less sunlight is available
   - Tracking usually increases available sunlight
2. High efficiency can translate to reduced land use, but not necessarily
   - Trackers may shade each other
   - Loss with shading can be very dependent on design and geometry

CPV progress/status

Multijunction cells > 41% in lab; 37-39% in production; systems as high as 25% AC

About a dozen multijunction cell companies (30-40%)

About three dozen companies high-X CPV

About two dozen companies low-X CPV

Some companies working on 1 MW installations

Production capability now > 100 MW/y

Why has it taken so long???

Why so hard? – need infrastructure

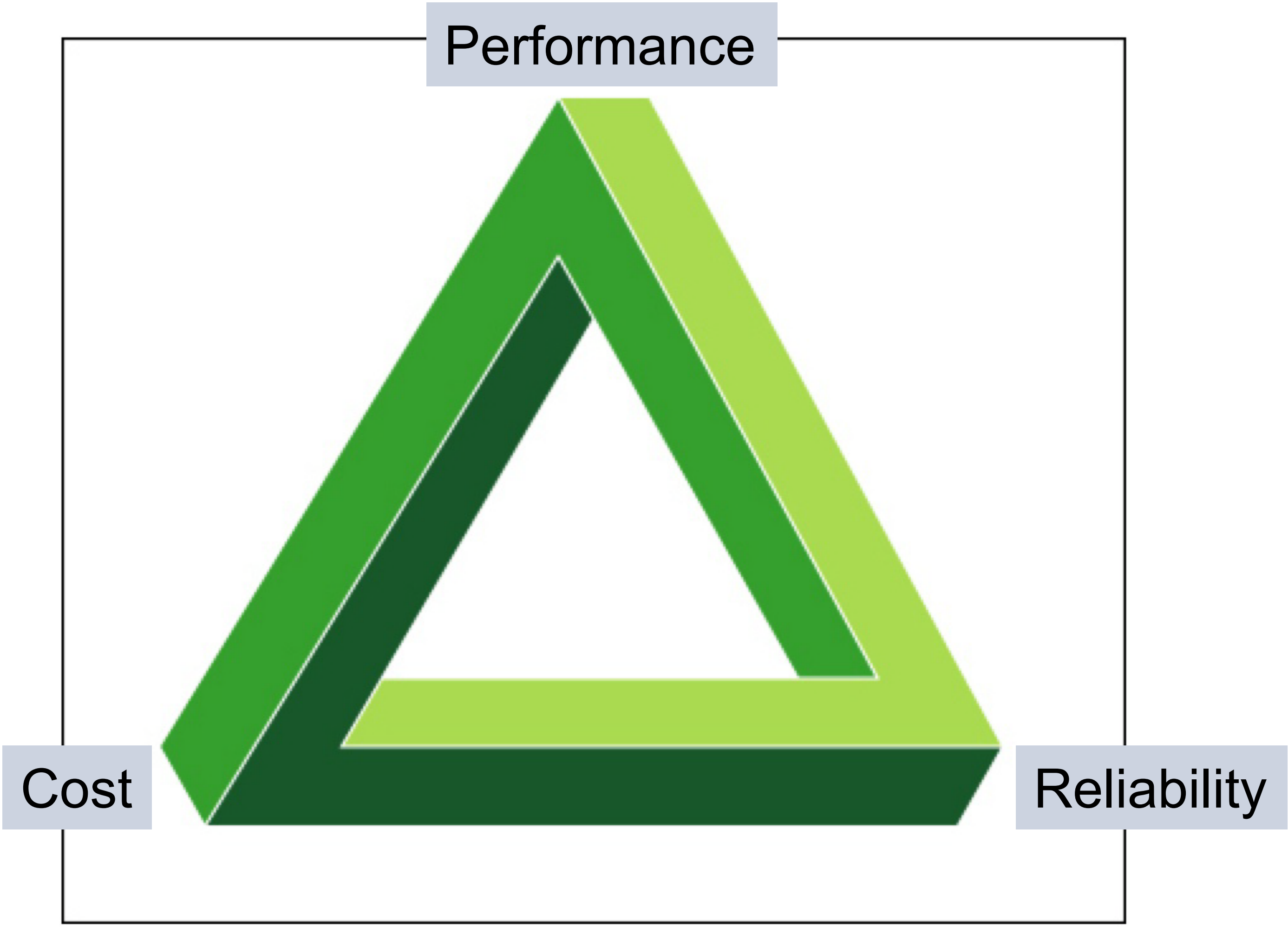
In 1990s, PV community decided that building-integrated, customer-owned, customer-sited would be the future: little interest in CPV, so little funding

Investment in CPV came later than for other technologies, so CPV infrastructure development lags

Some of today's investors are secretive, preventing companies from working together to create infrastructure

Infrastructure = standards, knowledge of how to test for reliability, development of supply chain, etc.

Why so hard? – many tradeoffs



Use two views

Design
Bird's eye view

Diagnose
Worm's eye view

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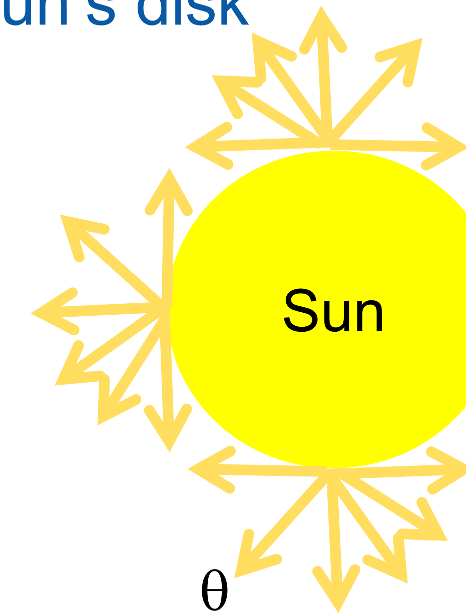
Fundamentals - concentrating optics

Finite size of sun limits concentration – acceptance angle must be at least as big as sun's disk

Sun emits light in all directions:



Earth

Sun

$\tan\theta$ = (sun radius)/(sun-earth distance)

$\tan\theta = (7 \times 10^{8}\ \text{m})/(1.5 \times 10^{11}\ \text{m})$

$\theta = 0.27\ °$

Fundamentals – non-imaging optics

Nonimaging Optics – Roland Winston, Juan Minano, Pablo Benitez, Academic Press, 2004.

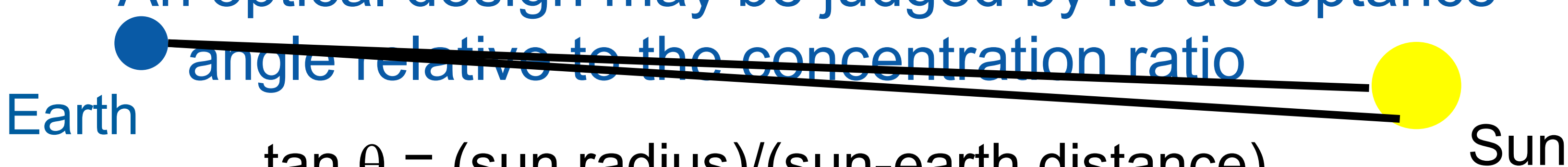
Concentration limit (C_{max}):

linear focus $C_{max} = n/(\sin\theta) \sim 200$ X (if n=1)

point focus $C_{max} = n^2/(\sin^2\theta) \sim 40{,}000$ X (if n=1)

In practice, a larger acceptance angle is desired to allow alignment and tracker error; for C = 500 X, the (half) acceptance angle may approach 2.5°, or higher if n>1

An optical design may be judged by its acceptance angle relative to the concentration ratio



$\tan\theta$ = (sun radius)/(sun-earth distance)

$\tan\theta = (7 \times 10^8 \text{ m})/(1.5 \times 10^{11} \text{ m})$

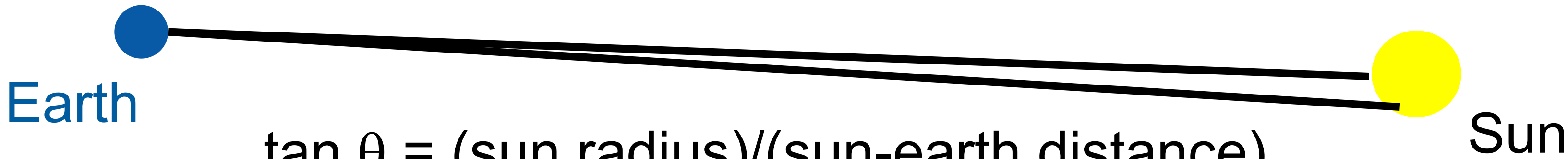
$\theta = 0.27°$

Fundamentals – acceptance angle

If acceptance angle of optics is ± 0.27°, then there is zero tolerance for alignment and imperfections: measured acceptance angle will be ~ 0.03°

Acceptance angle measured for module or system may reflect alignment more than optics

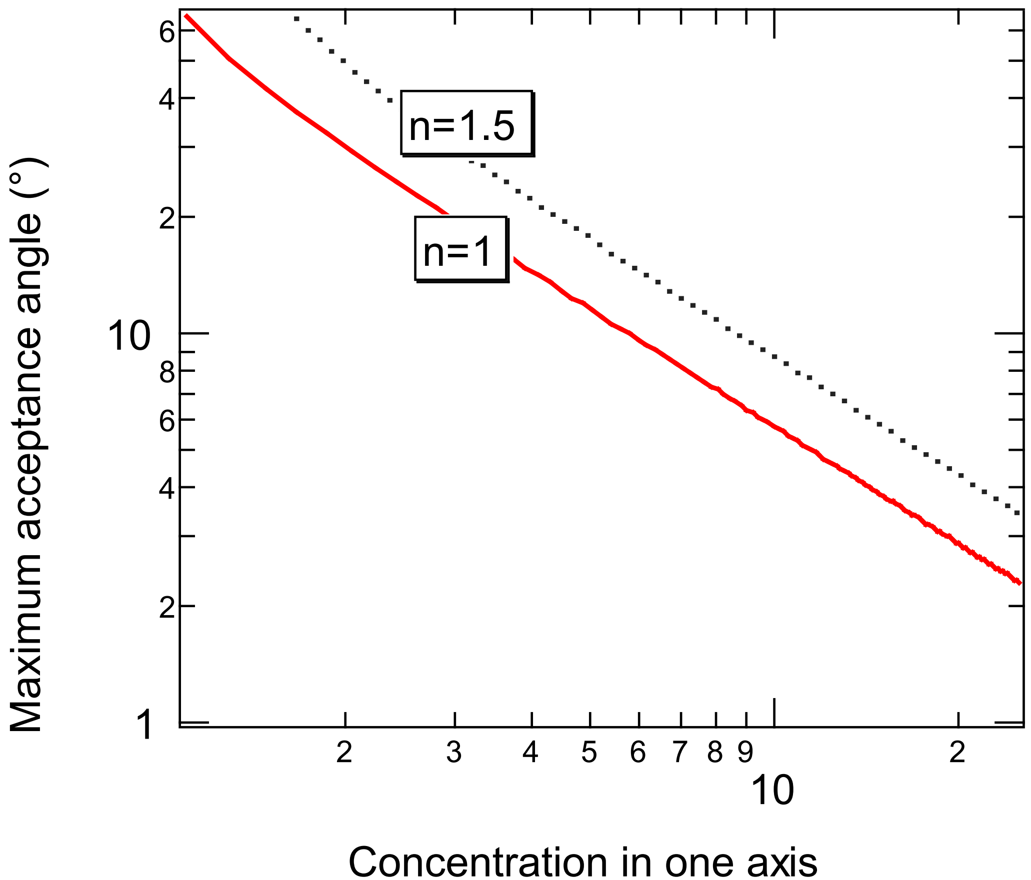
Reported acceptance angle may be quoted for 90%, 80%, or 50% point



$$\tan\theta = \text{(sun radius)}/\text{(sun-earth distance)}$$
$$\tan\theta = (7 \times 10^8 \text{ m})/(1.5 \times 10^{11} \text{ m})$$
$$\theta = 0.27°$$

Fundamentals – non-imaging optics

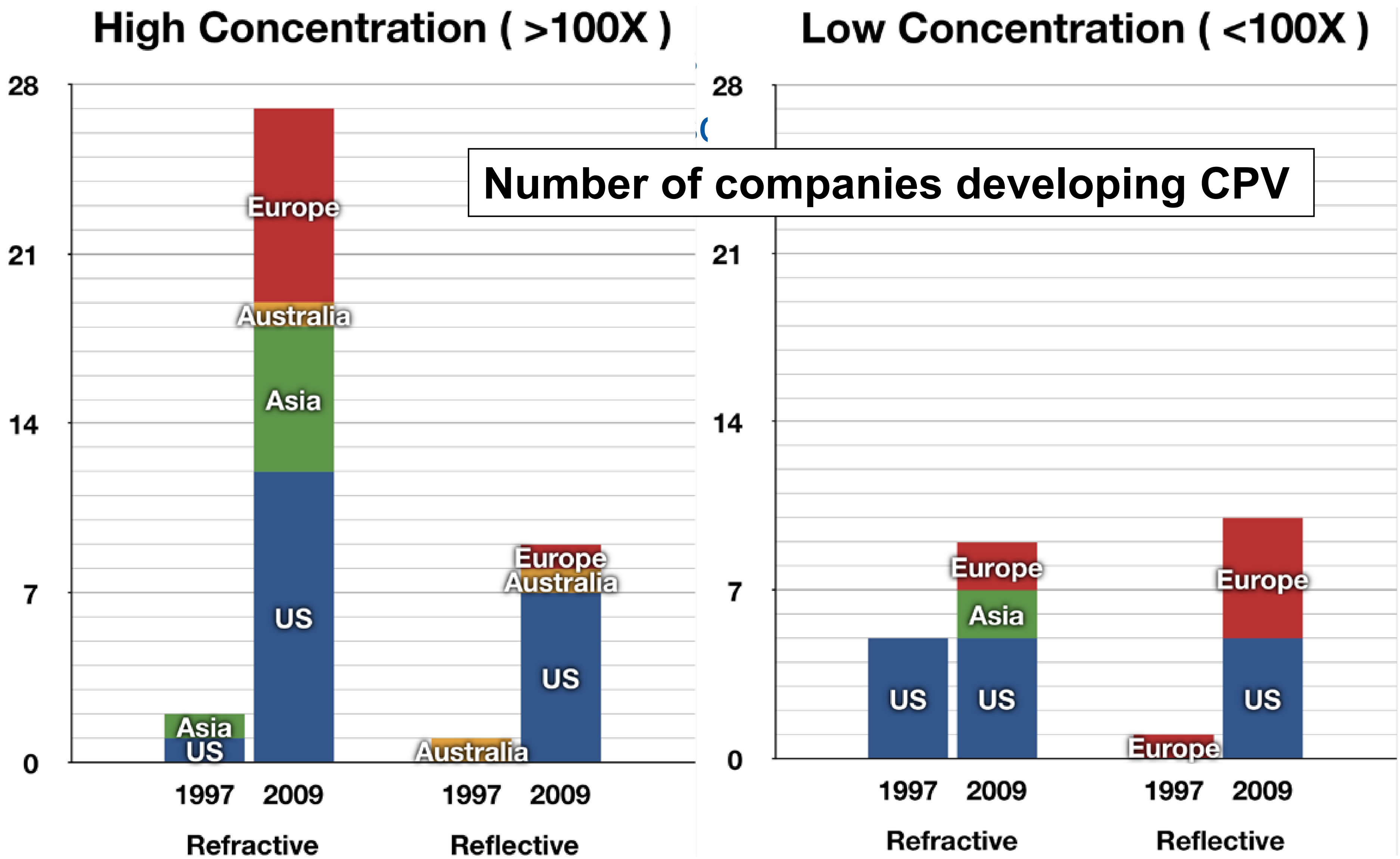
For low-X approaches, tracking may not be essential



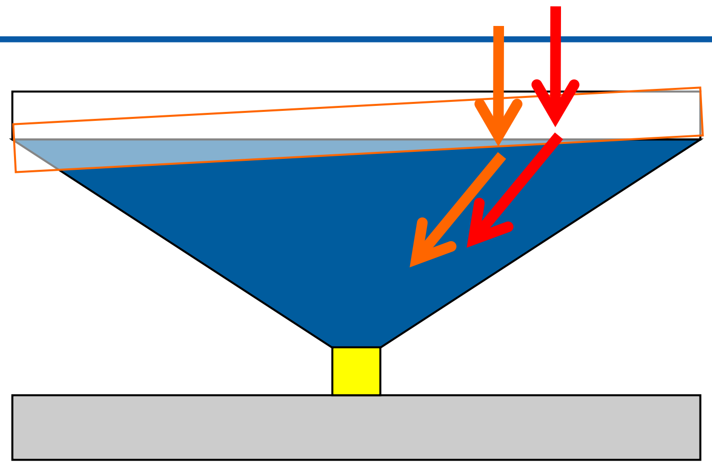
Can't collect diffuse light outside of this angle for given concentration

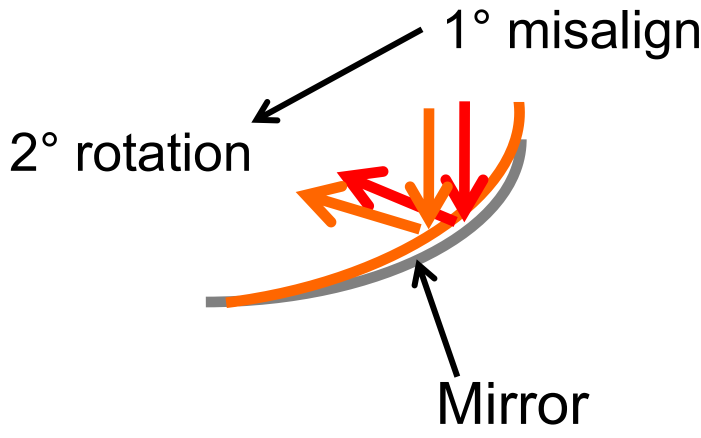
For point focus, concentration is squared

Reflective vs refractive: statistics are shifting



Refractive vs reflective – alignment tolerance





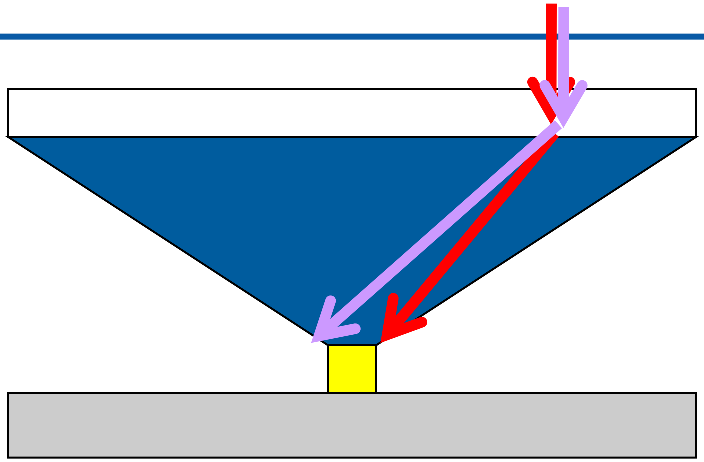
Refractive elements are more tolerant to misalignment

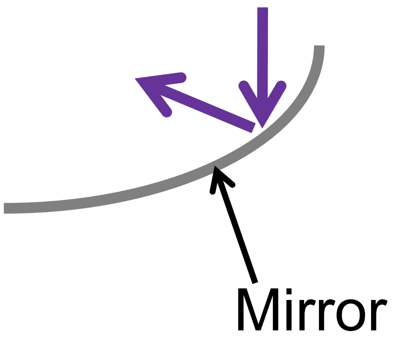
1° alignment error causes ~0.5° change in refracted light

Reflective elements must be accurately aligned

1° alignment error causes 2° change in reflected light

Refractive vs reflective – chromatic aberration





Refractive

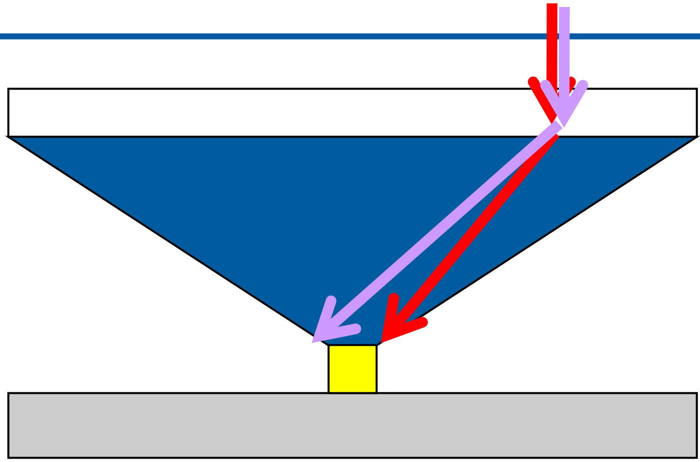
chromatic aberration

Blue light has shorter focal length

Reflective

NO chromatic aberration

Refractive vs reflective – chromatic aberration

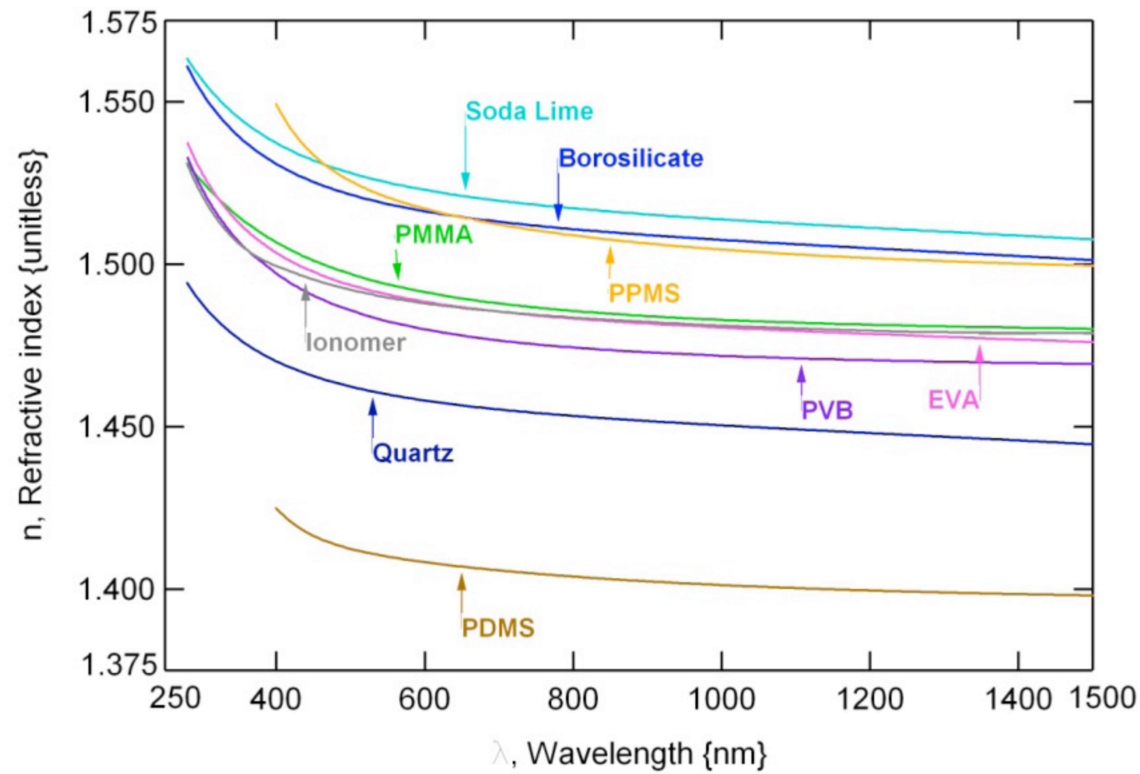


Refractive

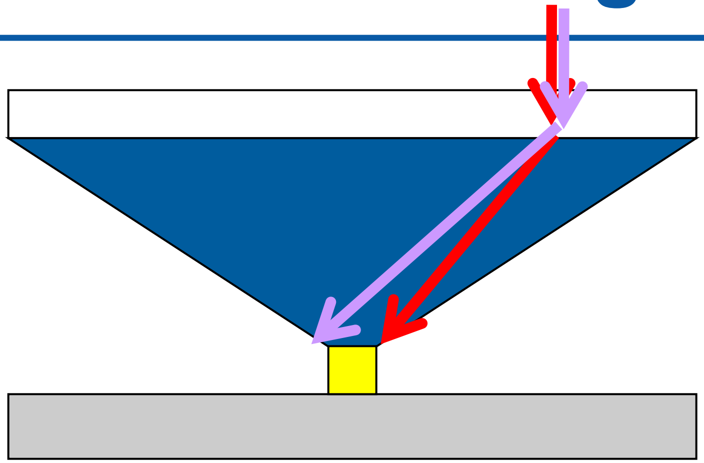
chromatic aberration

Focal length may change by ~2%

Miller, et al SPIE 2009

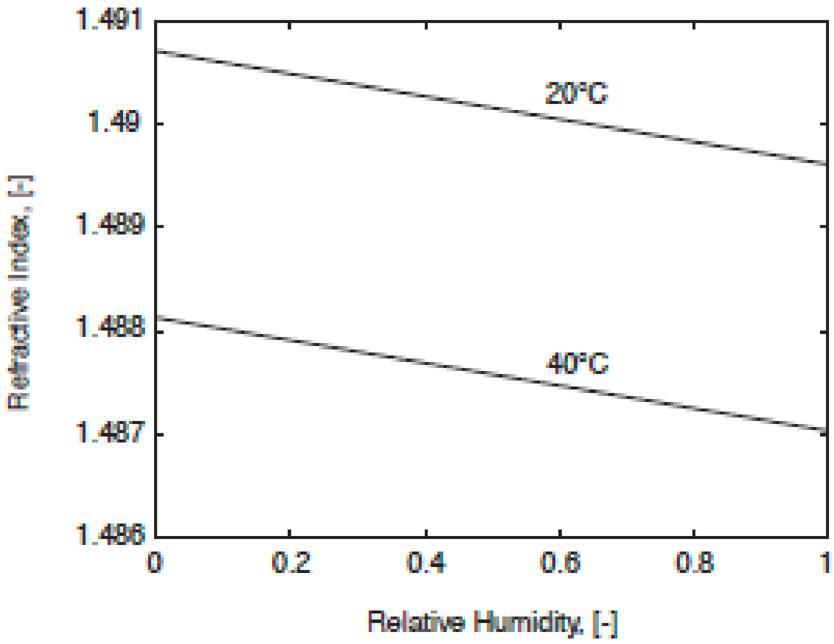


Refractive – changes with T & RH are small



Refractive aberration

Ralf Leutz



Focal length change < 1%

Effect of chromatic aberration – from R. Winston

Source Spectrum	Optical Efficiency	Acceptance Angle (Degrees)
550 nm	84.8%	1.68
AM1.5 clipped between 300nm and 1900nm	83.2%	1.62

Difference in optical efficiency is mostly due to the absorption spectrum of the materials.

Difference in acceptance angle is due to “chromatic aberration”.

Configuration: Primary + Secondary

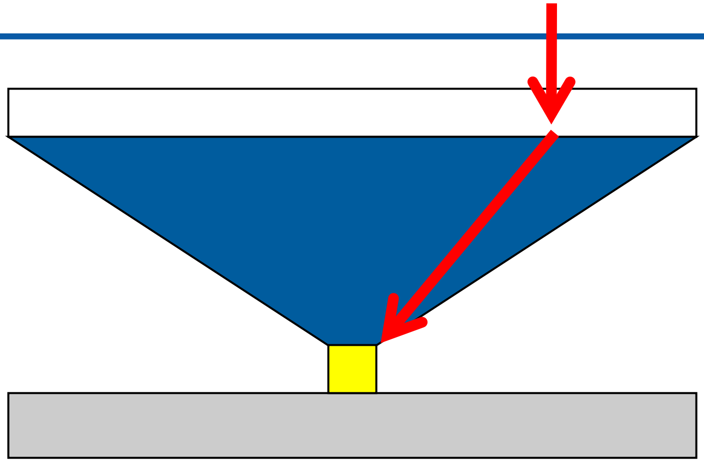
- Primary: Fresnel lens, material: PMMA
- Secondary: non-imaging optics, material: glass

Geometric Concentration: 711X

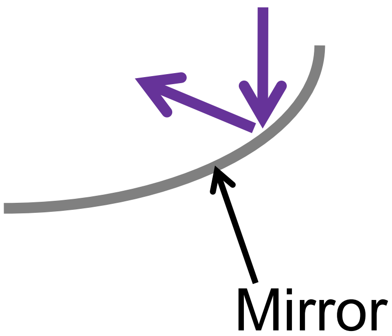
Maximum Incident angle on cell: 65 Degree

System is designed for 550 nm

Refractive vs reflective – many details



1. Cost
2. Weight
3. Optical performance



Refractive

Fresnel lens – imperfections

Soiling; abrasion

Glass vs PMMA vs Glass/silicone

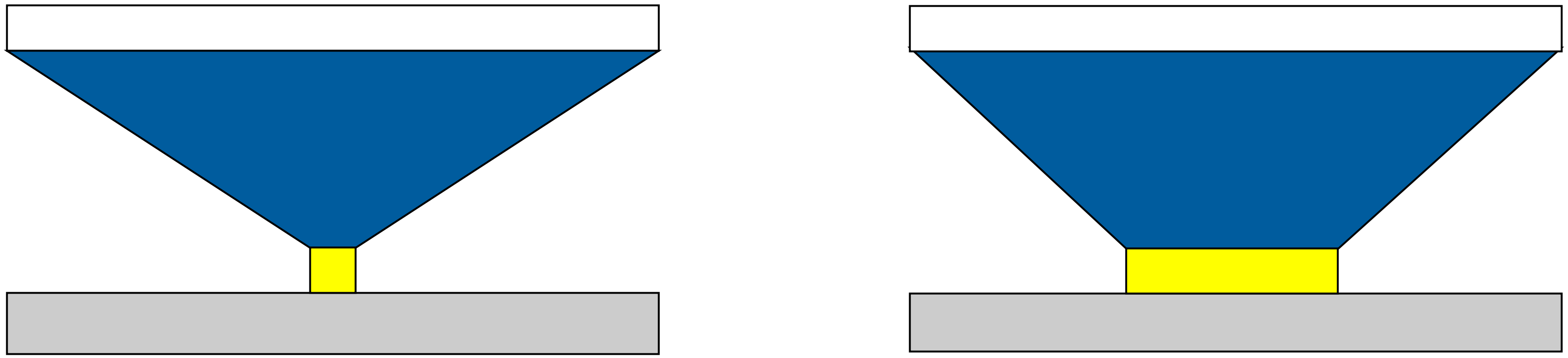
Reflective

Front vs back-surface mirror

Soiling; abrasion

Off axis, or shade cell

Concentration ratio – for multijunction



Cell cost drives design to > 1000X

Can cell cost decrease?

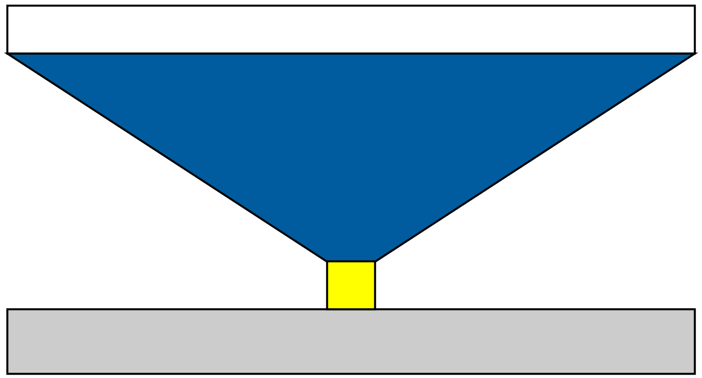
If you're designing for over 500X, ask yourself why you'll be successful

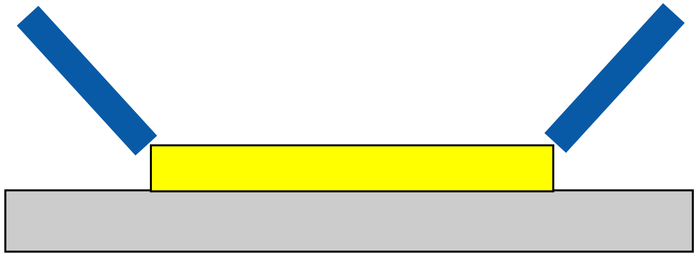
Tracker drives design to < ~500X

Smart tracker isn't enough

- thermal expansion
- wind
- cost of rigid structure

Concentration ratio – for silicon





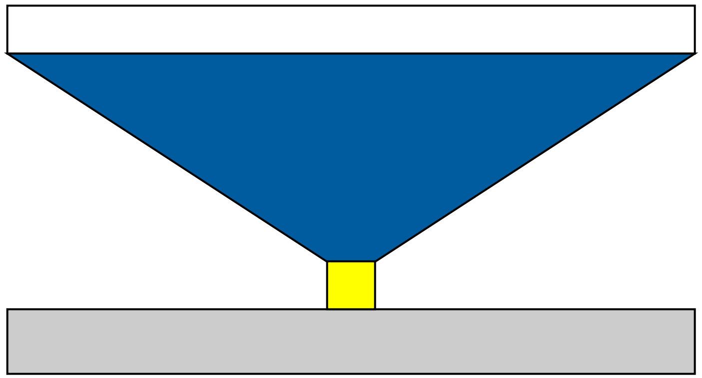
Higher concentration:

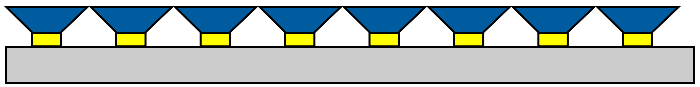
- Lower cell cost
- Cell packaging/cooling is smaller area

Lower concentration:

- Can use Si modules
- Tracking accuracy is easier
- Easiest product development

Cell size design trade offs





Large cells and optics

Reduced part count

Helps make structure rigid

Extreme is dish with replaceable receiver

Can use active cooling

Modularity can be advantage

Small cells and optics

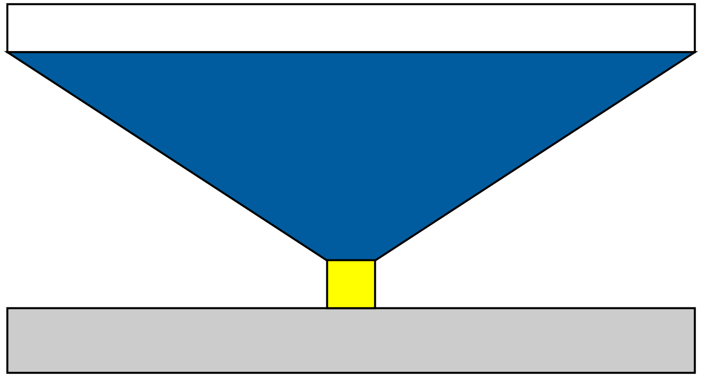
Reduced materials cost

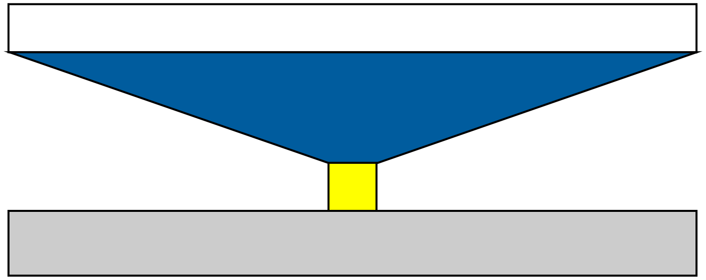
Aesthetic appeal

Heat is distributed

Smaller currents

Design trade offs – f number





Higher f number

Alignment tolerance is wider (bigger depth of fields)

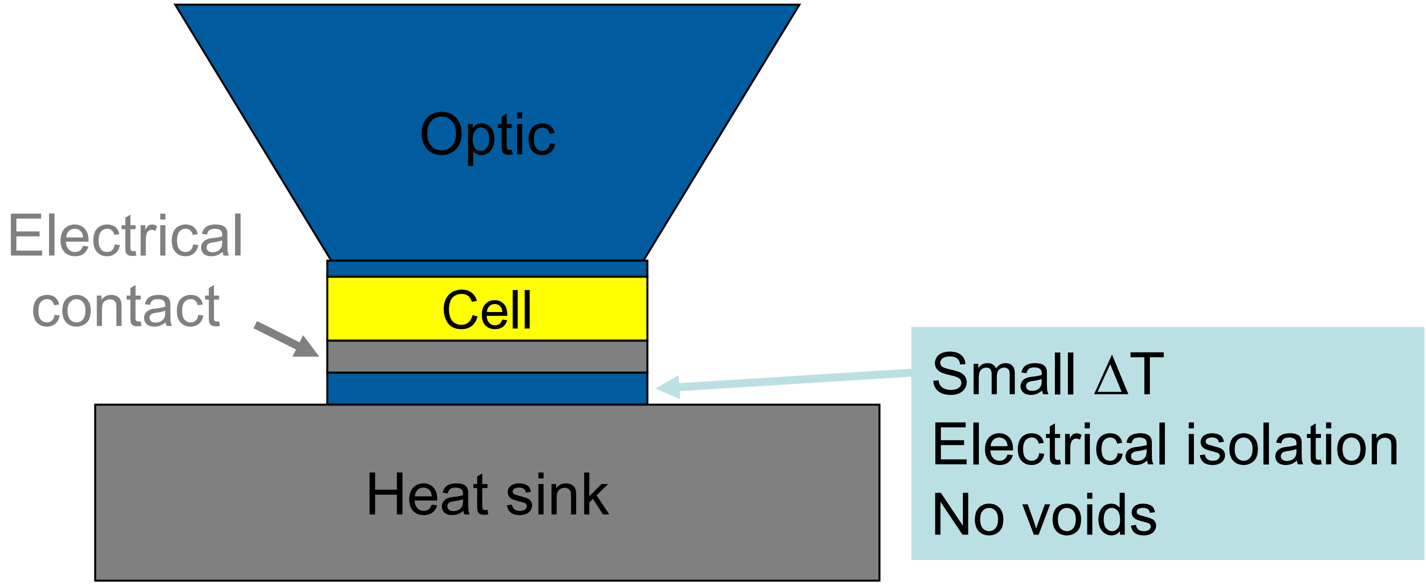
Lower f number

Reduces thickness

Innovative designs may have aesthetic appeal

If you use low f number, analyze the effects of imperfect optics and alignment

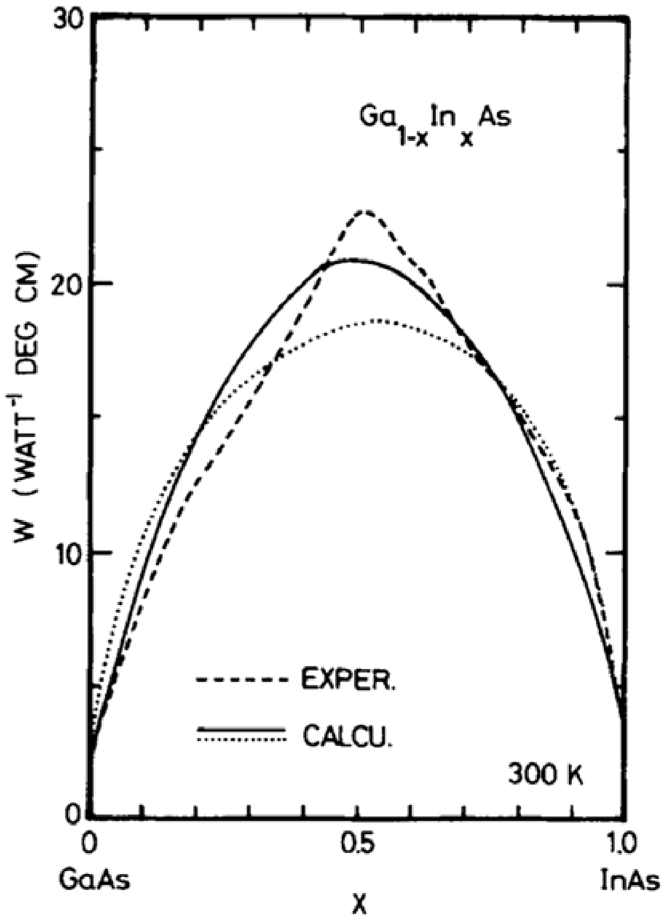
Design trade offs – thermal management

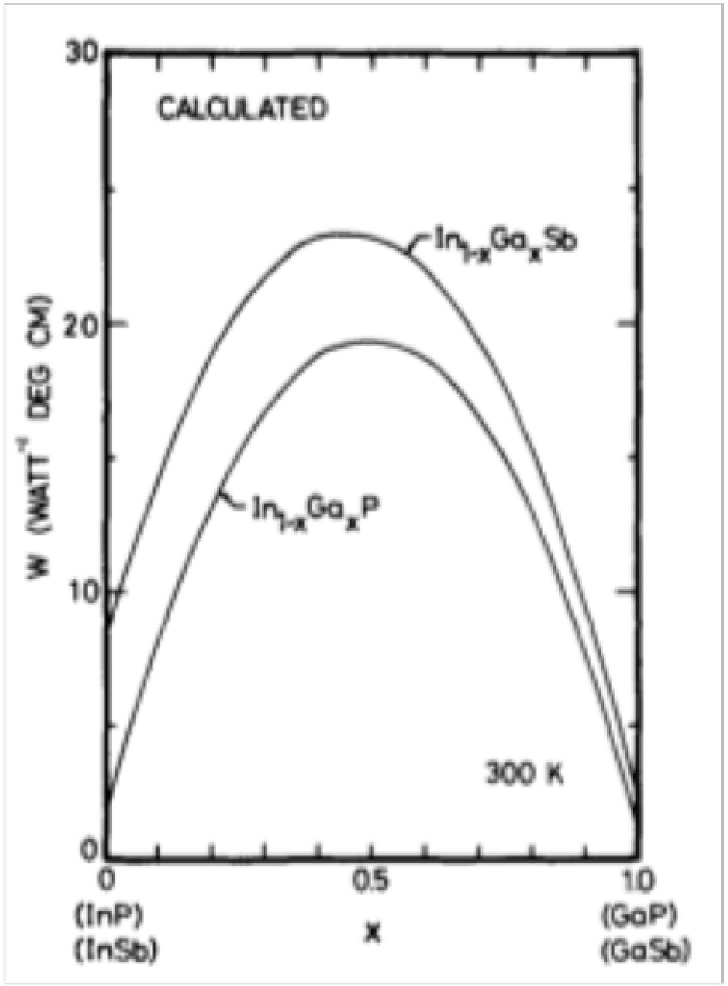


- Pure, single-crystal materials usually have good thermal conductivity
- Impurities and structural defects (dislocations or grain boundaries) can affect thermal conductivity

Thermal resistivity varies with composition

Thermal transport through a pure, single crystal is much higher than for imperfect crystal





Adachi, J. Appl. Phys. 54(4) p.1844 (1983)

Crude thermal analysis - ΔT within cell

	Composition	Thickness (µm)	Thermal conductivity (W/cmK)	ΔT for heat flux of 23 W/cm^2 (°C)
3J on Ge	GaInP	1	0.05	**0.05**
	GaAs	3	0.46	**0.02**
	Ge	175	0.6	**0.7**
Inverted 3J metamorphic	GaInP(50%In)	2.7	0.05	**0.1**
	AlGaInP(grade)	1	0.05	**0.05**
	GaInAs(4%In)	2.7	0.2	**0.03**
	GaInP(grade)	3	0.05	**0.1**
	GaInAs(37%In)	3	0.05	**0.1**

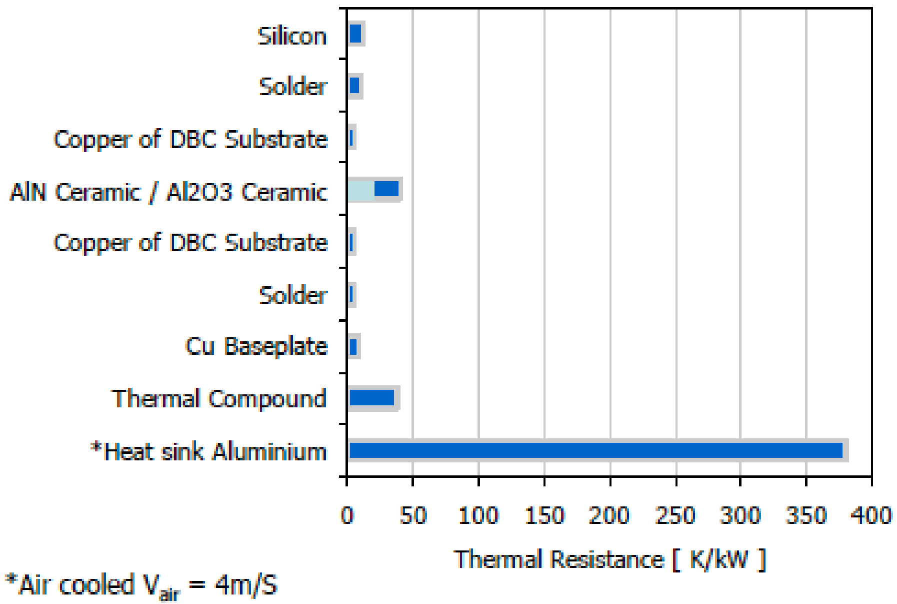
500 suns @ 850 W/m^2; 85% optical efficiency; 35% cell efficiency: the waste heat is 23 W/cm^2. (Ignore radiative transfer)

T drop within cell is *not* a serious problem under most circumstances

Crude thermal analysis – ΔT to heat sink

Direct bonded copper

Composition	Thickness (μm)	Thermal conductivity (W/cmK)	ΔT for heat flux of 23 W/cm^2 (°C)
Solder (epoxy)	30	0.4 (0.02)	0.2 (4)
Cu	250	3.9	0.1
AlN (Al_2O_3)	600	1.7 (0.25)	0.8 (6)
Cu	250	3.9	0.1
Solder (epoxy)	30	0.4 (0.02)	0.2 (4)



Credle, Dehmel, Schulz-Harder ICSC5 (2008)

Crude thermal analysis – ΔT to ambient

Conclude:

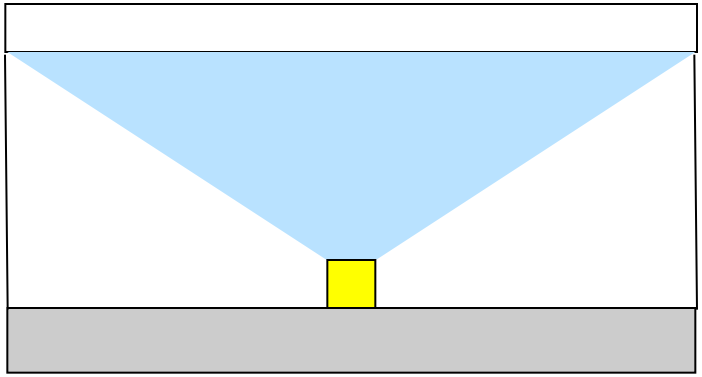
1. ΔT within cell is small
2. ΔT between cell and heat sink is larger
3. ΔT between heat sink and ambient is largest

T drop from heat sink to ambient may be similar to flat-plate's module-to-ambient ΔT

Technology	Mounting	ΔT for ~1000 W/m^2 (°C)
Flat plate	Open rack	**~30**
Flat plate	Insulated on back	**~60**

Do the optics act as insulation?

Design trade offs – how to keep the dirt out?



Issue: need to keep dirt and water out

- Condensation of water can obscure lenses
- Condensation of water can fry cells
- If air tight, then pressure changes deform system
- Cells may run hot

Mundane issue can be huge engineering challenge

Design trade offs – keep the water out

Water condensation on lenses

Araki, ICSC5, 2008

Mundane issue can be huge engineering challenge

Bird's eye view – factory vs installation

Build at the factory

Reduces installation costs

Build in the field

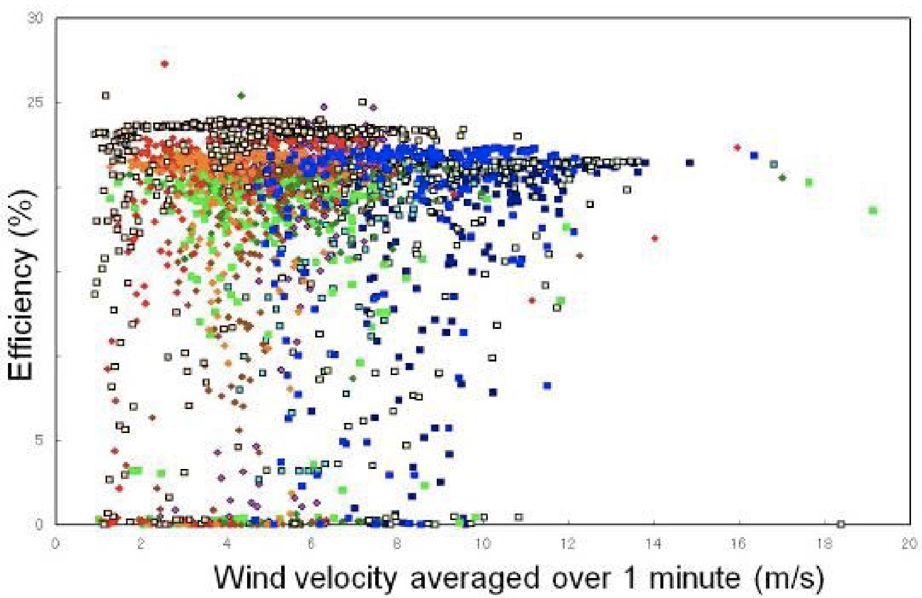
Reduces transport costs

Bird's eye view – wind effects

The losses associated with wind stow depend on the local weather and the control parameters:

-Wind speed for stow

-Time stay in stow

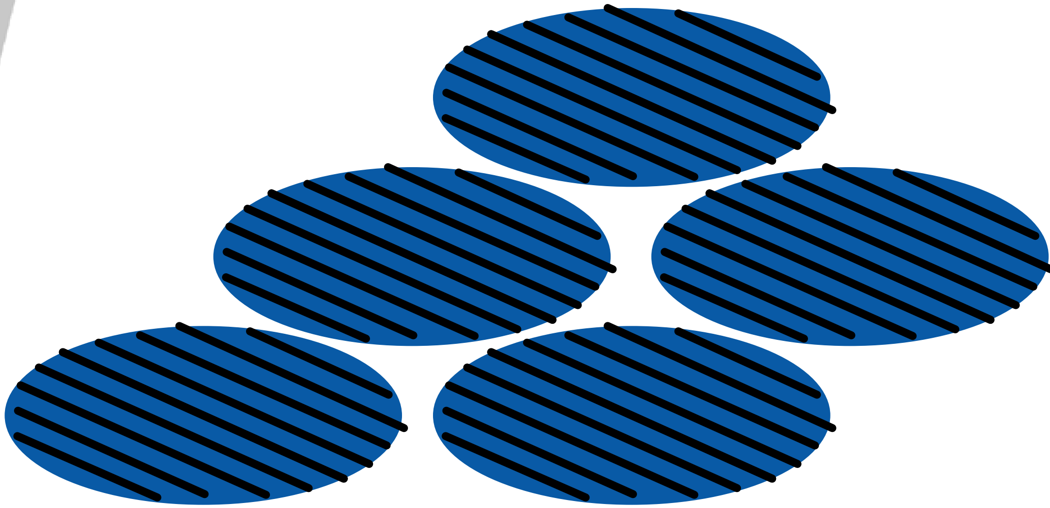


Araki, 33rd PVSC 2008

High winds can cause loss of efficiency if acceptance angle is small

Bird's eye view – system shading

Pedestal



Carousel

Pivot

Shading can affect system performance;
Shading of every cell is different from shading one cell in a string
New solutions are now available

Bird's eye view – system configuration

Amonix photo

General Energy photo

Pedestal is less disruptive

- Dual land use
- Bureau of Land Management – don't disrupt habitat
- Minimal site preparation
- Fast installation

Carousel

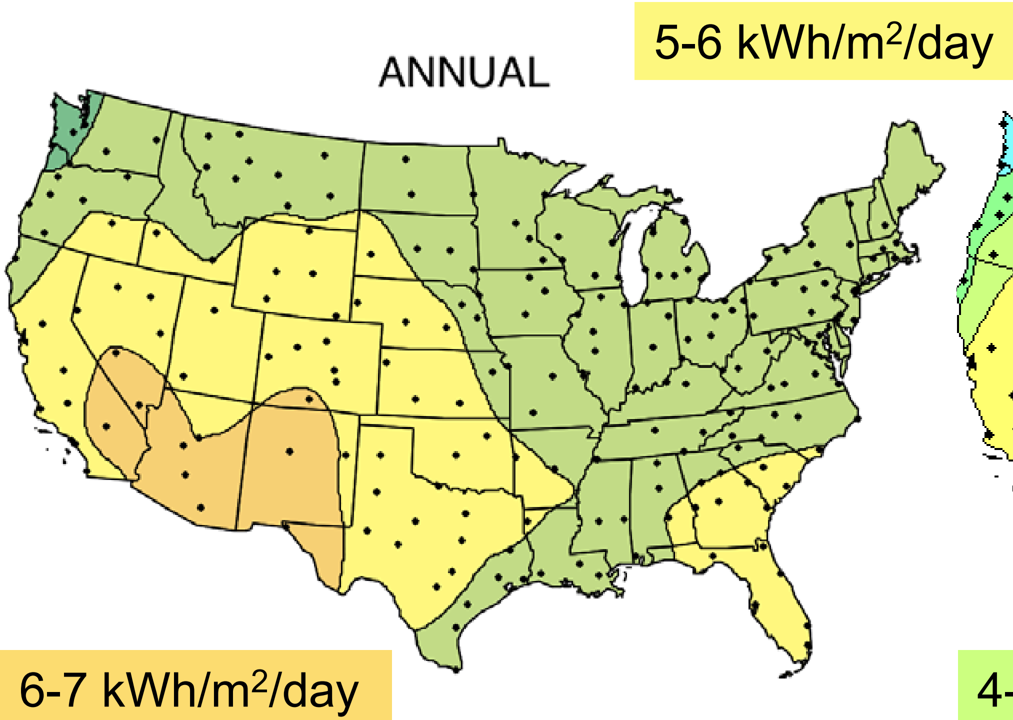
- Can maximize land use
- Avoid being in the wind, so don't need as much strength
- Can use on roof top
- Need to be able to adjust
- Soiling; plant growth?

Bird's eye view – 1987 Barstow installation

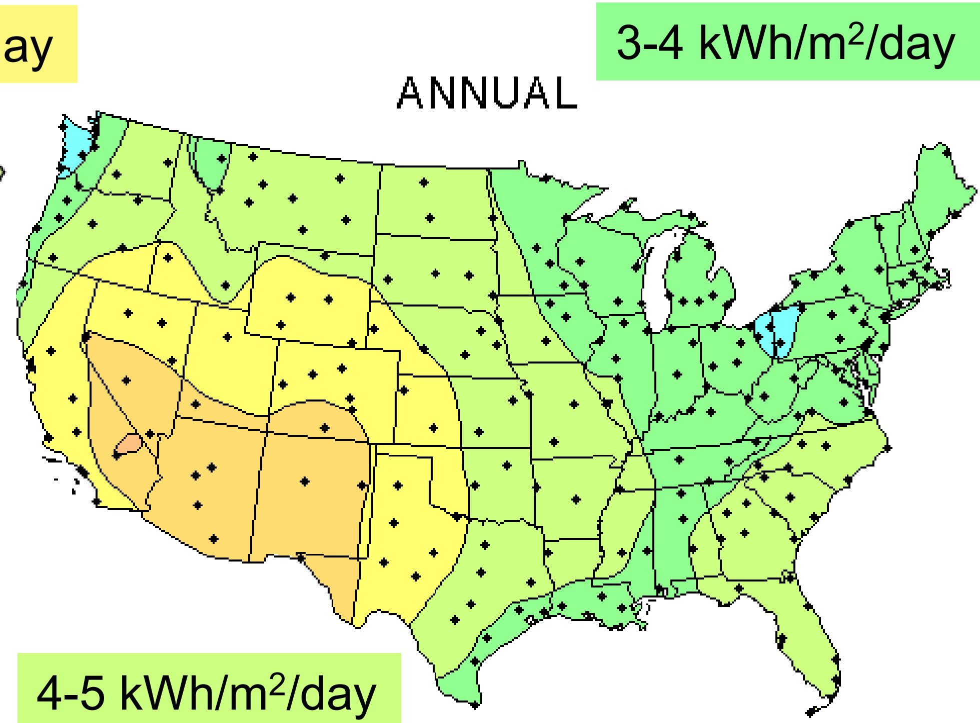
More than 1 MW installed in 1980s

General Energy photo

Markets by location; CPV sunshine is better in west



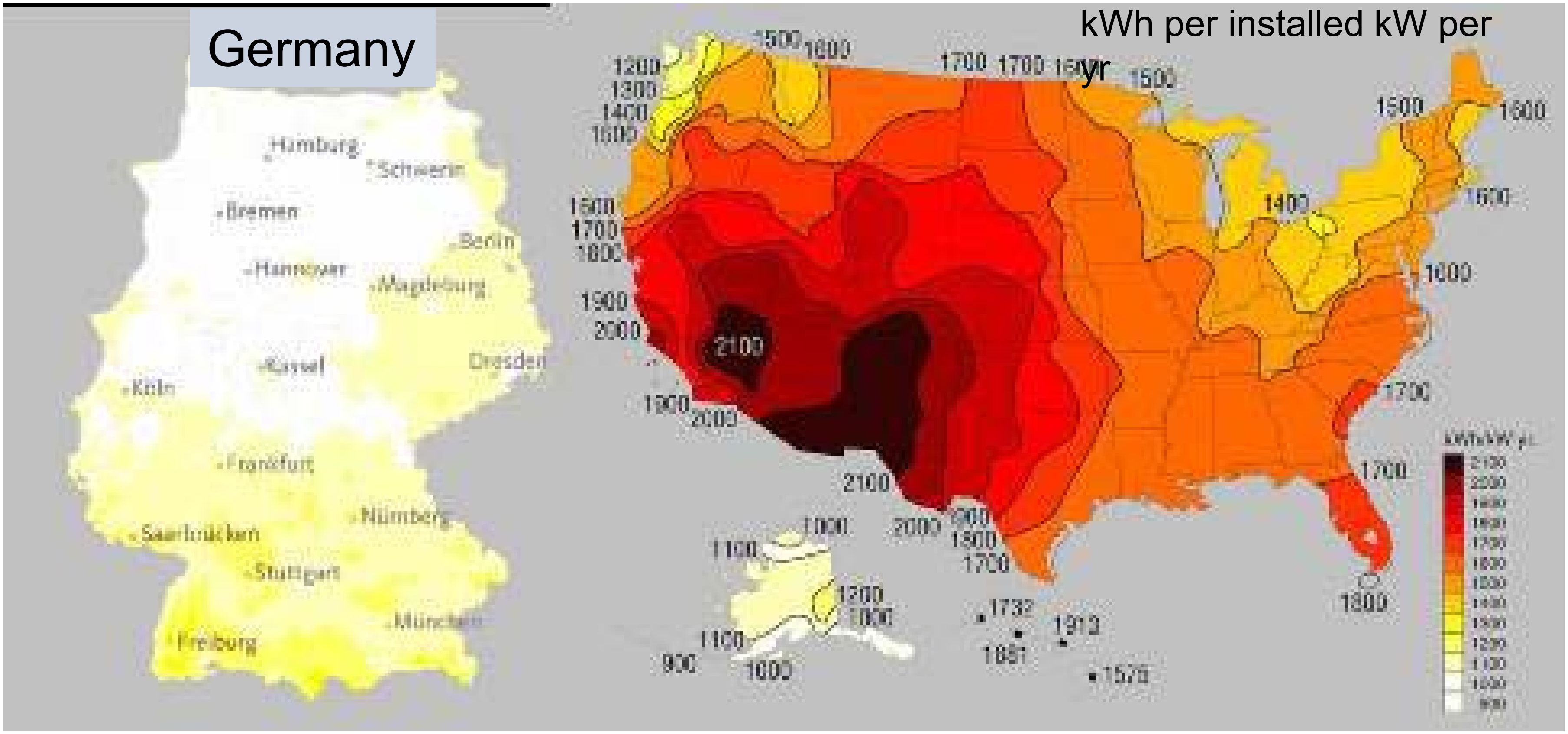
Fixed, latitude tilt
Global



Two-axis tracked
Direct (DNI)

http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/atlas/

Markets by location; but sunshine isn't everything



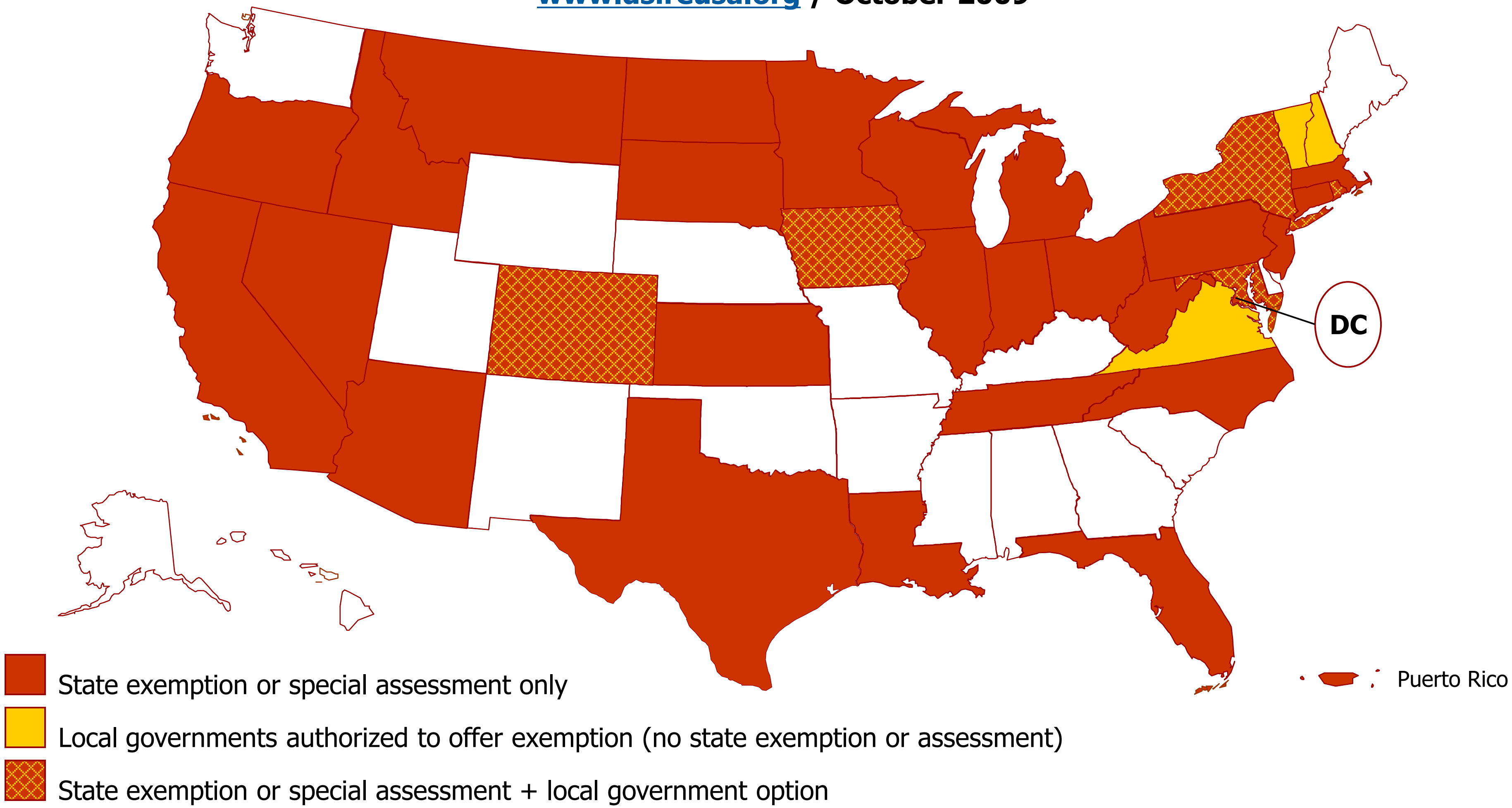
Germany has one of biggest markets despite poor solar resource

http://votesolar.org/images/Germany_US_2.jpg

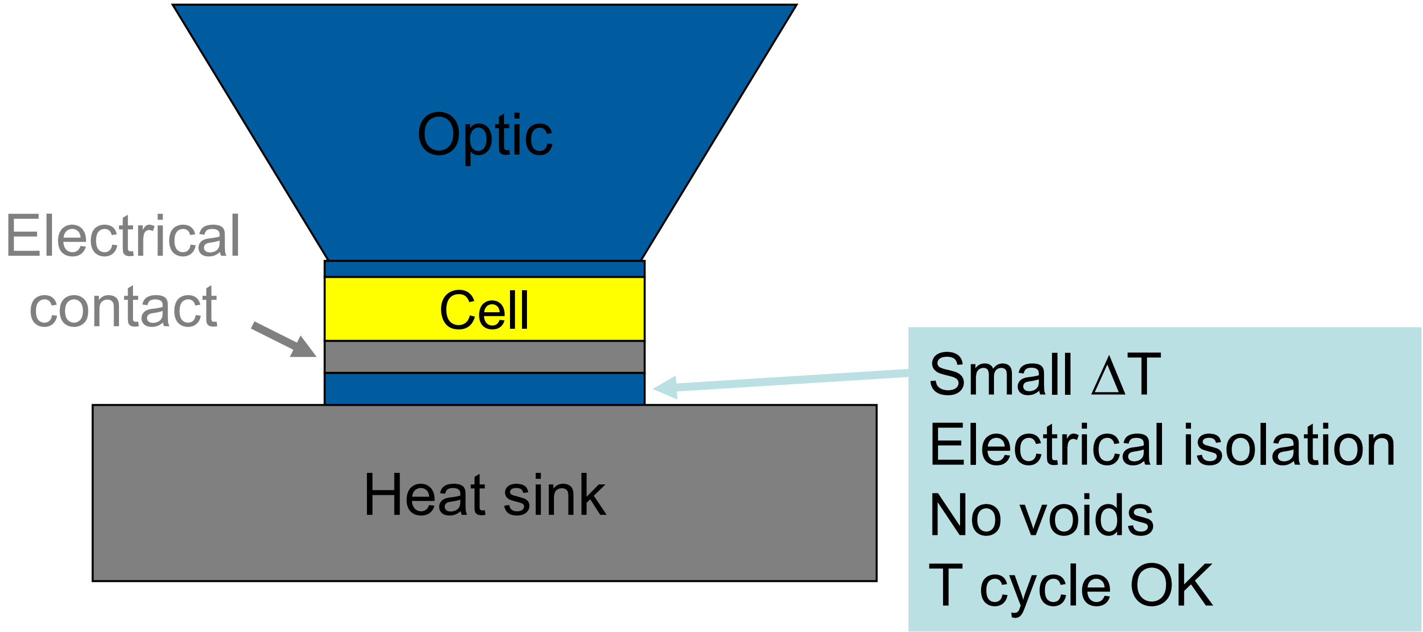
Property Tax Incentives for Renewables

See this website for related information

www.dsireusa.org / October 2009



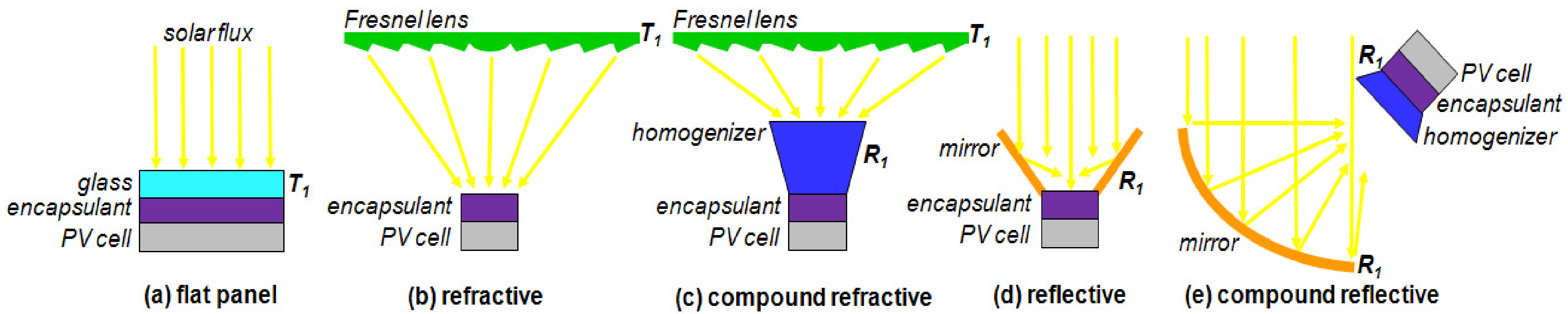
Reliability - bond to heat sink



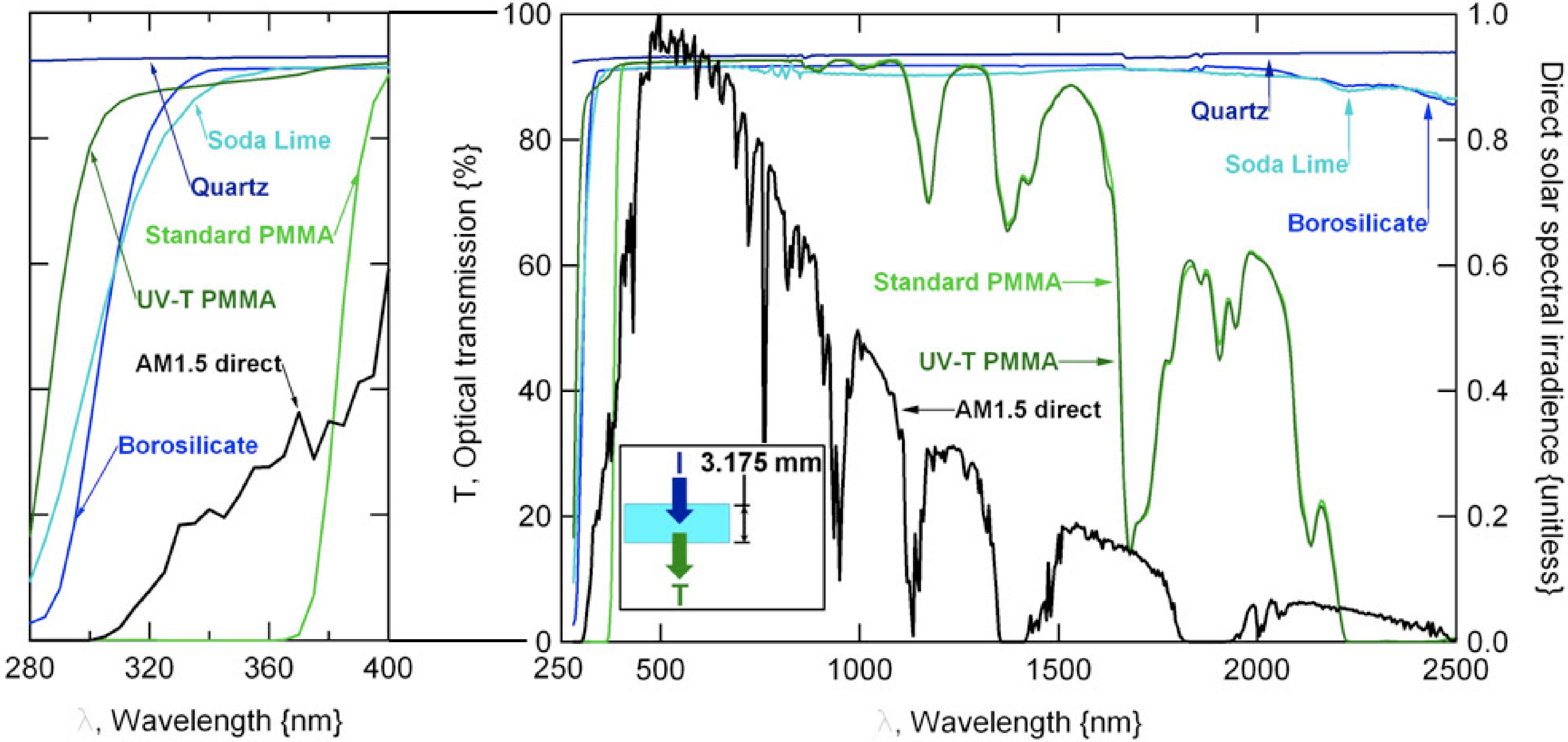
- Borrowing experience from power electronics and DBC (direct bonded copper) makes this a smaller issue
- Currently, there is a debate about the best way to test this bond – see standards section

Reliability – UV exposure

Analysis of transmitted optical spectrum enabling accelerated testing of CPV designs
SPIE 2009 David Miller, et al



Reliability – UV exposure



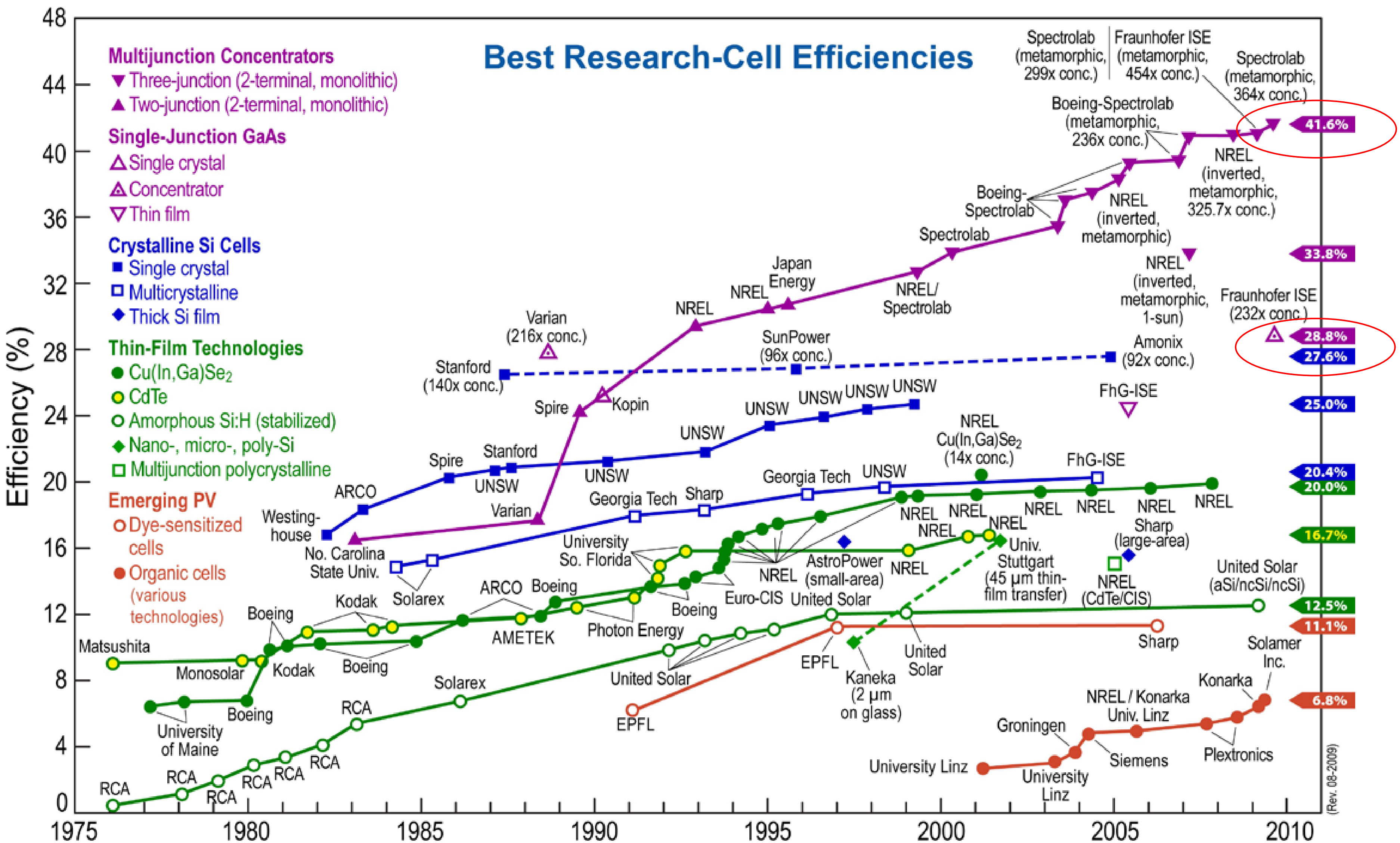
PMMA absorbs UV strongly, protecting cell, so UV stress is not so high

SPIE 2009 David Miller, et al

Outline

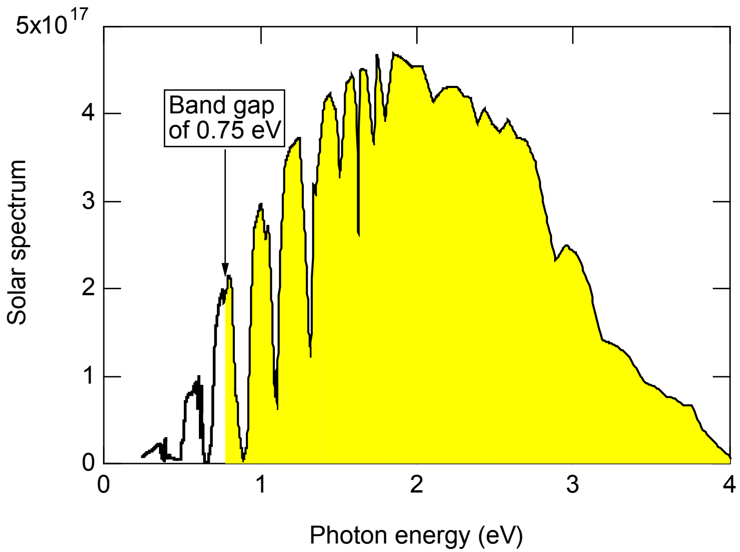
- Overview of PV – Opportunity for CPV
- Fundamentals of concentrating PV
  - Advantages
  - Primary approaches (High & low concentration)
  - Designing from the system perspective
- Design considerations
  - Thermodynamic limit of concentration
  - Refractive vs reflective optics
  - Concentration ratio, f number, etc.
  - Thermal considerations
  - Keeping the dirt and water out
  - Cells (multijunction & silicon)

Smallness enables use of highest efficiency cells

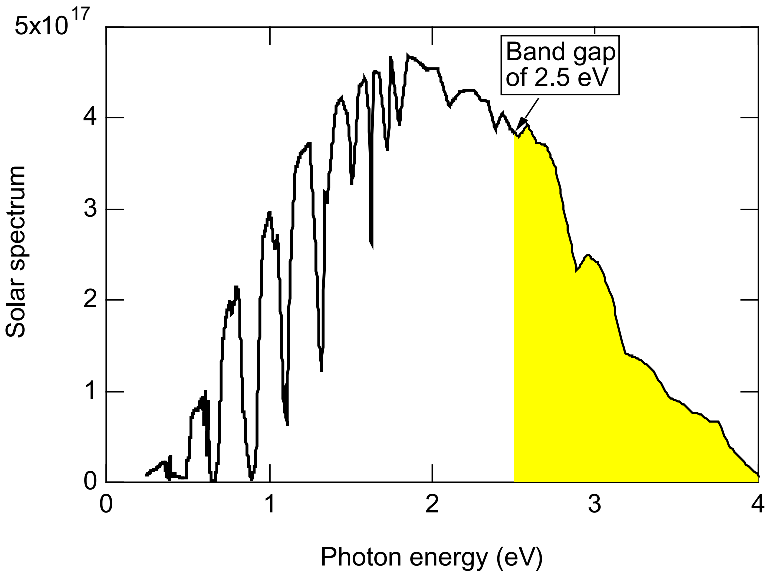


Why multijunction?

Power = Current X Voltage



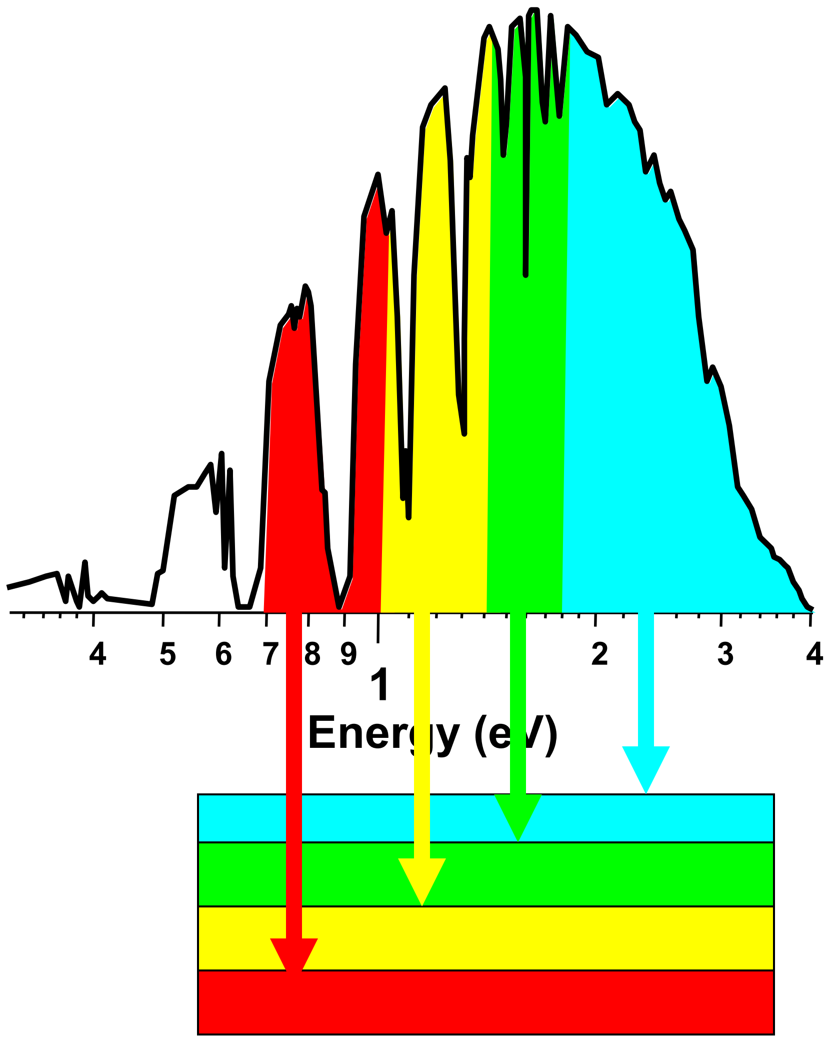
High current,
but low voltage



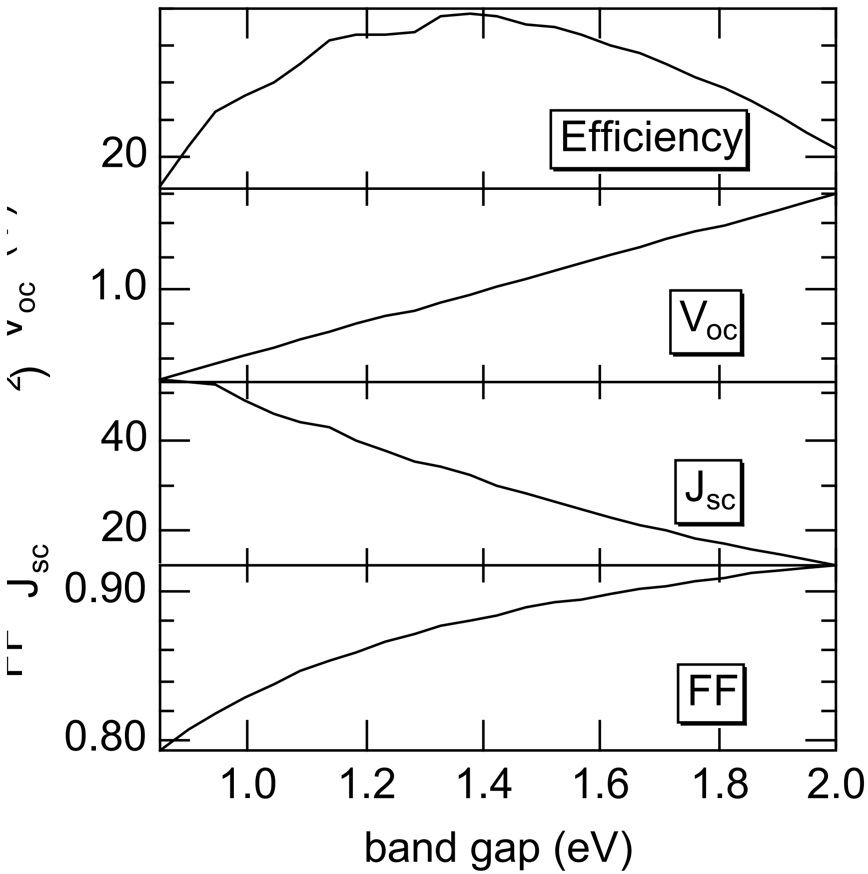
High voltage,
but low current

Highest efficiency: Absorb each color of light with a material that has a band gap equal to the photon energy

Multijunction cells use multiple materials to match the solar spectrum



Expected efficiency depends on band gap

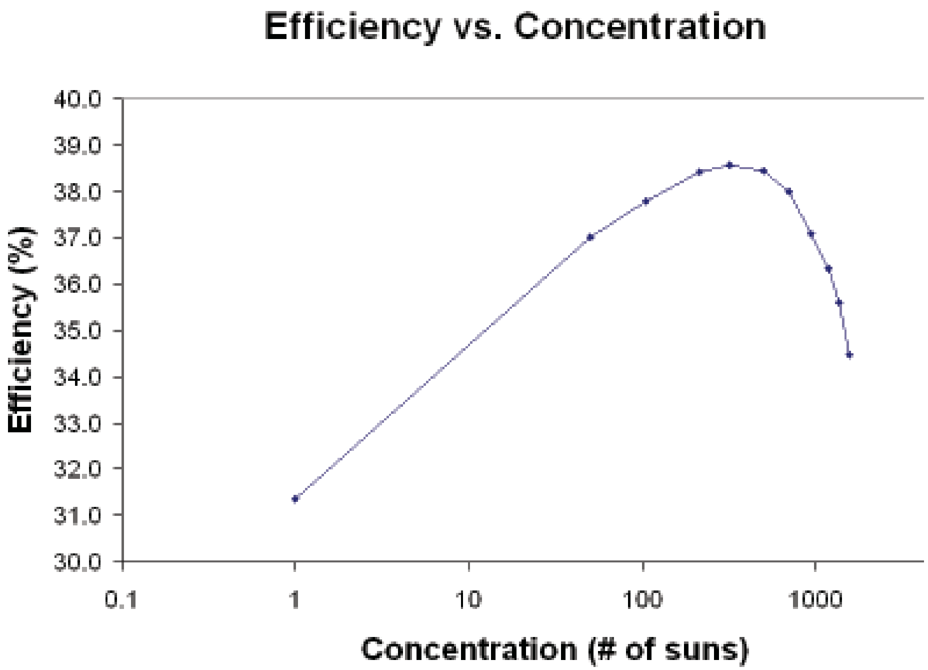


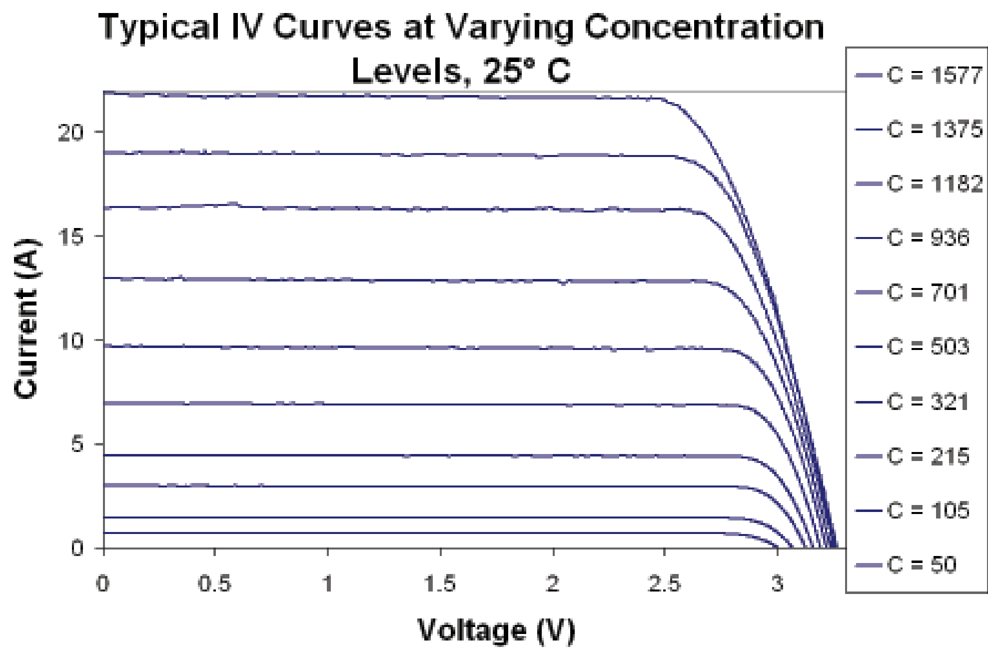
Calculation for an ideal device with GaAs-like materials properties (except for E_g) at T=300K. Spectrum used is AM1.5 global. Friedman

Could have higher efficiency for monochromatic light

or, we should look for a set of materials to match portions of the spectrum

Efficiency increases with concentration





I ∝ flux

V ∝ log(flux)

Power = I*V ∝ flux*log(flux)

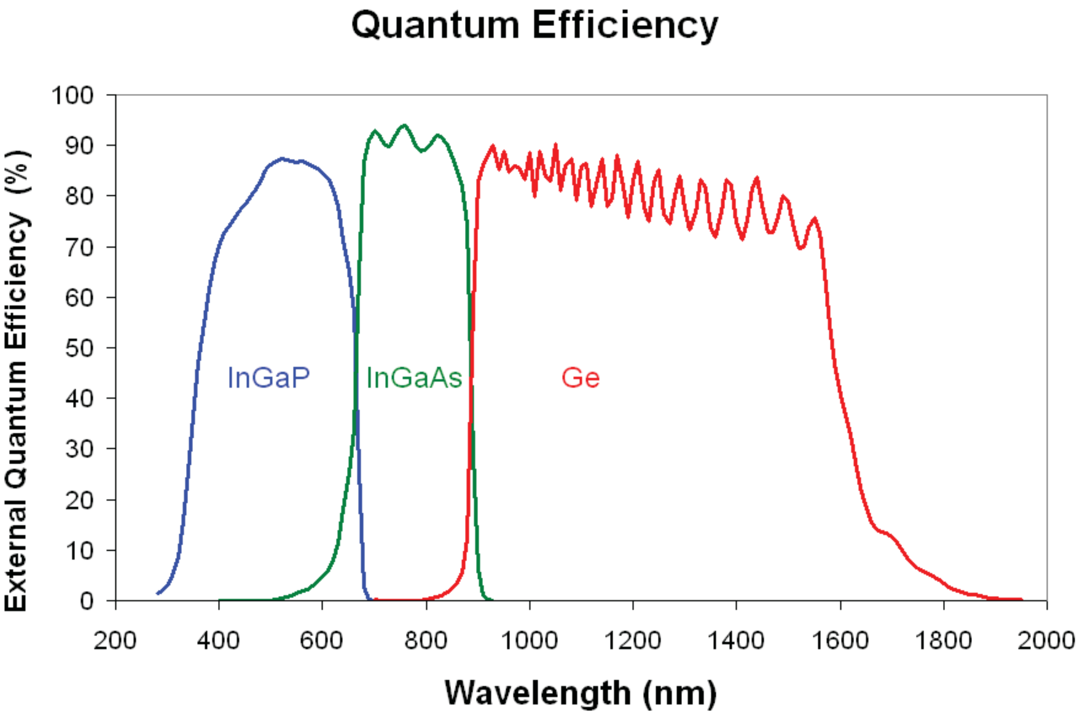
Efficiency ∝ log(flux)

Efficiency increases with concentration until the series resistance becomes a problem

At 7 A and 3 V, 4 mΩ causes 1% loss

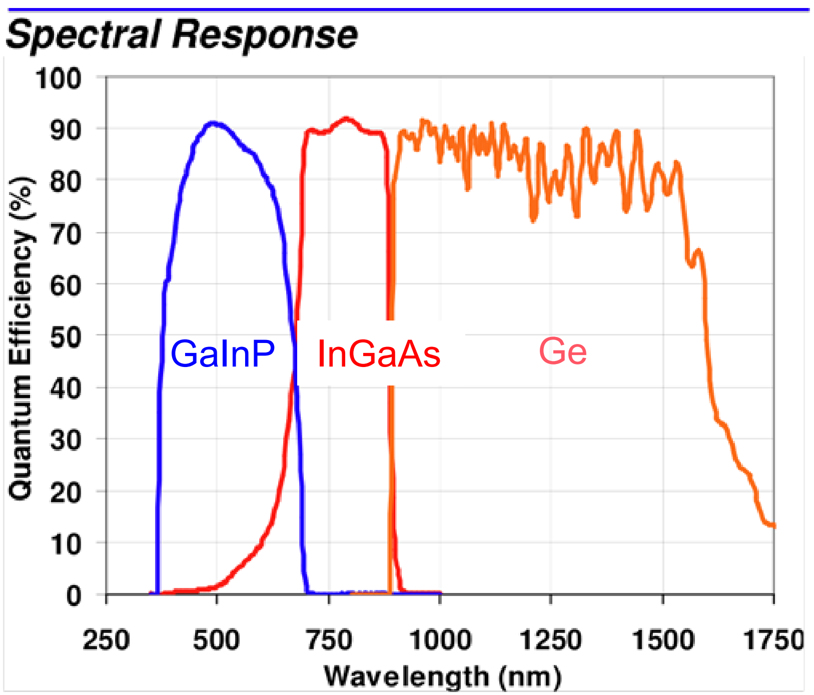
Graphs from http://www.emcore.com/assets/photovoltaics/CTJ_B_Web.pdf

Response of three junctions



http://www.emcore.com/assets/photovoltaics/CTJ_B_Web.pdf

Data for commercial cells



Three junctions are measured using light bias

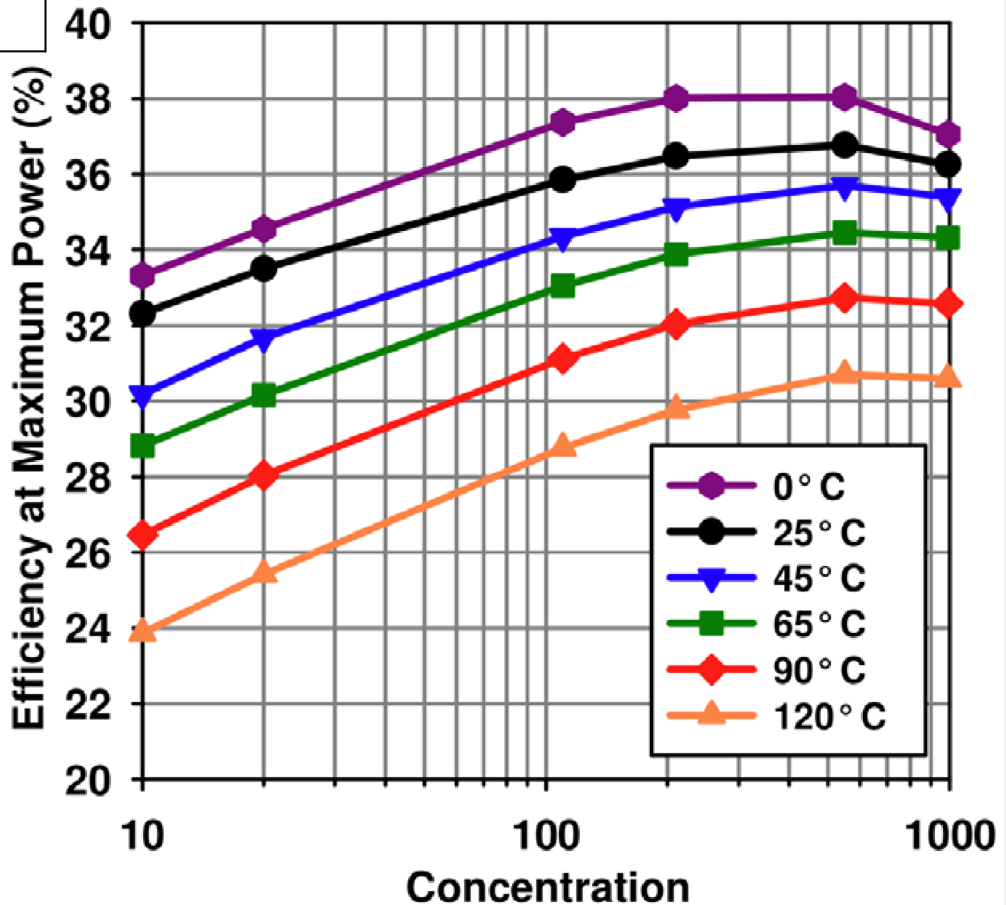
http://www.spectrolab.com/DataSheets/TerCel/C1MJ_CDO-100.pdf

Temperature coefficients: ~-0.2%/°C

Temperature Dependence at 800 Suns
ΔVoc = -4 mV/°C
ΔJsc = 7.2 mA/°C
ΔEfficiency = -0.06% (absolute)/°C

http://www.emcore.com/assets/photovoltaics/CTJ_B_Web.pdf

Data for commercial cells



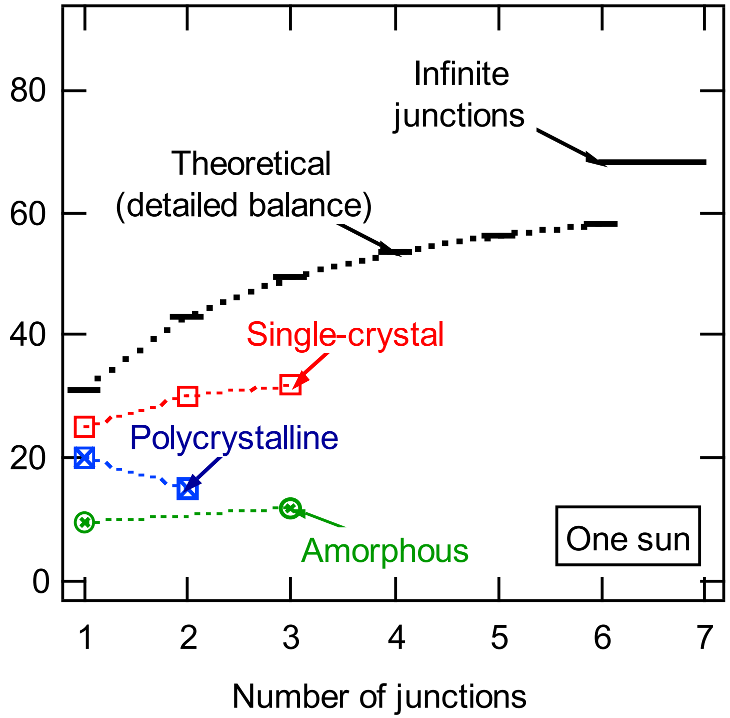
http://www.spectrolab.com/DataSheets/TerCel/C1MJ_CDO-100.pdf

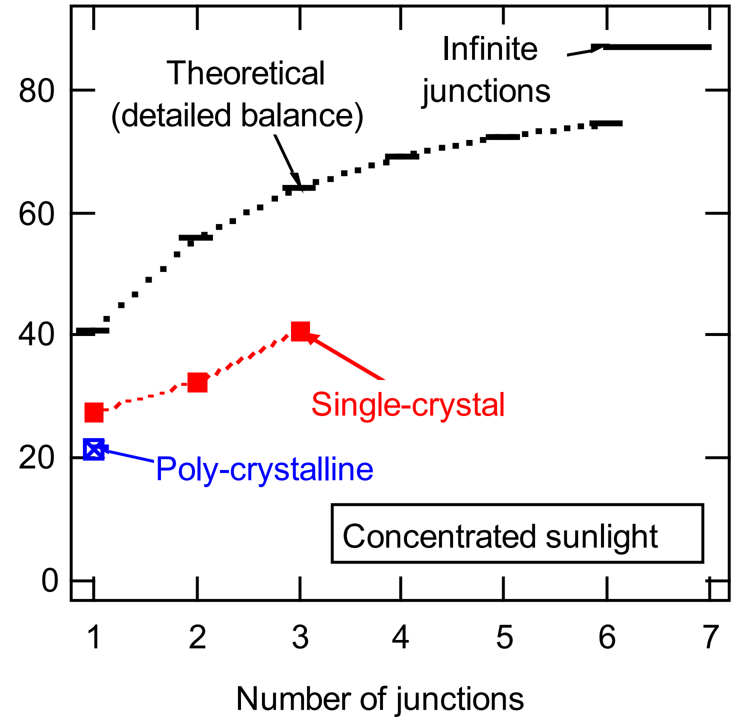
Temperature coefficients
- smaller than for c-Si
- smaller at higher conc.
- can depend on spectrum

Friedman "Modeling of tandem cell temperature coefficients" 25th PVSC, p. 89 (1996).

Is there room to grow?

Theoretical & experimental efficiencies



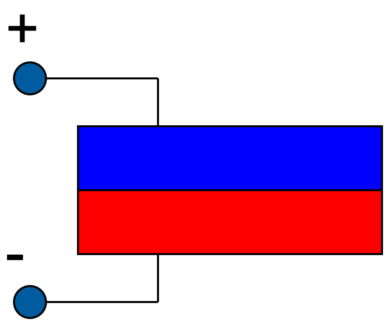


Marti & Araujo, Solar Energy Mat. & Solar Cells **43** p. 203 (1996)

Kurtz, et al Prog. In PV, 2008.

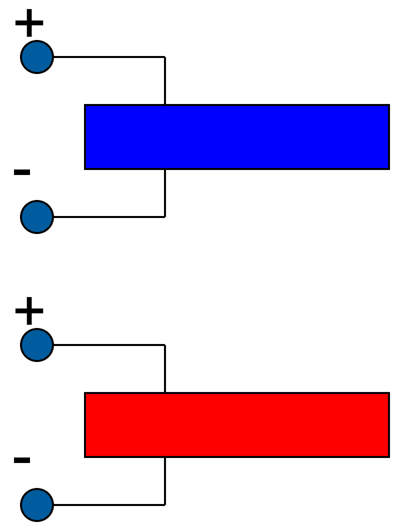
Higher efficiencies by: 1. more junctions, 2. use concentration, 3. improve material quality

Approaches to multijunction



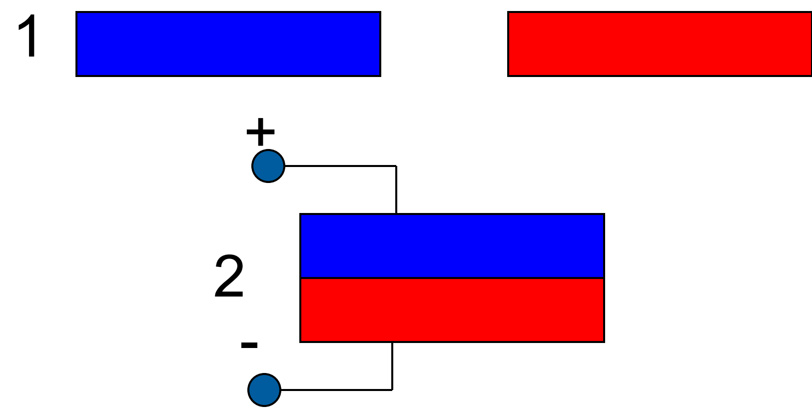
Monolithic

41.1%
champion
Fraunhofer



4 (or more)-terminal
Mechanical stack

42.8%
champion
DARPA

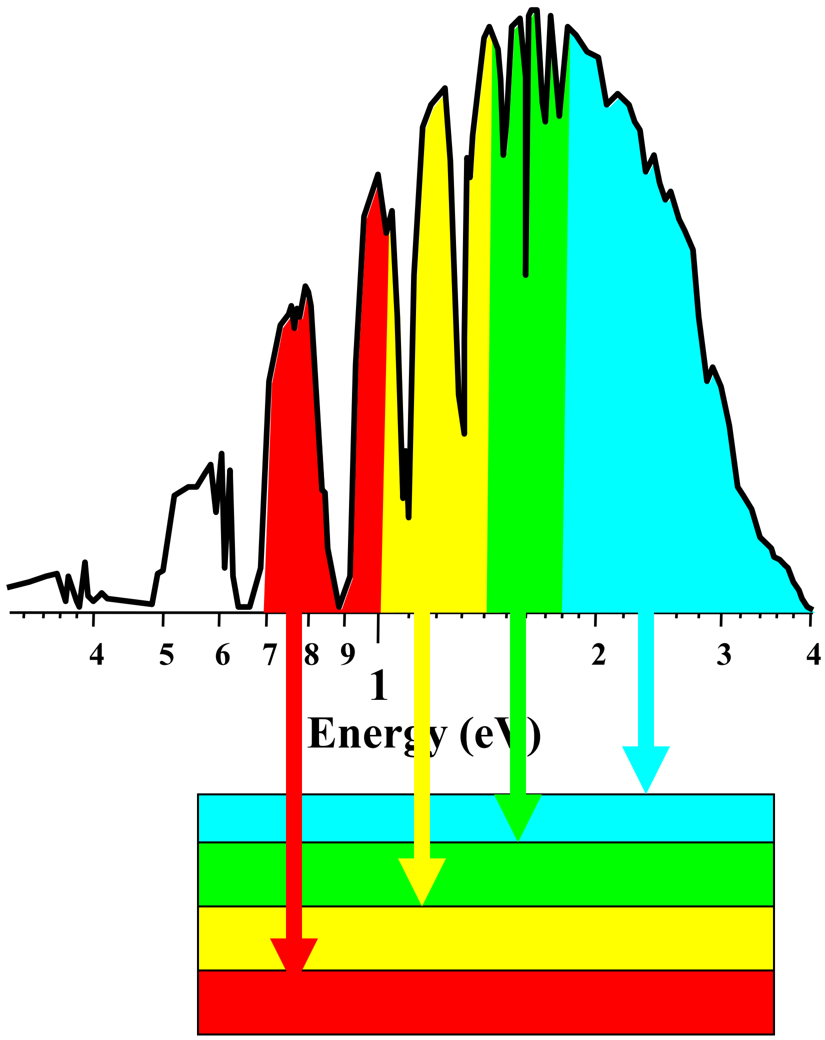


Wafer bonded

Many other
configurations

Multijunction cells can be assembled in many ways

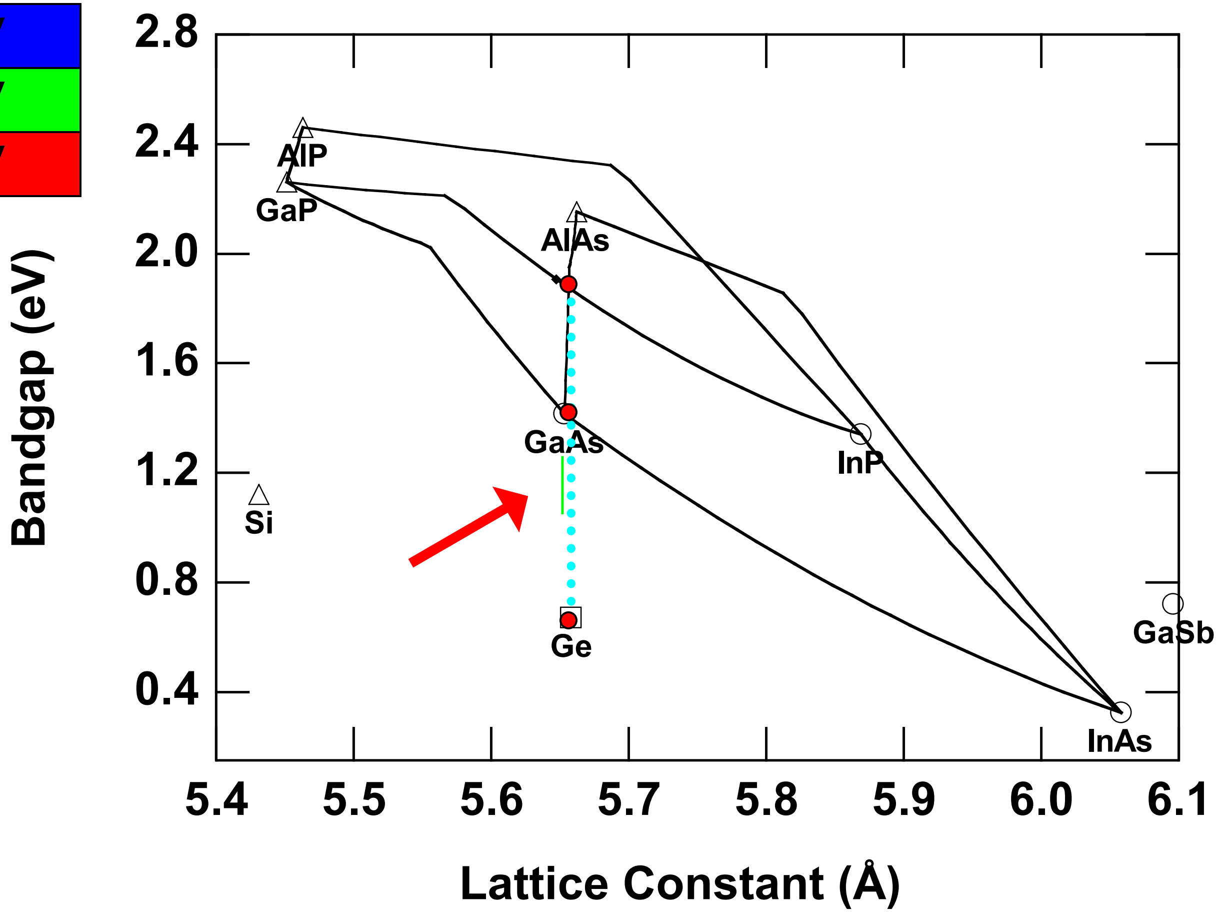
Choose materials with band gaps that span the solar spectrum



For series connection (monolithic approach): equal photocurrents

Lattice-matched 3 junction

1.9 eV
1.4 eV
0.7 eV



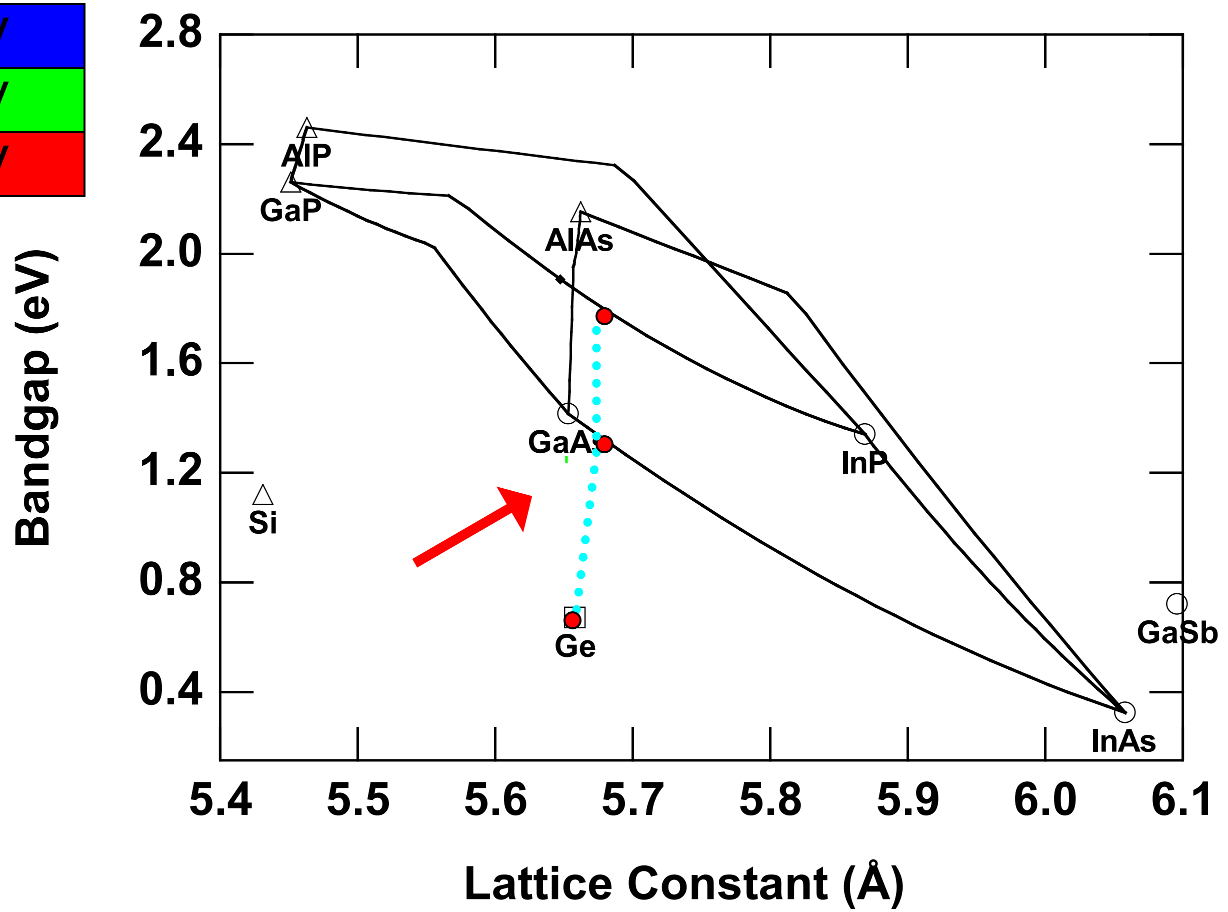
41.6%
Spectrolab

Lattice matched materials give high crystal quality

Current record: http://boeing.mediaroom.com/index.php?s=43&item=810

Lattice-mismatched 3 junction

1.8 eV
1.3 eV
0.7 eV



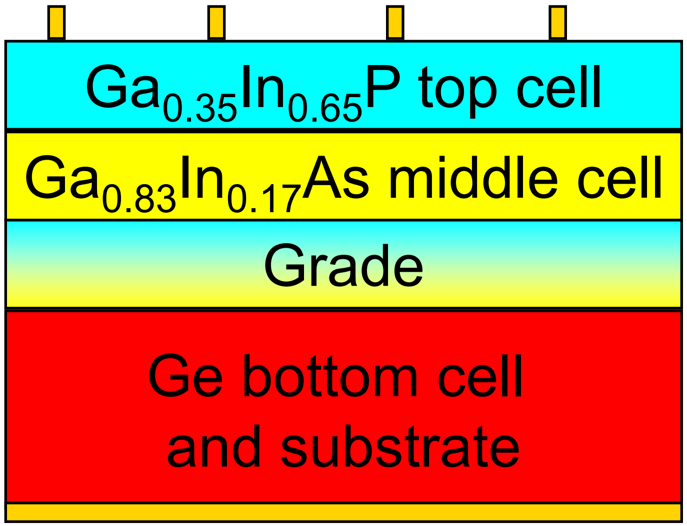
41.1%
Dimroth
2009

http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise

41.1% efficiency cell (Fraunhofer ISE)

3 junctions: top two are mismatched

Not to scale
Tunnel junctions
not shown

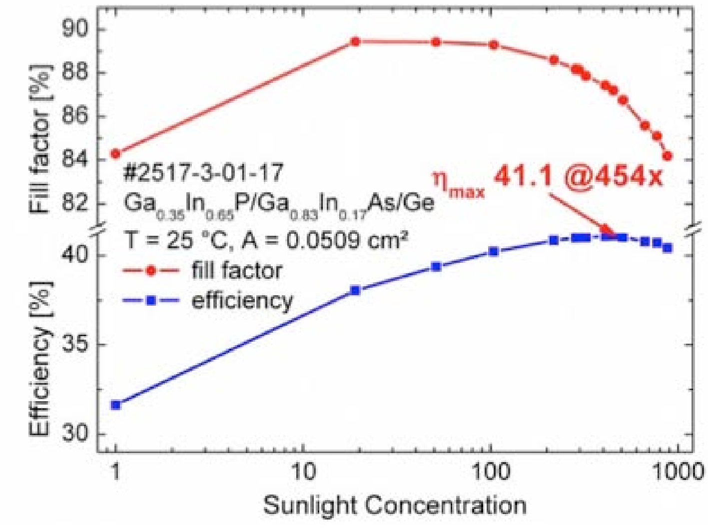


1.75 eV
1.3 eV
0.7 eV

n-on-p junctions
connected by
tunnel junctions

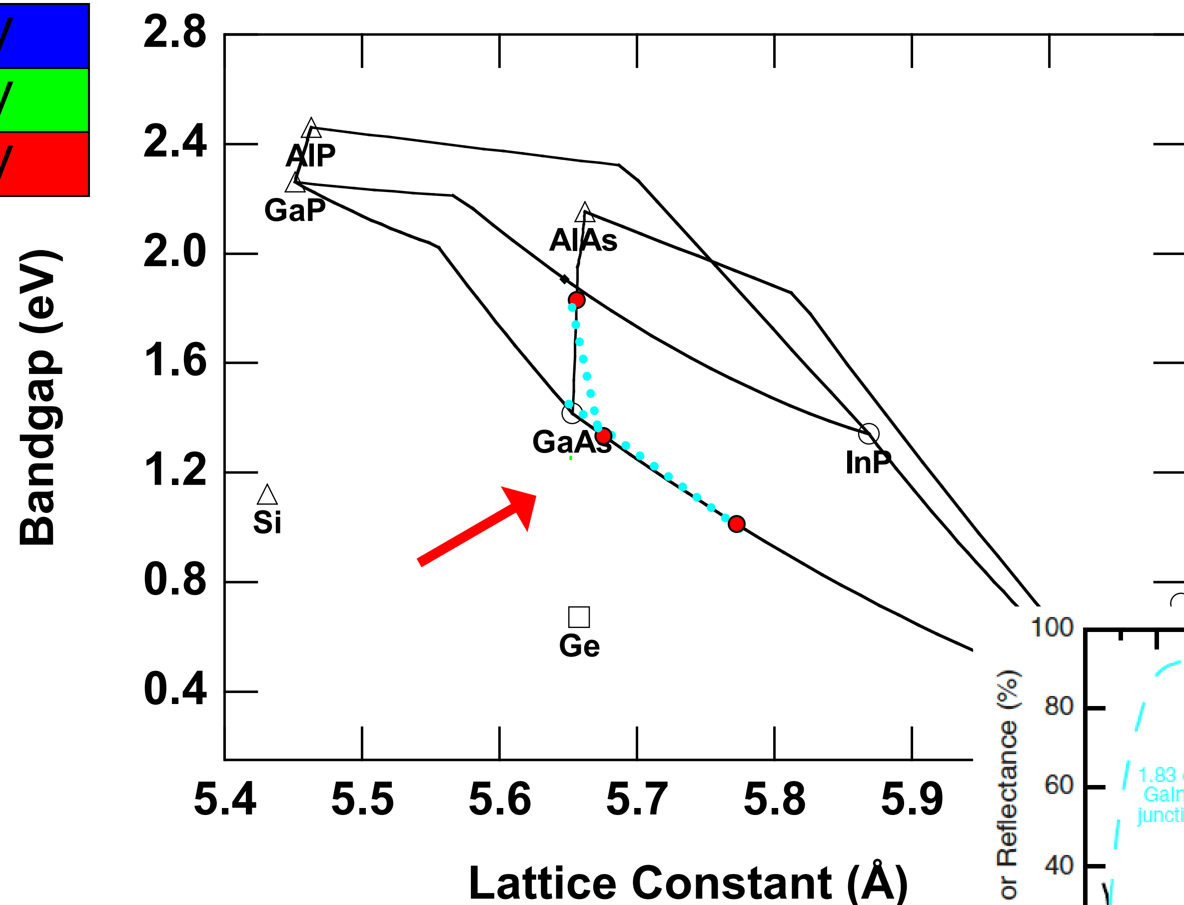
http://www.ise.fraunhofer.de/press-and-media/press-releases/press-releases-2009/world-record-41.1-efficiency-reached-for-multi-junction-solar-cells-at-fraunhofer-ise

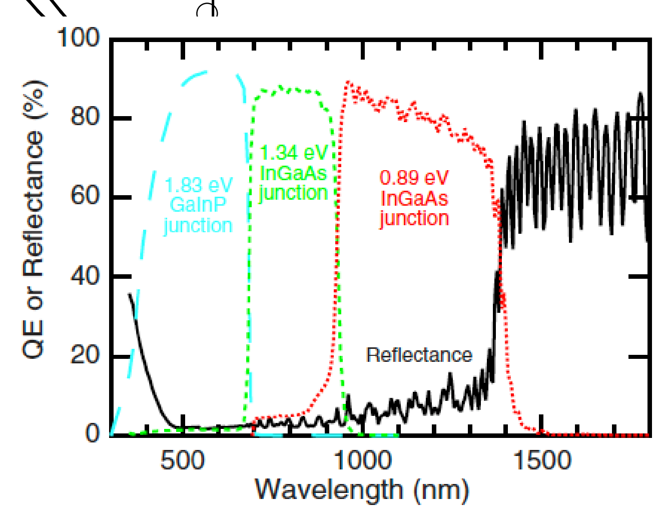
41.1% record by Fraunhofer ISE



Inverted lattice-mismatched (IMM)

1.8 eV
1.3 eV
0.9 eV





40.8%
Geisz
APL
2008

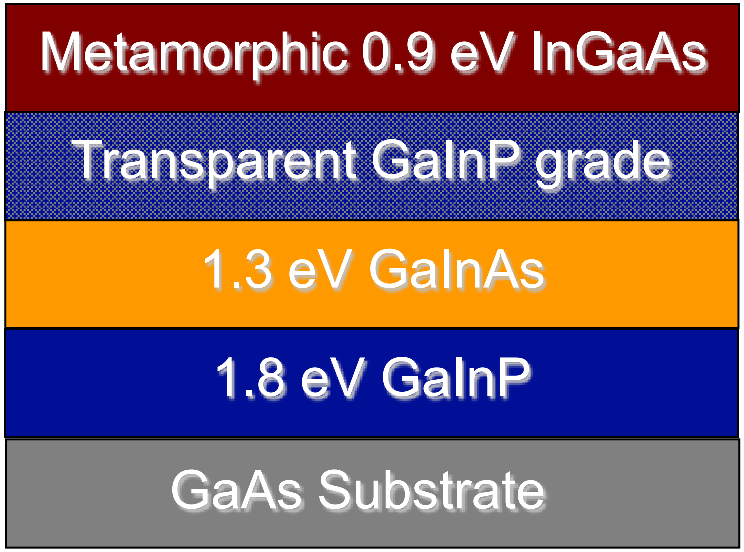
Lattice matched materials are grown first

Inverted metamorphic approach

GaInP/Ga(In)As/GaInAs Ultra-Thin Tandem Cell

Advantages:

- Path to higher efficiency – 40.8% so far
- Reuse of substrate or use of impure substrate can reduce cost (and use of semiconductor material)



Invented by Mark Wanlass
40.8%: John Geisz, APL, 2008
R&D 100 Award.

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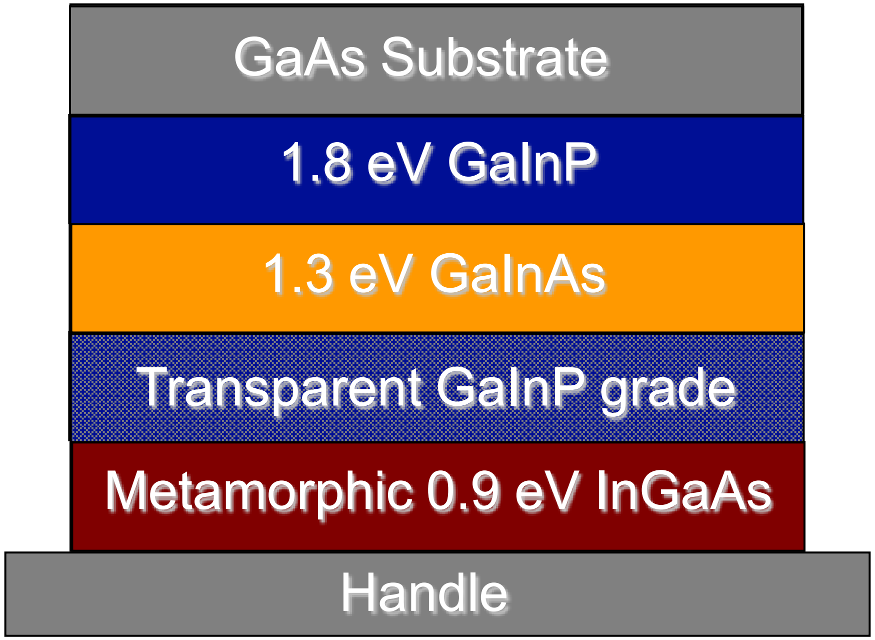

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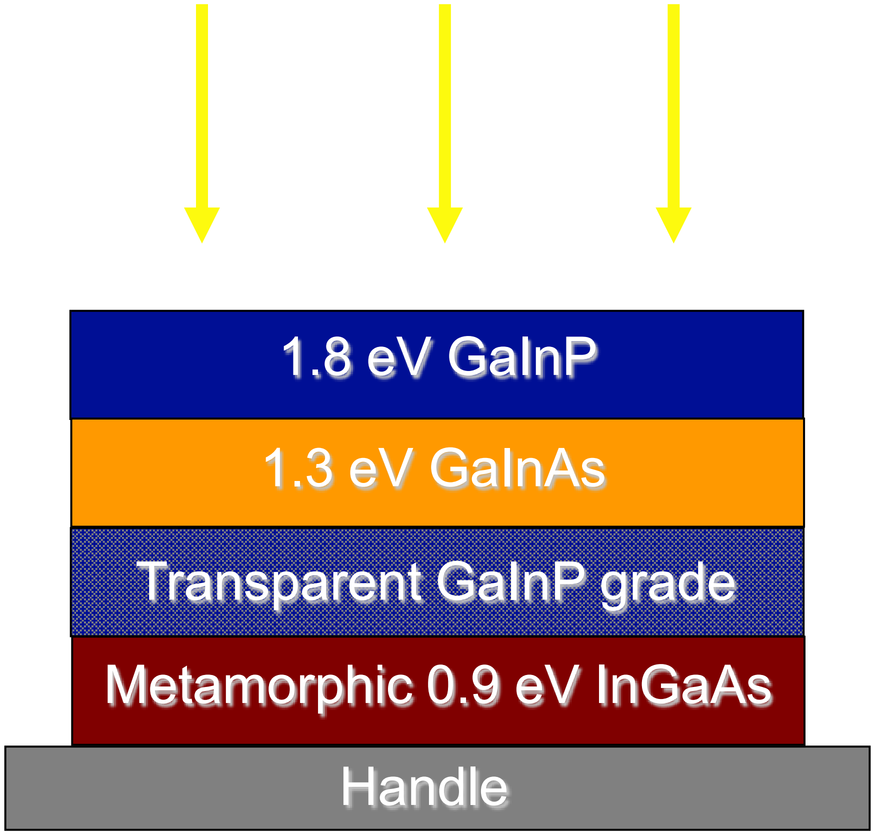
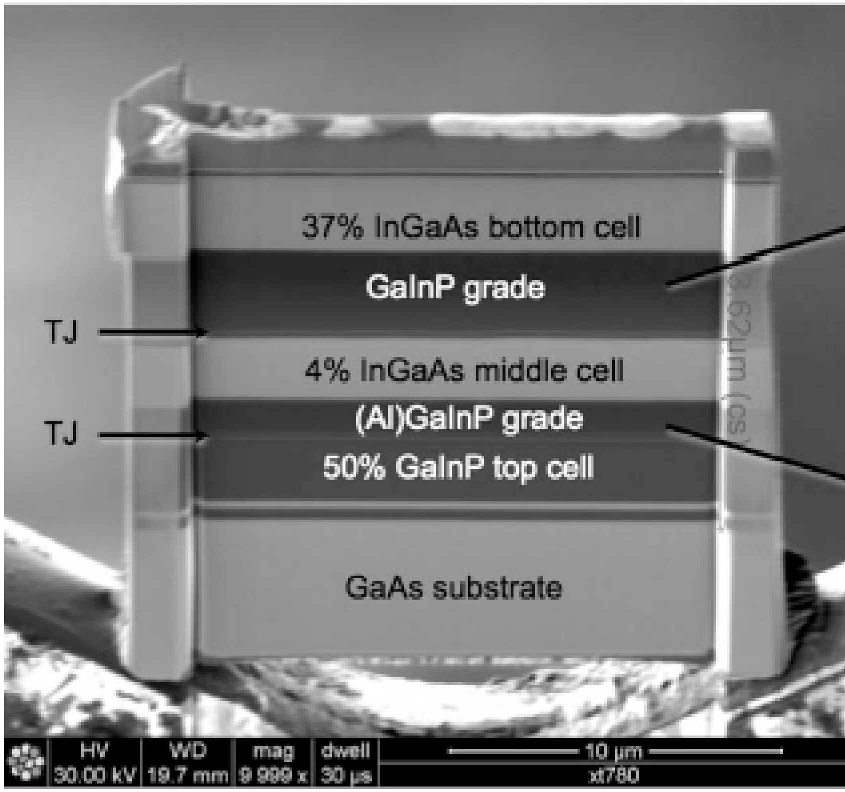
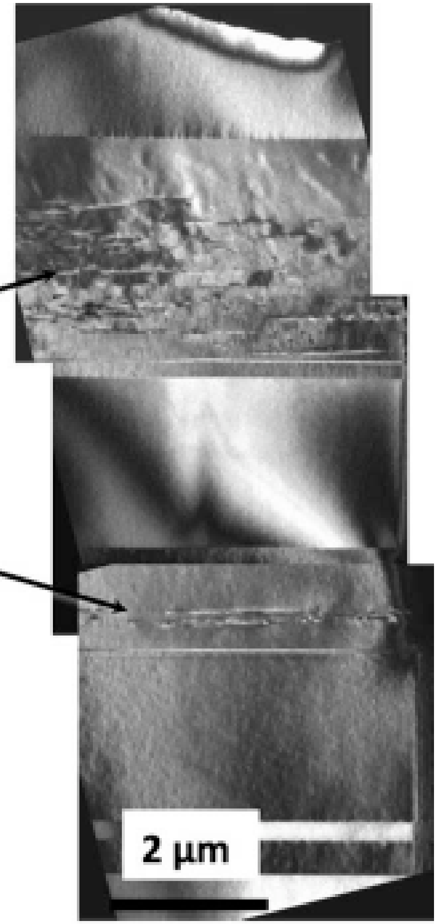


Invented by Mark Wanlass
40.8%: John Geisz, APL, 2008
R&D 100 Award.

Lattice mismatched growth (IMM)



Ion beam image

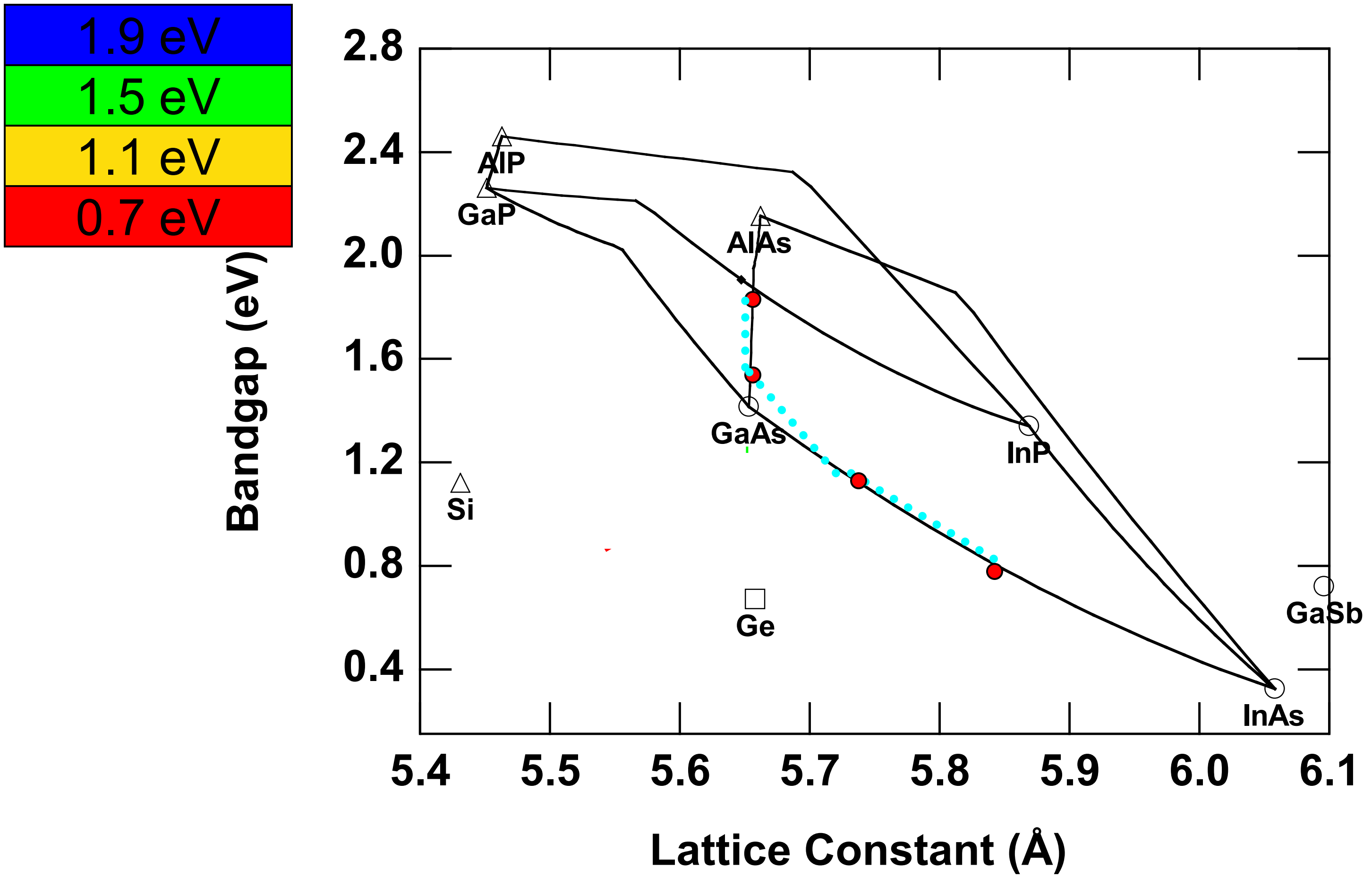


220DF TEM

Step grade of composition can confine defects to graded layers

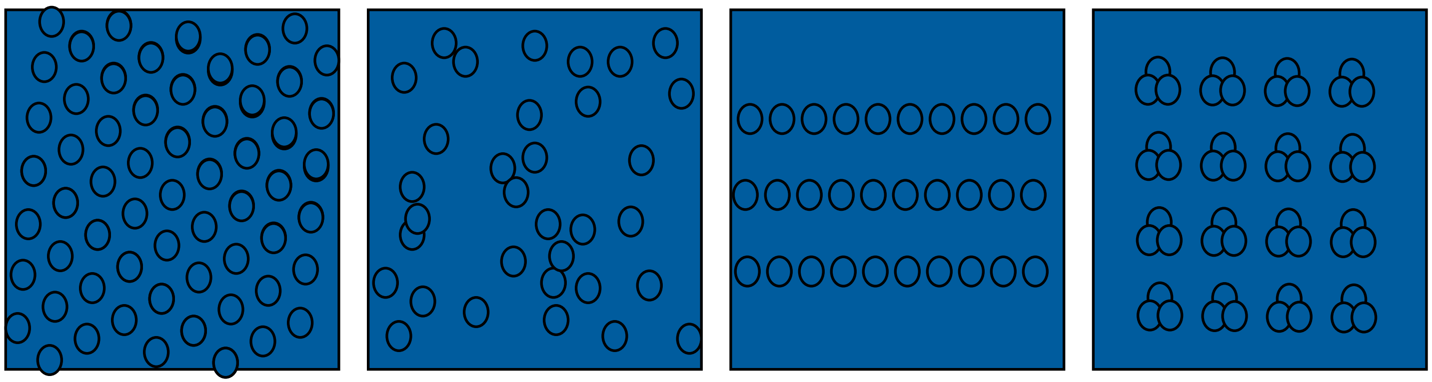
Geisz, et al Appl. Phys. Lett. 93, p. 123505 (2008)

Next generation inverted lattice-mismatched



The inverted structure opens the parameter space

Ways to add In to GaAs to make GaInAs



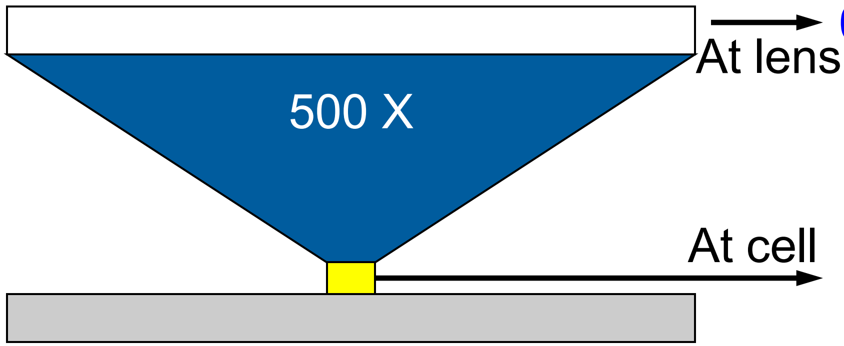
Ordered Random Quantum wells Quantum dots

Combine multiple materials

Modular approach is limited only by creativity

- band gap combinations matched to solar spectrum
- *material quality should be excellent*

Useful numbers (& challenge)

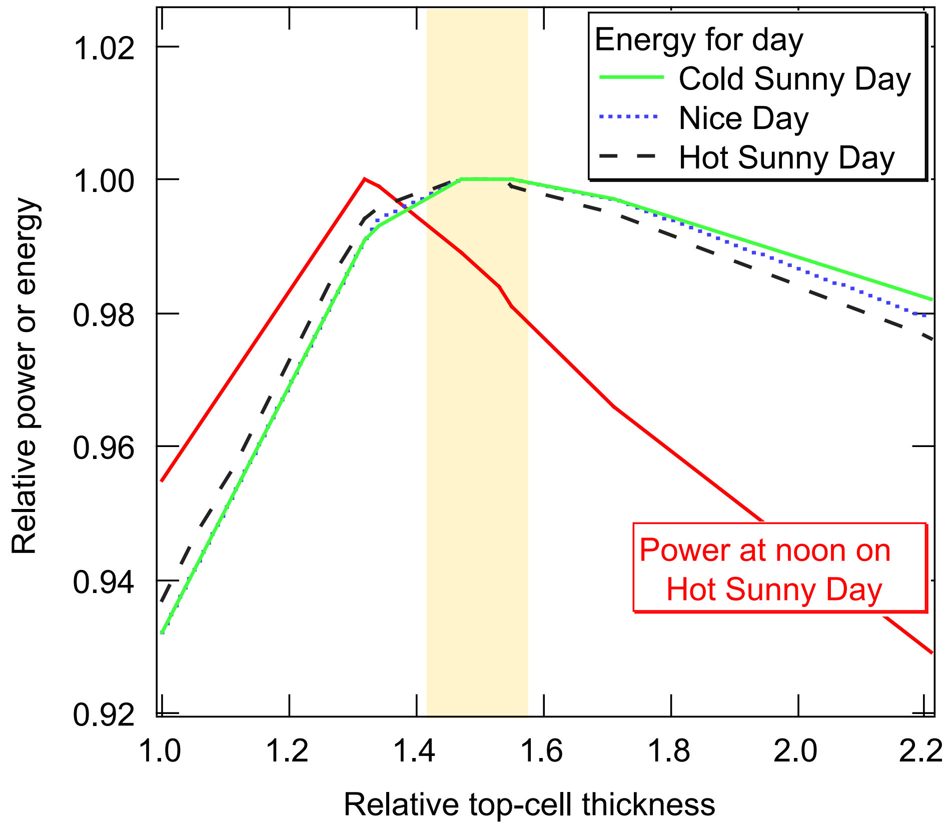


	Irradiance	Area	Power
At lens	0.1 W/cm^2	40,000 cm^2 4 m^2	4 kW input
At cell	50 W/cm^2	100 mm wafer 78 cm^2	1 kW output

- *1 MW requires ~ 1000 4 inch (100 mm) wafers @ 500X*
- *Estimates may be as optimistic as 350 4" wafers/1 MW @ 1000X*
- Actual numbers depend on yield, active area/wafer, optical losses, etc.

- *Cost target for largest (up to 4 TW/yr) market is \$1/W for module (\$2/W installed), with cell being small part of that (~\$100/4 inch wafer for 4 TW/yr market)*
- *\$1000/wafer can enter market now, but will limit size of market in future*

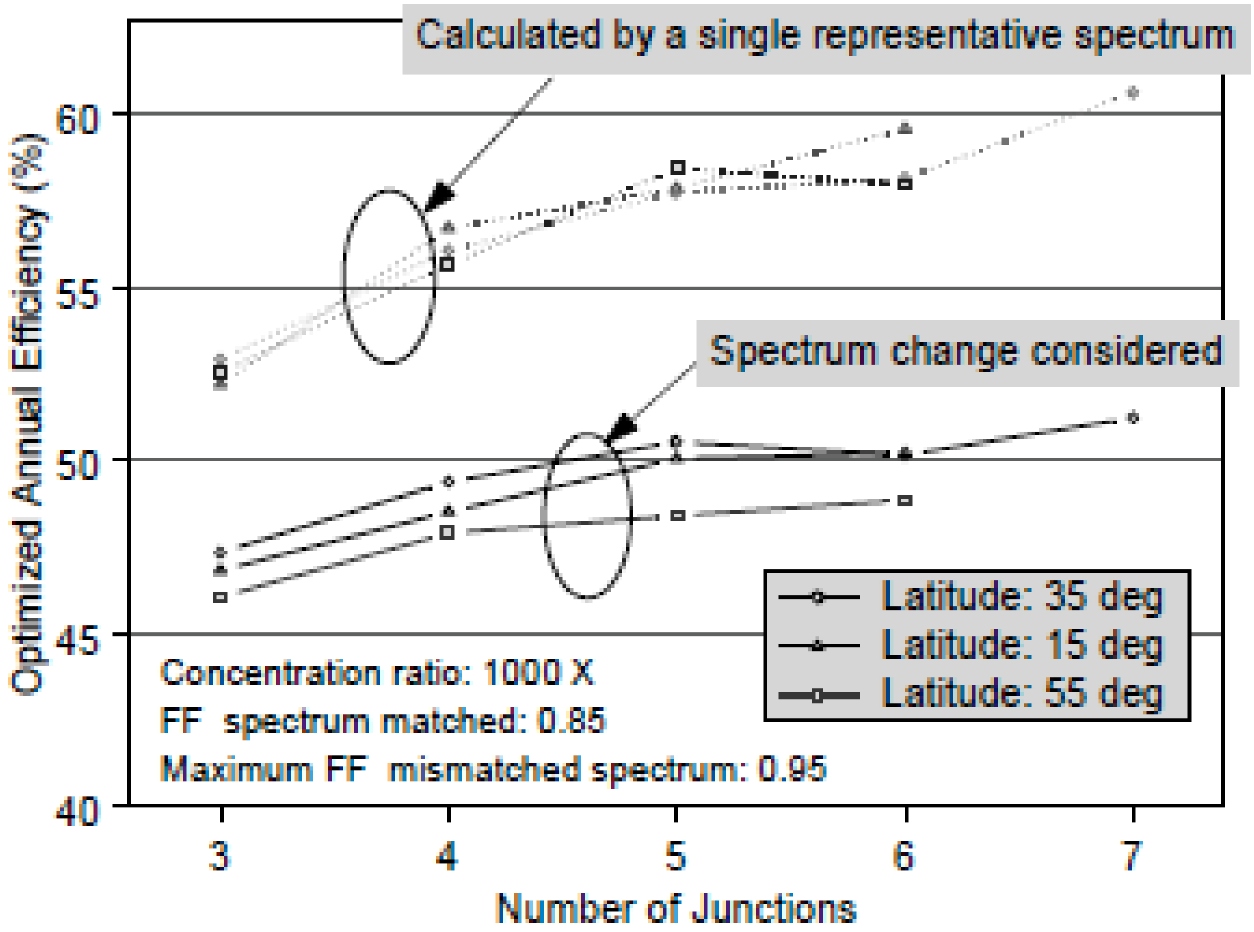
Effect of changing spectrum



Derived from McMahon, 29th PVSC

The instantaneous power is somewhat sensitive to cell design, but the energy is much less sensitive. The loss is a few per cent, but the average performance is fairly consistent. Complicates troubleshooting.

Effect of changing spectrum



Araki "Which is the Best Number of Junctions for Solar Cells under Ever-changing Terrestrial Spectrum?" 3rd WCPEC (2003)

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  - Advantages
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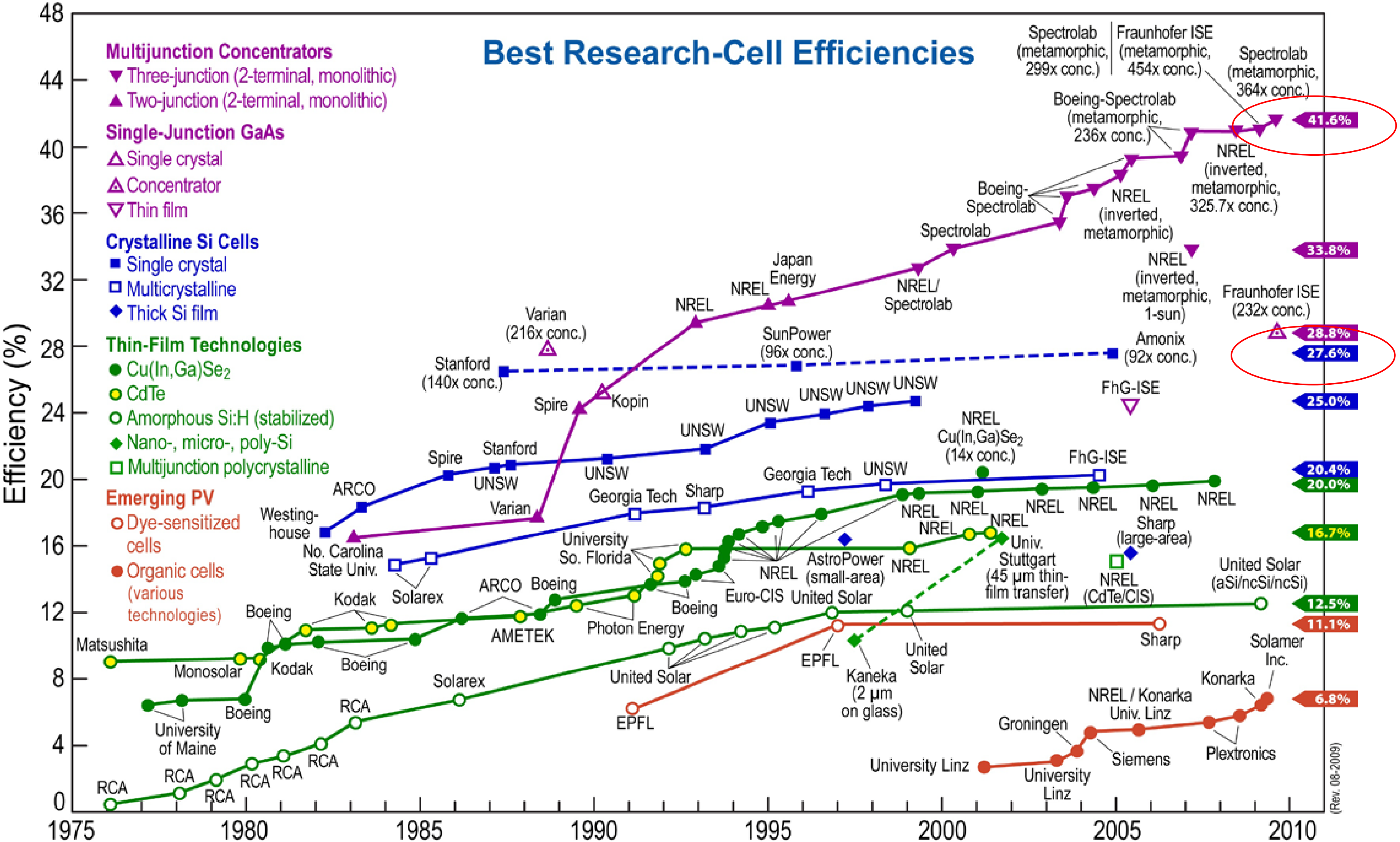
- Design considerations
  - Thermodynamic limit of concentration
  - Refractive vs reflective optics
  - Concentration ratio, f number, etc.
  - Thermal considerations
  - Open vs closed
  - Cells (multijunction & silicon)

Smallness enables use of highest efficiency cells



Silicon concentrator cells (<250X)

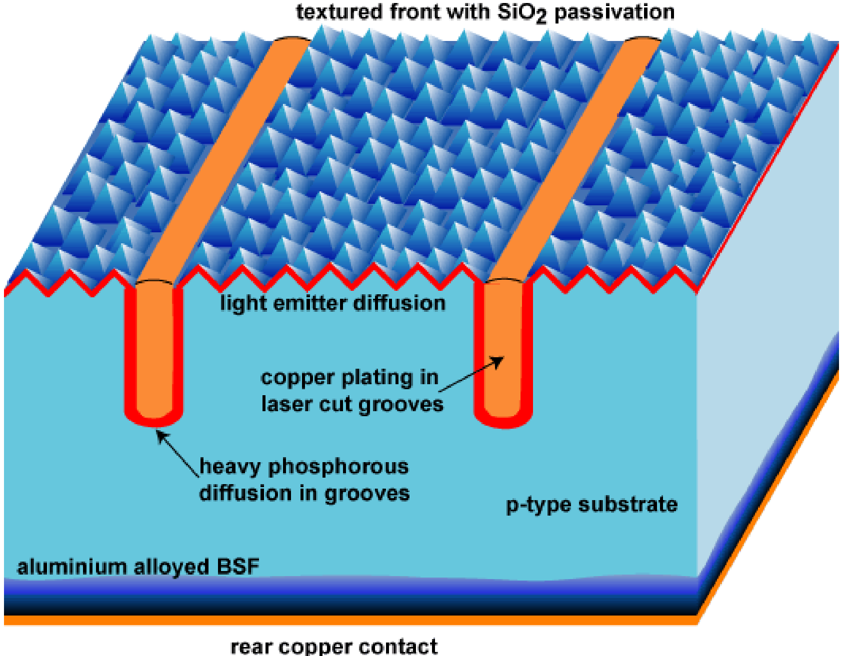
- For low concentration, may be able to use one-sun cells or modules
- For higher concentration, need to lower series resistance: 6 A for a 150 mm cell @ 1 sun.
- Auger recombination limits efficiency above ~100X
- SunPower was first to offer 'off-the-shelf' silicon concentrator cells (for ~250X)
- Today, SunPower makes the highest efficiency one-sun cells
- Many companies are capable of making these cells, but availability of silicon concentrator cells has been a problem for 20 years

Silicon cells – back point contact

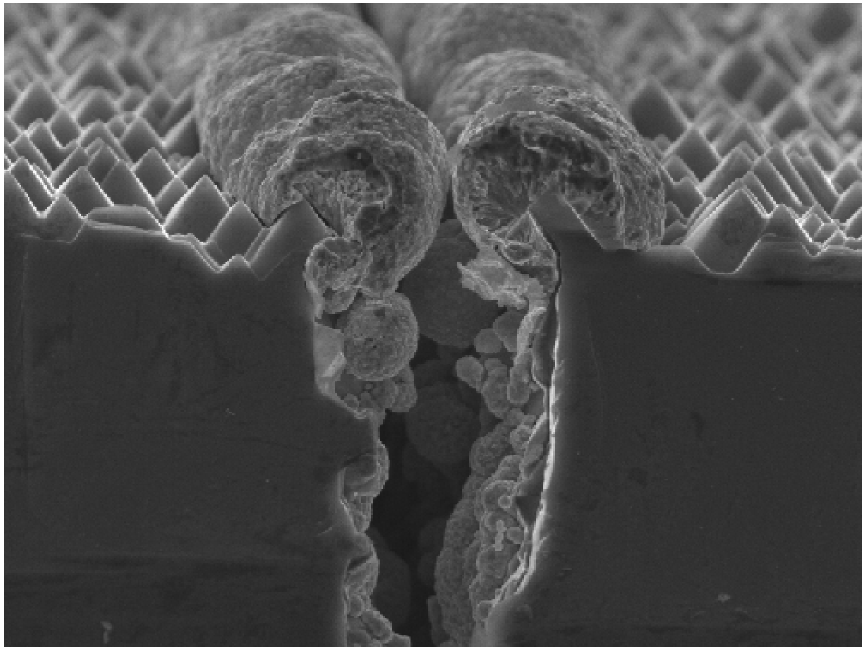
- No grids on front
- Carefully passivated front and minimal contact area on back can lead to high efficiency
- Possible to handle large currents because contacts are on back
- 22% efficiency at one sun; concentration can increase to ~28%
- T coeff -0.38%/°C (at one sun)

Silicon cells – buried laser groove

- Front grids are put in a groove formed by a laser
- Reduces shadowing losses for given grid conductance



http://pvcdrom.pveducation.org/MANUFACT/BCSC.HTM



Bird's eye view – many tradeoffs

There are dozens of design tradeoffs/choices with no clear winners and optimum may change

New ideas/technologies will affect optimal design

Optimal design is very dependent on application

Each company reaches a different conclusion

What will CPV systems look like 100 years from now?

Commodity market

Think of the light bulb

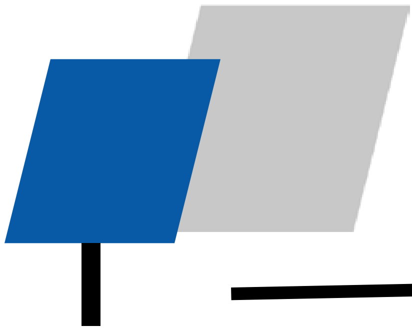
How much has it changed in the last 100 years?

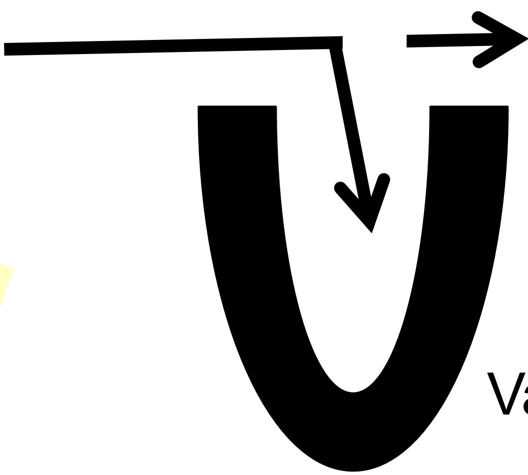
Maturing industry

Luxury
100 years ago

Costs pennies
Today

Valley of death – too many options





The grass is greener…..

Valley of death

The engineer wants to tweak, then gets lost in the valley of death. Often, the business manager rather than the engineer should decide when to move into manufacturing.

Outline

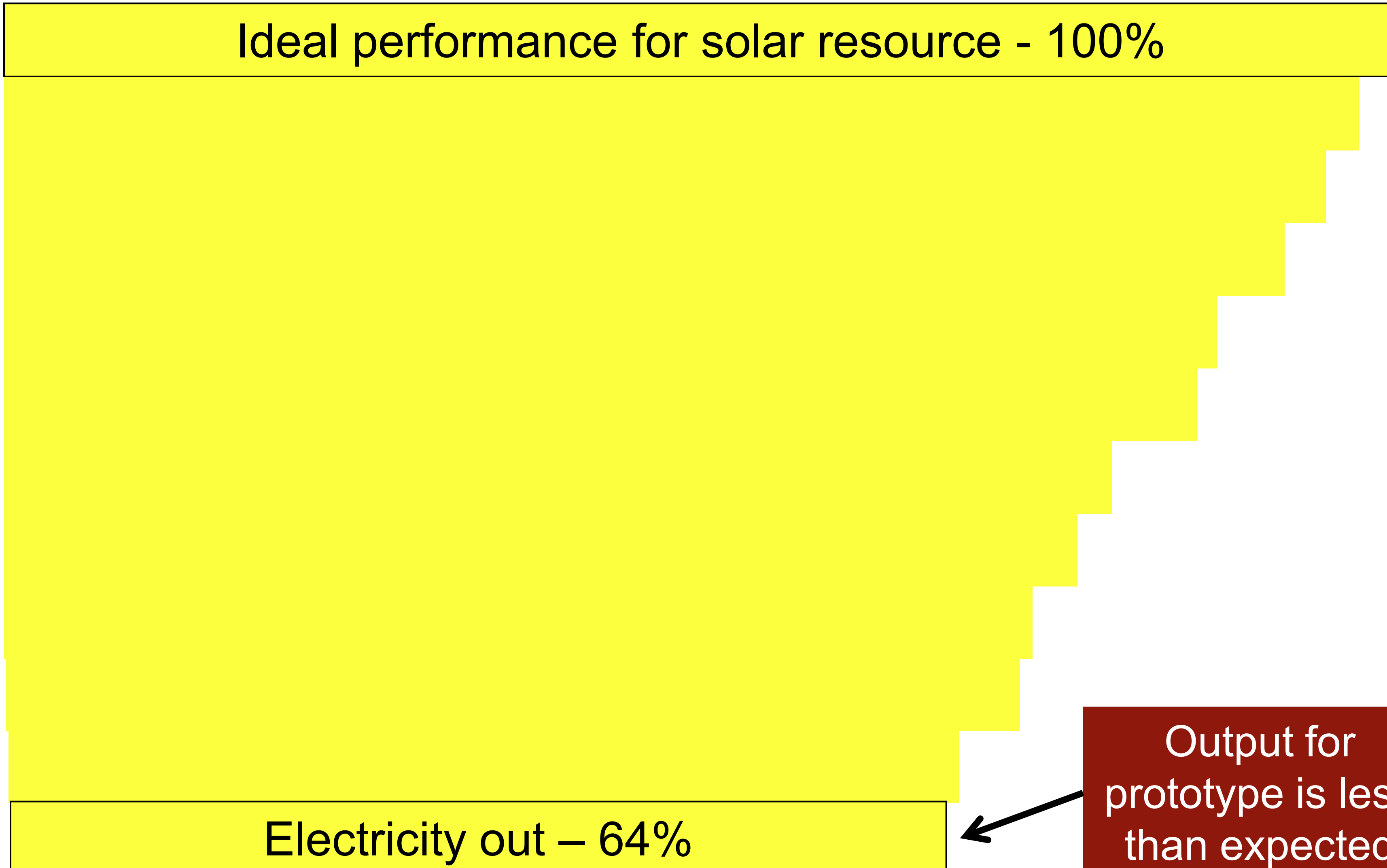
- Overview of PV – Opportunity for CPV
- Fundamentals of concentrating PV
    - Why CPV?
- Design considerations
    - Bird's eye view
- Sorting it out
    - Worm's eye view
- Status of industry
    - Standards
    - Many companies
    - Improving performance
    - Ramping up

Use two views

Design
Bird's eye view

Diagnose
Worm's eye view

Worm's eye view – what happened?



Output for prototype is less than expected

Many losses, what happened?

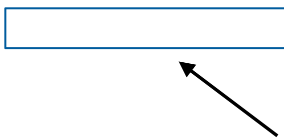
Worm's eye view – what happened?

- Ideal performance for solar resource - 100%
- First reflection loss - 96%
- Imperfect optics - 93%
- Second reflection loss - 89%
- Secondary optics loss – 84%
- Cell nonuniform illumination - 82%
- Cell temperature - 75%
- Cell spectrum - 73%
- Cell stringing - 70%
- Resistance of wiring - 69%
- Tracker misalignment - 65%
- Electricity out - 64%

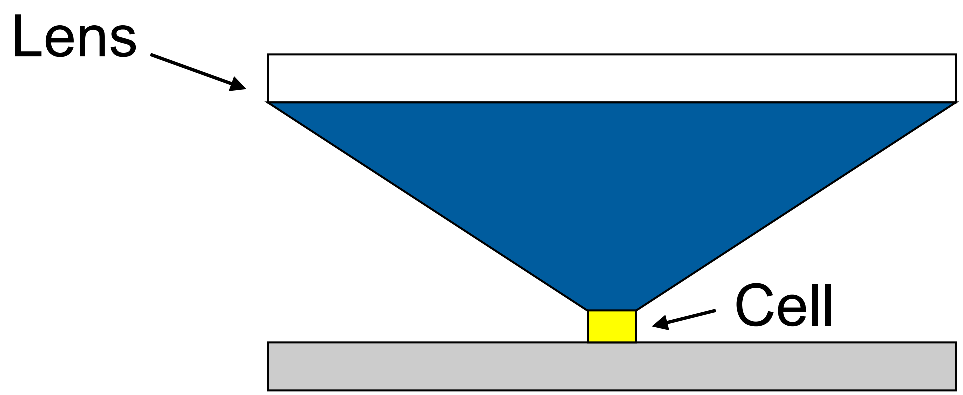
So many potential losses, how do we identify solutions?

Worm's eye view – Start with components

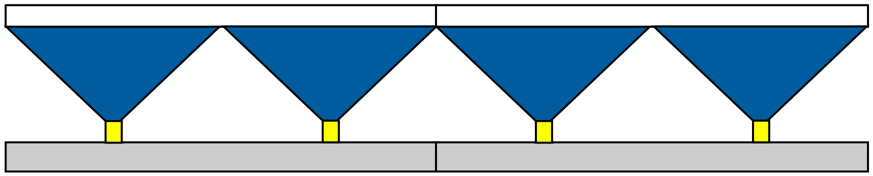
Characterize components first



Then move to lens-cell combination



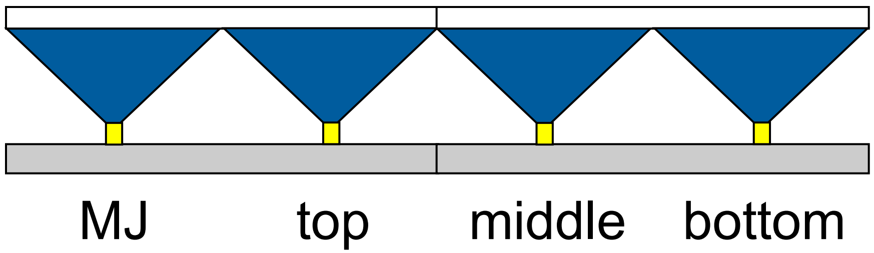
Move to module only after understand single cell

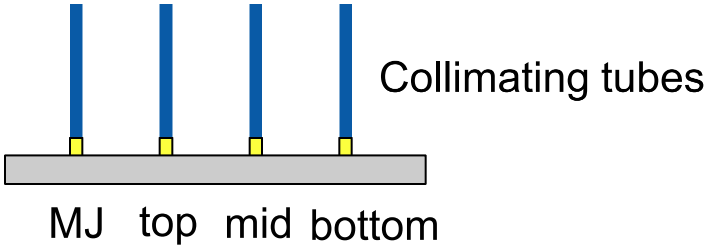


Module may show different effects because of variable alignment, etc.

Worm's eye view – Spectral issues

Demand matched reference cells from your cell supplier





Why use matched reference cells?
- Quantify optical efficiency for each junction
- Depth of field and acceptance angle may be different for each junction (Use special mount that allows you to move each cell)
- Evaluate current matching of multijunction cell for optical design (may vary as a function of alignment)
- Reference cells quantify variation in spectrum
- *Thorough characterization before start stringing cells*

Worm's eye view – Use all parameters

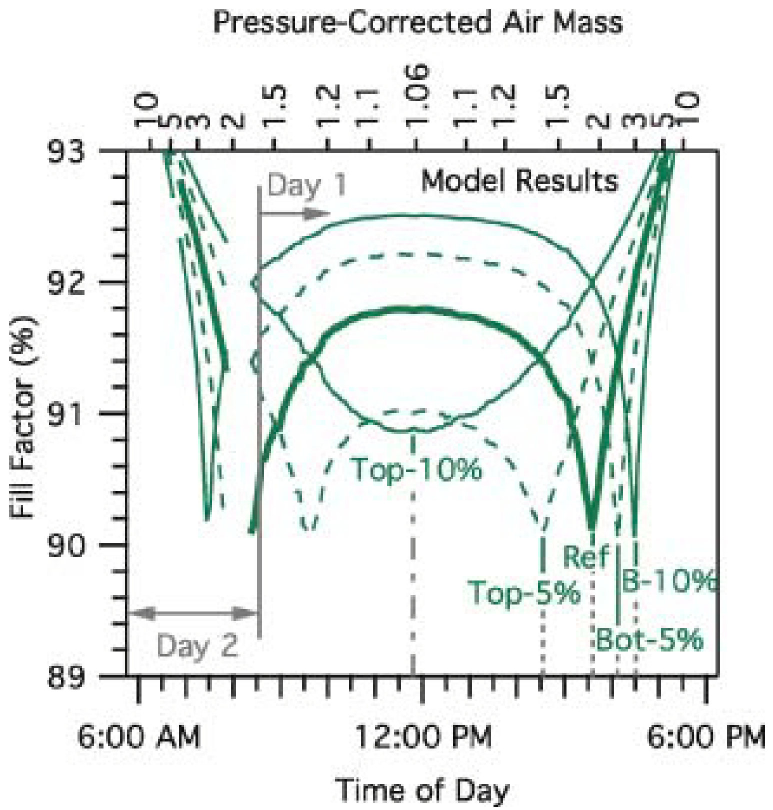
Short-circuit current - optical efficiency

Open-circuit voltage – cooling (adjust for concentration using transient)

Fill factor for reference cells - electrical resistance or shorts; non-uniform illumination

Fill factor for multijunction cell – spectral effects for cells, but what about for modules?

McMahon – PIP 2008



Worm's eye view – Sorting out a module

Be creative; cover the optics; use thin-film filters with partial transmission

Characterize module at maximum power point – short-circuit will miss many problems

Module should have same acceptance angle as single cell/optic

If not, measure cell temperature or use filter to see which cell is limiting the current; bypass diodes should not be hot; fill factor of module should be similar to ff of single cell without showing evidence of bypass diodes turning on

Forward bias emission should be consistent

Concentrators – reliability challenges

- Wide variety of designs
- Qualification test is not well established
- Companies spend time developing their own accelerated tests to speed product development cycles
- Very few companies have heritage with field testing
- Everyone wants to bring a product to market immediately

- However, modularity of CPV may be an advantage

Outline

- Overview of PV – Opportunity for CPV
- Fundamentals of concentrating PV
  - Why CPV?
- Design considerations
  - Bird's eye view
- Sorting it out
  - Worm's eye view
- Status of industry
  - Standards
  - Many companies
  - Is it a turning point?

Standards for CPV

- Standards provide a foundation for the industry
- Challenging because CPV comes in so many flavors
- CPV standards were not developed early on

- CPV standards are now progressing quickly

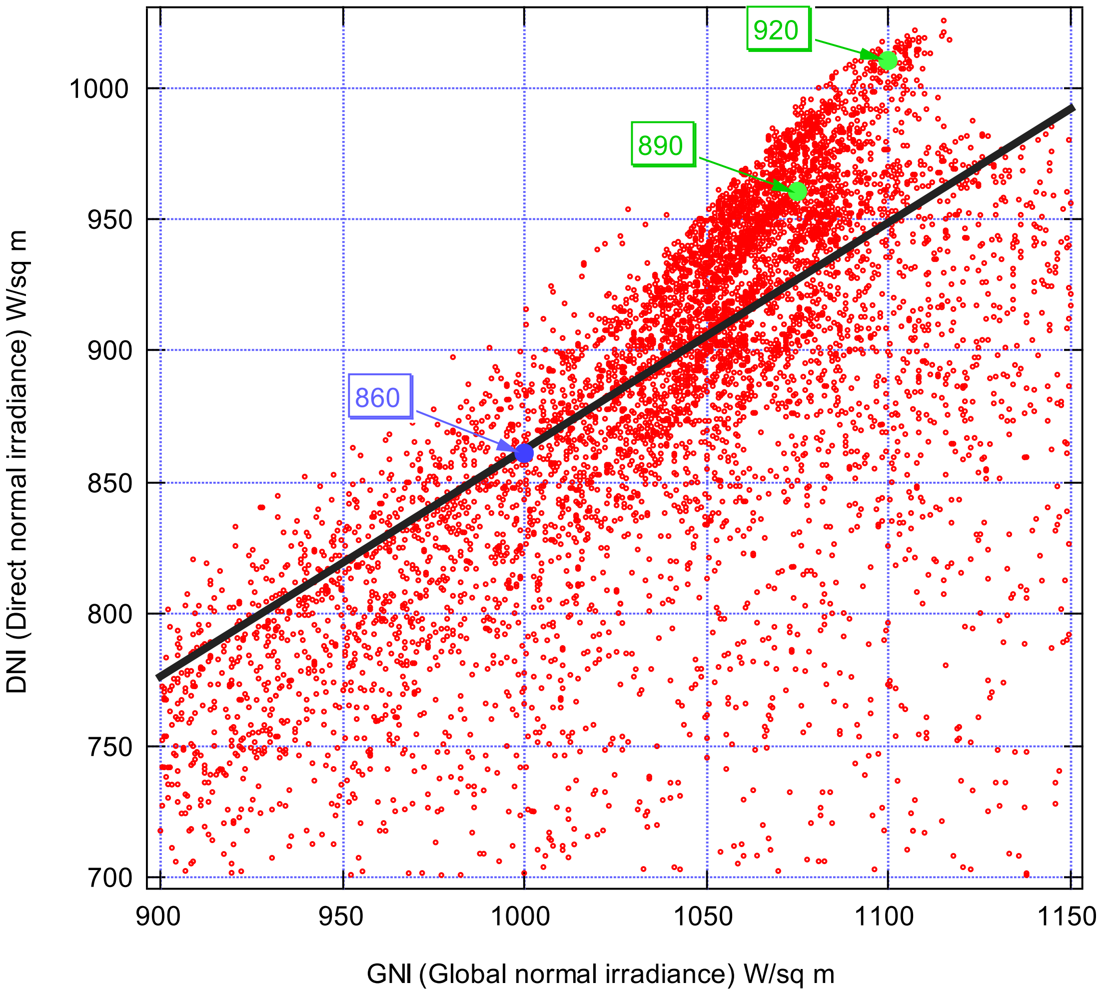
Power rating – 850 or 1000 W/m²?

Flat plate

- 1000 W/m²

CPV

- 850 W/m²



Data taken in Golden, CO (no filtering)

Tags give ratio of DNI/GNI normalized to 1000 W/m²

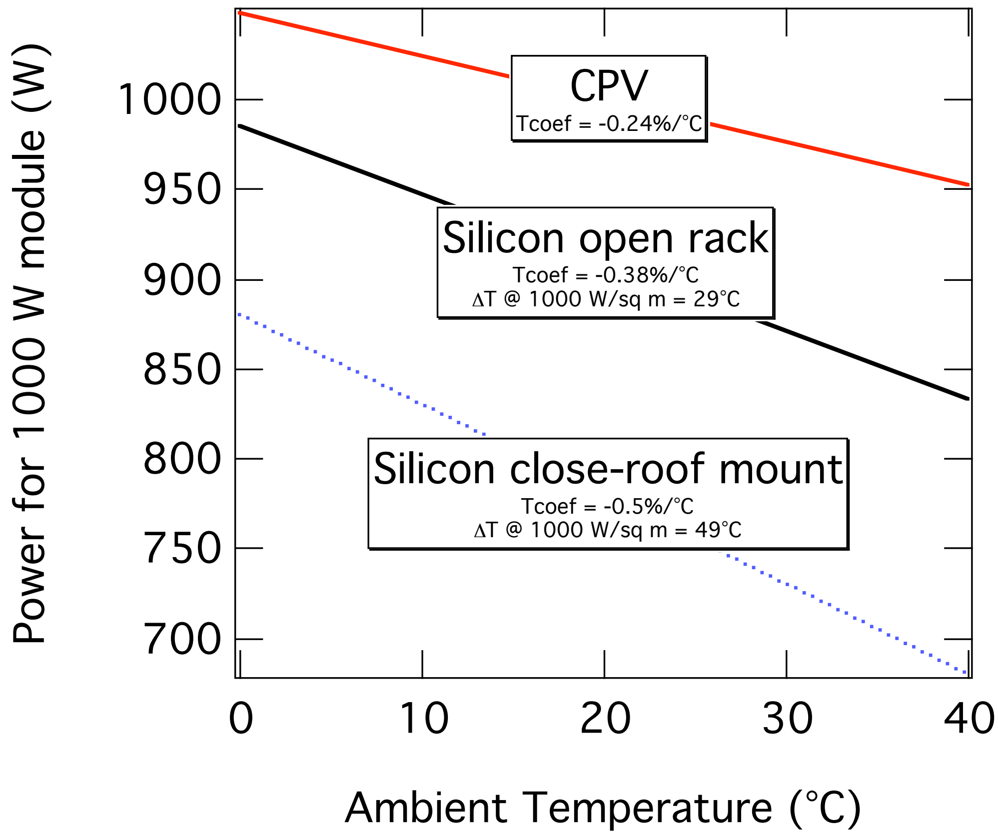
Power rating – ambient, cell, or heat sink T?

Flat plate module rating

- 1000 W/m²
- 25°C module T
- Si: T coef ~ -0.38 or -0.5%/°C

CPV module rating

- 850 W/m²
- 20°C ambient T
- T coef ~ -0.24%/°C



Graph shows expected power assuming irradiance is same as irradiance used for rating

Is this fair?

Implies higher capacity factor

Which gives better indication of performance?

Standards – Power rating

- Currently being developed by IEC
- PVUSA used 850 W/sq m DNI, 20°C ambient T, and 1 m/s wind
- ASTM E2527 uses 850 W/sq m DNI, 20°C ambient T, and 4 m/s wind
- ASTM G173 spectrum for direct beam, integrates to 900 W/sq m
- Debate is ongoing about
  - 1000 vs 850 W/sq m irradiance
  - 20°C ambient vs 25°C "module" T
  - 1 m/s vs 4 m/s wind speed if use ambient

Standards – Qualification test: IEC 62108

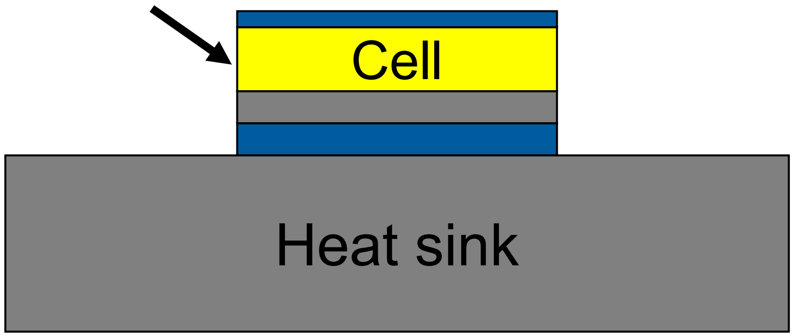
- Requires 7 modules and 3 receivers
- Tests include:
  - Outdoor exposure – Cumulative DNI 1000 kWh/m^2
  - Thermal cycling – 500 cycles from -40 to 110°C*
  - Bypass diode
  - Humidity freeze – 20 cycles from -40 to 85°C* (85% RH)
  - Damp heat – 85°C, 85% relative humidity for 1000 h
  - Mechanical load
  - Terminations
  - Hail impact
  - Hot spot

*Other options are available if 110°C is too hot for lenses

Standards – Qualification test: IEC 62108

- Current debate has to do with application of forward bias current during thermal cycling

Inject heat into cell to give real T profile



- Forward bias current causes cell failure if:
  - Thermal control is lost (what we want)
  - Cell is defective (not what we want)

Forward bias current may be best way to detect failure.
How much is optimal?

Concentrator system companies using low-X (mostly Si)

North America

- Covalent Solar
- ENTECH (> 100 kW in 1990s)
- Greenfield Solar
- JX Crystals (>100 kW in ‘07)
- MegaWatt Solar (50 kW in ‘08)
- Netcrystal
- Opel International
- Optony
- Pacific Solar Tech
- Prism Solar Technologies
- QD Soleil
- Skyline Solar
- Solaria
- Solbeam
- Stellaris
- SV Solar
- Thales Research

Europe/Israel

- Abengoa Solar
- Archimedes
- Cpower
- Maxxun
- Pythagoras Solar
- Silicon CPV
- Whitfield Solar
- WS Energia (263 kW in ‘08)
- Zytech Solar

Australia

- Sunengy

Asia

Everphoton

Concentrator system companies using III-V cells

North America
- Abengoa Solar
- American CPV
- Amonix
- Boeing
- Concentrating Technologies
- Cool Earth Solar
- Emcore
- Energy Innovations
- EnFocus Engineering
- ENTECH
- GreenVolts
- IBM
- Menova Energy
- Morgan Solar
- Opel International
- Pyron Solar
- Scaled Solar
- SolarTech
- SolFocus
- Soliant Energy
- SUNRGI
- Xtreme Energetics

Europe
- Concentracion Solar La Mancha
- Concentrix Solar
- ENEA
- Guascor Foton
- Isofoton
- Sol3g
- SolarTec
- Zytech Solar

Australia
- Solar Systems
- Green & Gold

Asia
- Arima Ecoenergy
- Daido Steel
- Delta Electronics (ending 12/09)
- ESSYSTEM
- EverPhoton
- Sharp

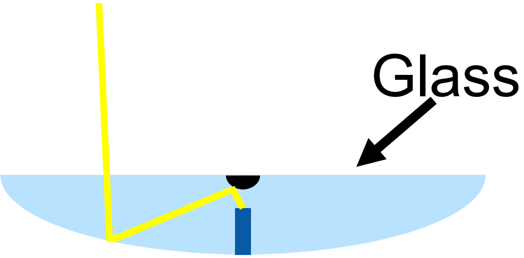
Amonix

- Founded in 1989
- Original design used Silicon; now use III-V
- ~410 kW in Arizona
- ~200 kW in Nevada
- ~1 MW in Spain
- ~8 MW jointly with Guascor in Spain
- Report 25% AC efficiency with III-V

Concentrix

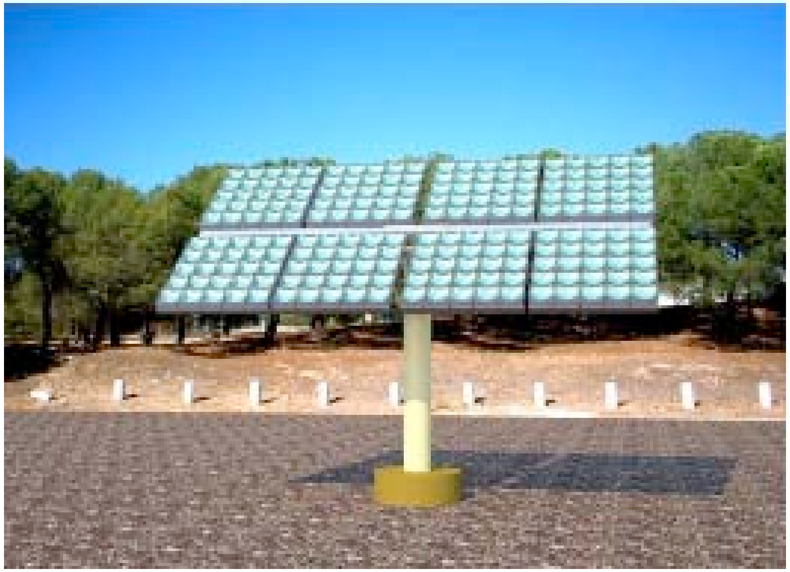
- 100 kW Casaquemada, Spain 23% AC efficiency (6 kW 25% and 27% for module)
- 25 MW/y production capacity
- Spun off from Fraunhofer ISE in 2005

SolFocus



- 200 kW in Puertollano, Spain
- 300 kW in Almoguera, Spain
- 10 MW field started in Greece
- $150M in funding; founded in 2005
- Design has relatively large acceptance angle

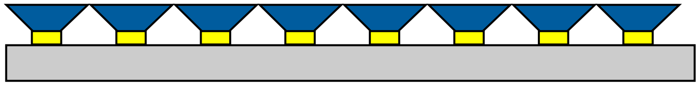
Boeing



- Using reflective optics (off-axis)
- Wide acceptance angle

Semprius

- Is example of companies bringing in new approaches
- Printing technique allows parallel assembly
- Large part count is acceptable when use parallel assembly
- Reduce amount of material to reduce cost



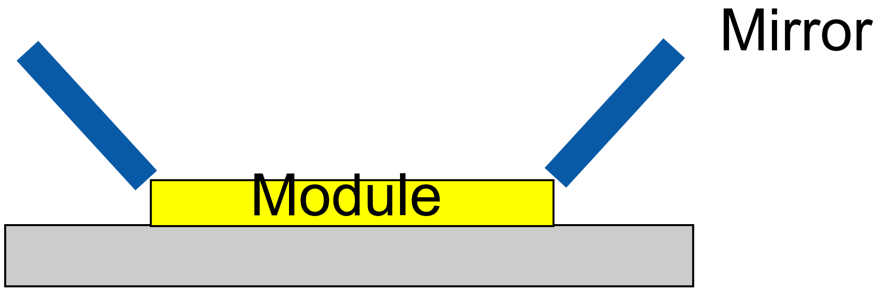
Many creative designs

Enfocus

Cool Earth Solar

Abengoa

- 1.2 MW low concentration in Sevilla, Spain in 2008 (largest low-X CPV); 2 GWh/yr
- 1.5 X (Iso-Photon) and 2.2 X (Artesa & SolarTech)
- 2-axis tracked



http://www.abengoasolar.com/sites/solar/resources/pdf/en/Sevilla_PV.pdf

http://www.abengoasolar.com/sites/solar/en/our_projects/solucar/sevilla_pv/index.html

III-V cell companies with datasheets

Spectrolab (cells and cells with welded leads)

- www.spectrolab.com/prd/terres/cell-main.htm
- Minimum average efficiency: 36% (38.5% announced) @ 50 W/cm^2
- Plan to ship 35 MW of cells in 2009 and 100 MW in 2010 (lattice-matched, 3-junction 500X cells)

EMCORE (cells and receivers)

- www.emcore.com/solar_photovoltaics
- Typical efficiency: 39% @ 500 suns

CESI (cells)

- www.cesi.it/pagina_2.asp?livello=2&cp=03040000&c2=03040800&c3=&cc=&lang=EN
- Efficiency > 30% @ > 100 suns

Other companies with multijunction cell capability (data sheets on request)

North America

- Cyrium
- JDSU
- Microlink
- RFMD
- Solar Junction
- Spire

Europe

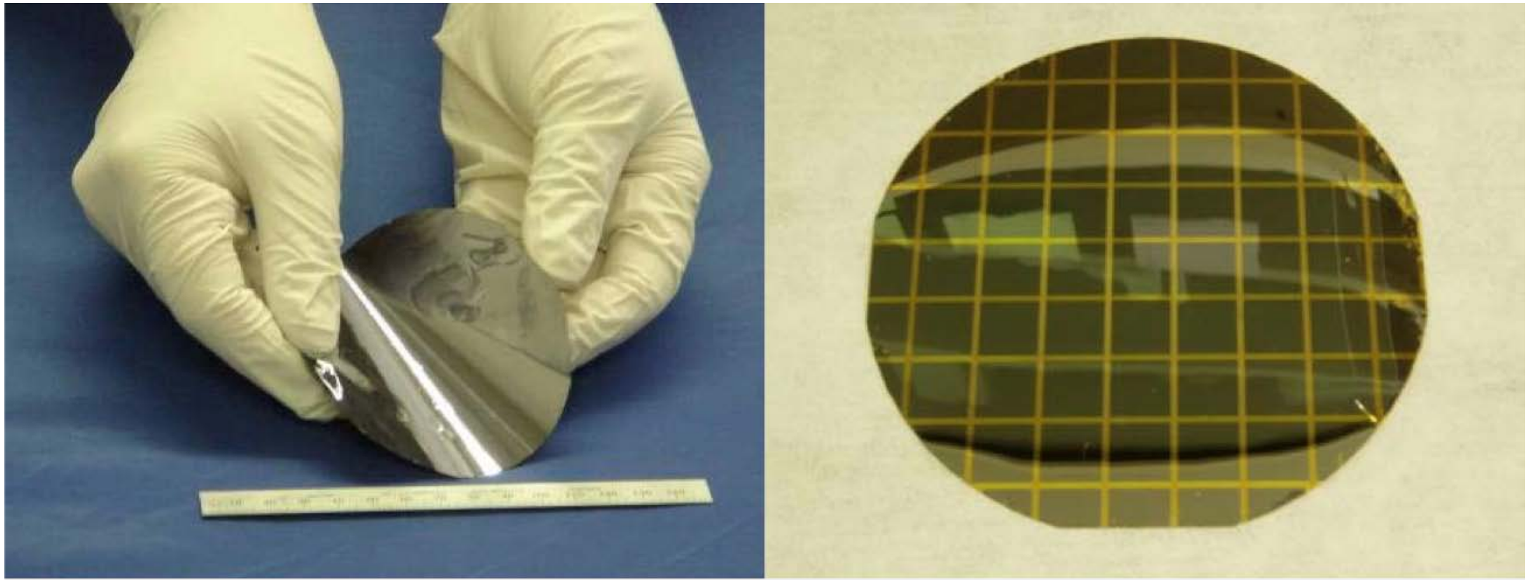
- **Azur Solar (RWE)**
- IQE
- QuantaSol

Asia

- Arima
- Epistar
- Sharp
- VPEC

Research laboratories, universities, and companies in R&D or stealth phases not included in this list

Microlink – remove cost of substrate?



Cells are flexible with a thickness <50 μm

Supply & Demand - of multijunction cells

Current supply

- Emcore/Spectrolab/Azur epi capacity: hundreds of MWs (500X)
- Capacity depends on space cell demand

Future supply

- New companies could dramatically increase supply
- Emcore/Spectrolab/Azur will expand under contract (6 months - 3 years lead)

Current demand

- Actual installation rates MW/yr
- Tens of MWs purchases for planned expansion

Future demand

- Projections vary dramatically
- Potential for GWs
- Expansion limited by automation
- Expansion limited by risk of unproven product
- Expansion limited by banking crisis

Receivers - system integration

(some designs require mounting of cells directly to optics)

Needs:

- System determines receiver design, so every CPV system may need new design
- Need automated cell mounting
- Receiver designs must be carefully tested

Current status:

- Off-the-shelf receivers typically use 1 cm X 1 cm cells
- Manufacturing of receivers remains a challenge for many companies

The need for custom-designed receivers (and their integration with the optics) is still challenged (should this be the job of the cell supplier, the system integrator, or a 3rd company?)…

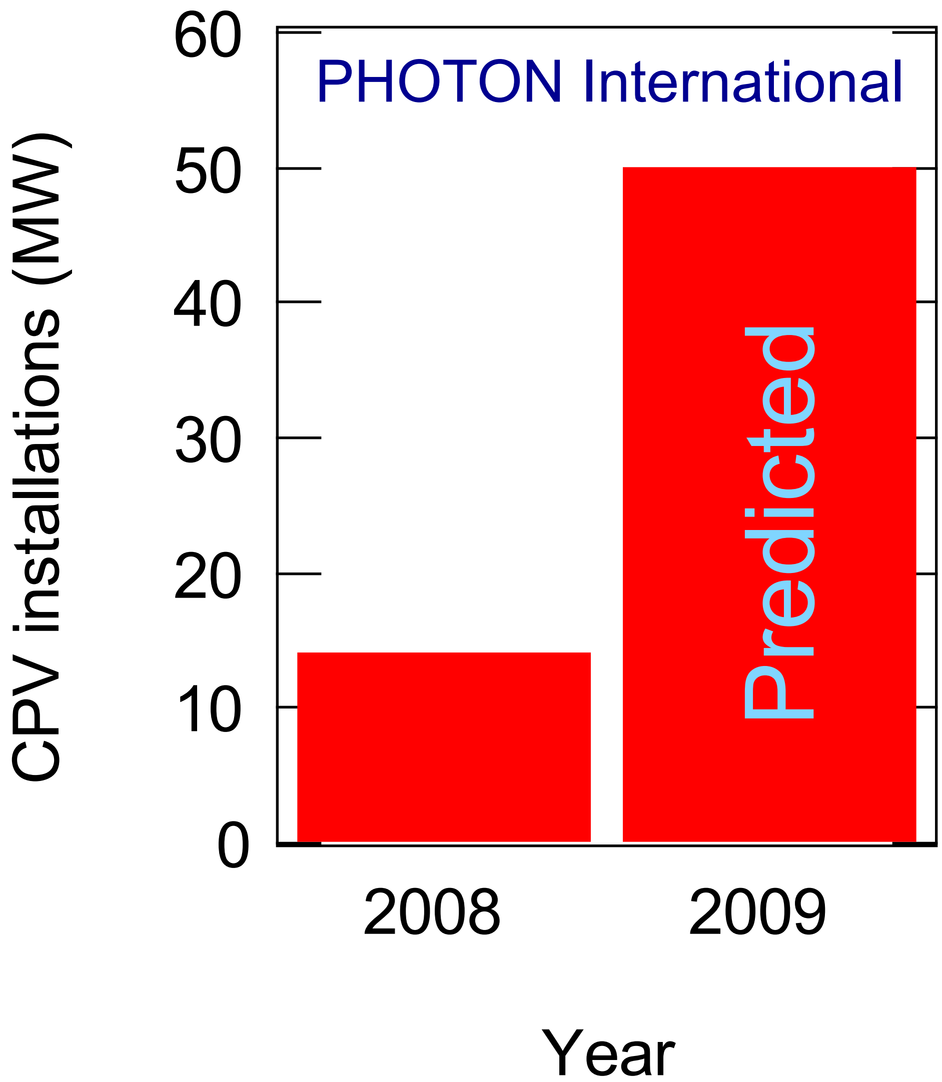
Other business needs

Substrates (Ge; could be GaAs in future)
Optics
Structural materials
Heat sinks
Electrical isolation
Alignment tools (automated assembly)
Trackers
Power conditioning

What has changed?

- Companies entering field now tend to be bigger and more experienced at large-scale production (e.g. RFMD, JDSU)
- System efficiencies are commonly ~25%
- Several companies approaching 1 MW in field
- Several companies are setting up manufacturing lines with 10s of MW capability
- Is the industry nearing a turning point?

Turning point for industry?



Is the CPV industry ready to ramp production?

Last year, PHOTON International predicted 50 MW in 2009

What will CPV look like 100 years from now?

Olson: "Many options are a curse and a blessing"

Thank you to the many who contributed to this and to the growing CPV industry