High-efficiency solar cells for large-scale electricity generation & Design considerations for the related optics

Sarah Kurtz

Jerry Olson, John Geisz, Daniel Friedman, Willliam McMahon, Aaron Ptak, Mark Wanlass, Alan Kibbler, Charlene Kramer, Scott Ward, Anna Duda, Michelle Young, Jeff Carapella

September 17, 2007

Optics for Energy

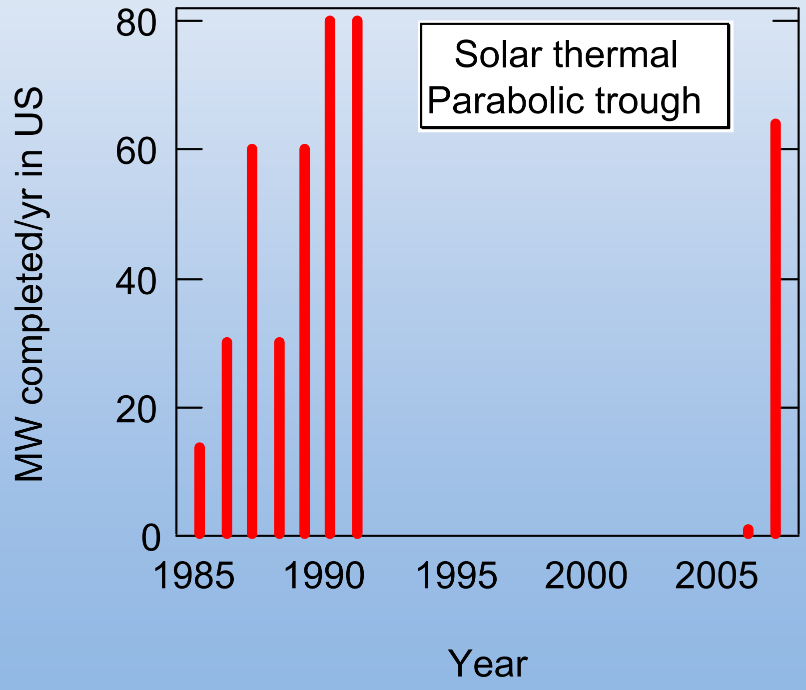
Frontiers in Optics (FiO) 2007 – 91st OSA Annual Meeting

Outline

- Solar is growing very fast
- Optical concentration
  - Reduces semiconductor material
  - Increases cell efficiency
- The physics of solar cells and high efficiency
  - Why using multiple junctions increases efficiency
  - Success of GaInP/Ga(In)As/Ge cell -- 40.7%
- Optics - design considerations
  - Overview
  - Solar thermal electricity generation
  - PV - high concentration 500X - 1000X (high efficiency)
  - PV - low concentration 2X-4X (Si)

Solar thermal electric

- Parabolic trough is the primary technology today
- Resurgence of interest
- ~ 400 MW installed
- Currently generates ~ 0.01% of US electricity
- Economical for > 100 MW in sunny areas



64 MW Solargenix Parabolic Trough Plant in Nevada - 2007

1-MW Arizona Trough Plant – near Tucson, AZ - 2006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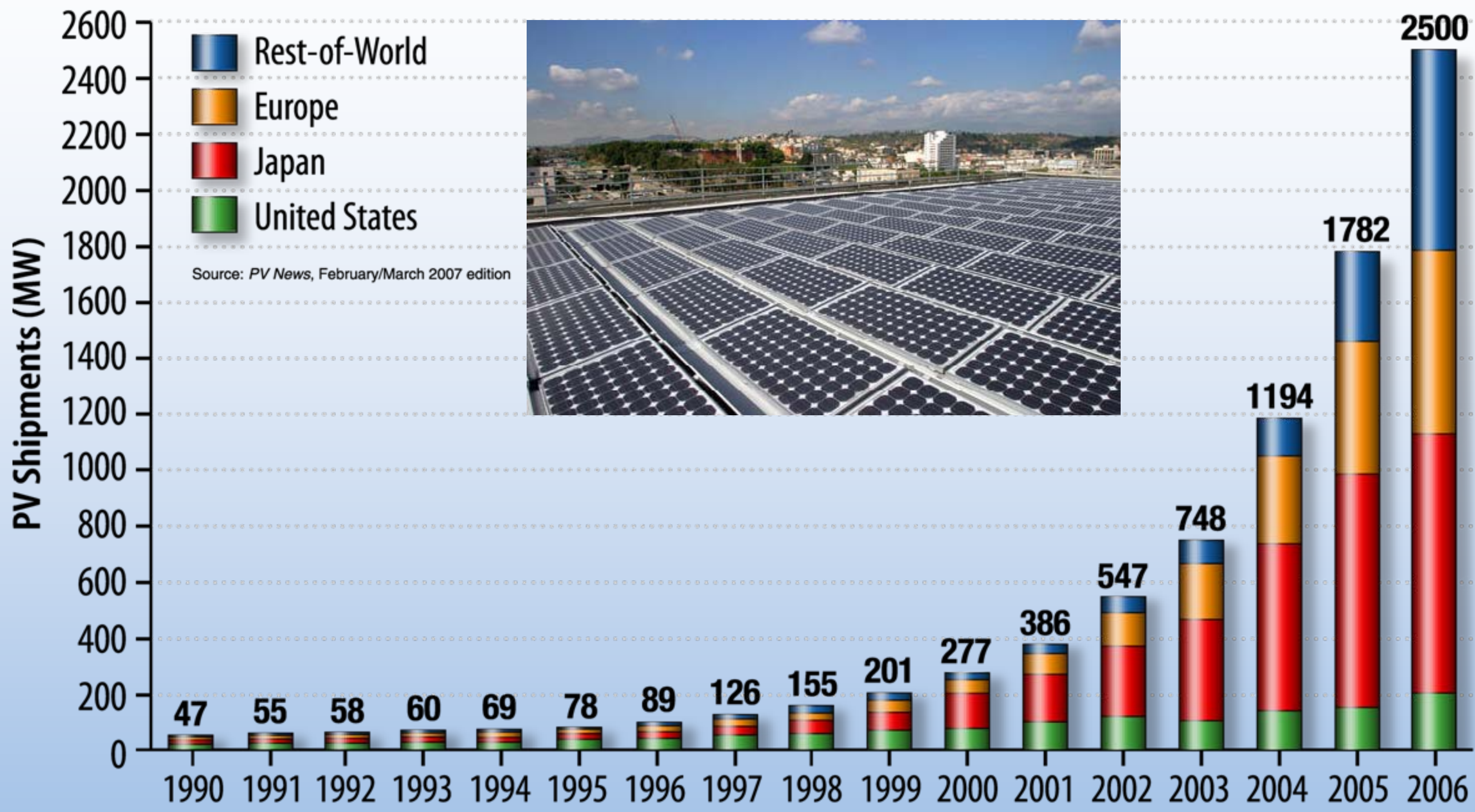
MARYLAND
SOLAR
DECATHLON



Growth of photovoltaic industry



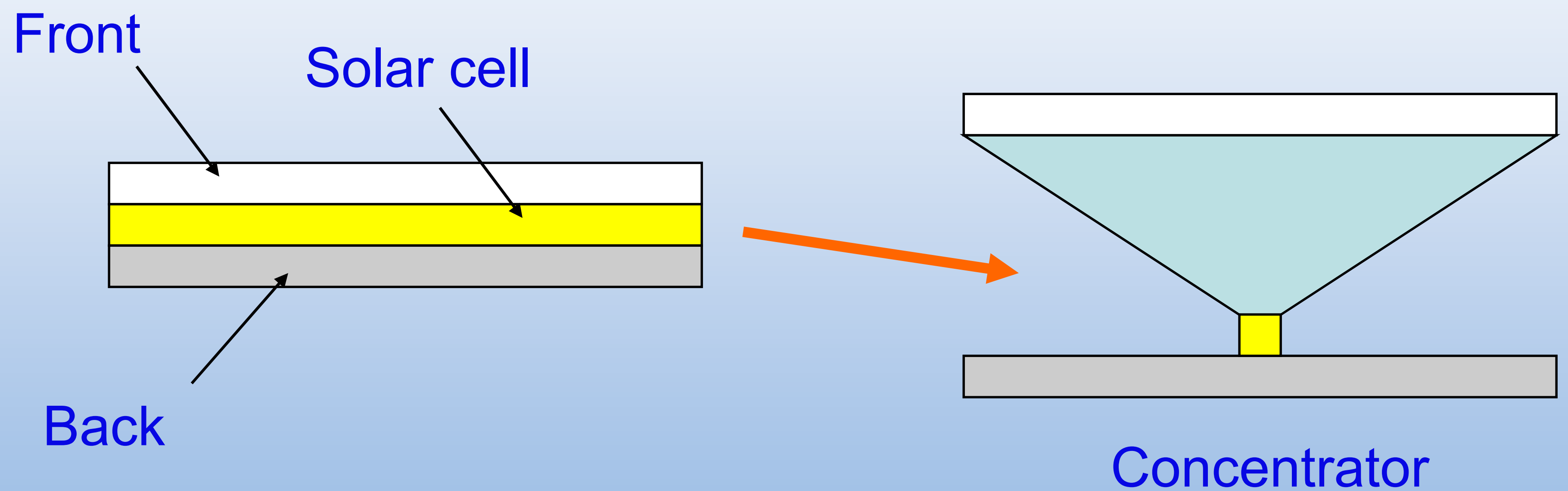
0.06% of electricity now comes from solar - extrapolates to > 5% in 2020

competitive with conventional electricity for 0.1% - 1% of market; more in future

Rogol, PHOTON International August 2007, p 112.

NREL National Renewable Energy Laboratory

Industry growth is currently constrained by Si availability
Reduce semiconductor material by concentrating the light



Concentration:

1. Reduces semiconductor use
2. Allows use of higher efficiency cell (higher system efficiency)

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- The physics of solar cells and high efficiency
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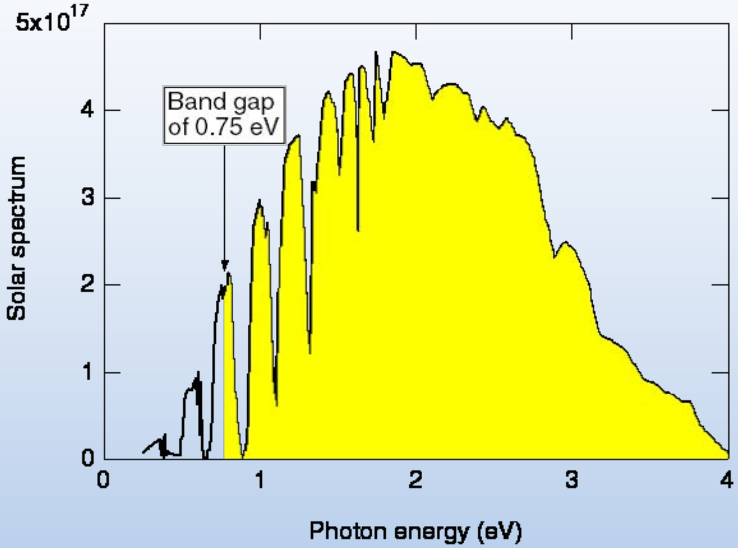
  - Success of GaInP/Ga(In)As/Ge cell --> 40.7%
- Optics - design considerations
  - Thermal
  - PV - high concentration
  - PV - low concentration

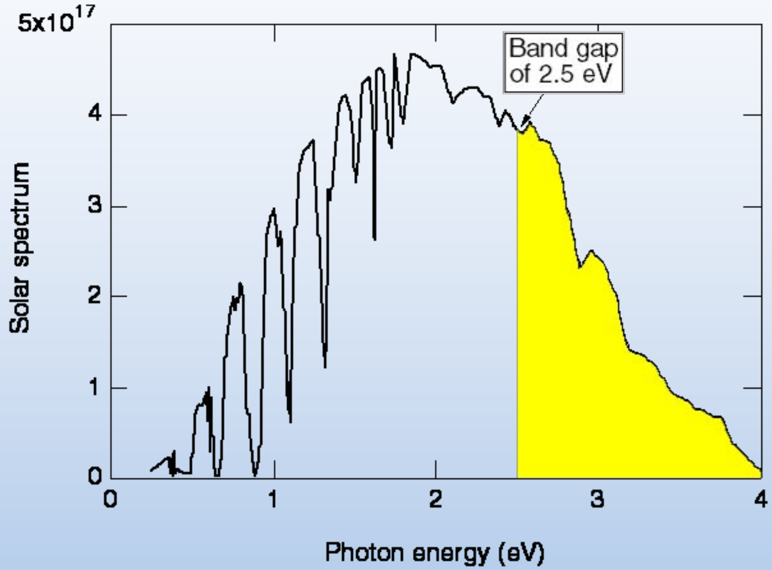
Optics in solar cells - getting the light into the active layers

- Broad-band anti-reflection coatings
- Light trapping (textured surface on front or back for Si)
- Many different approaches will be covered in other talks

Why multijunction?
Power = Current X Voltage



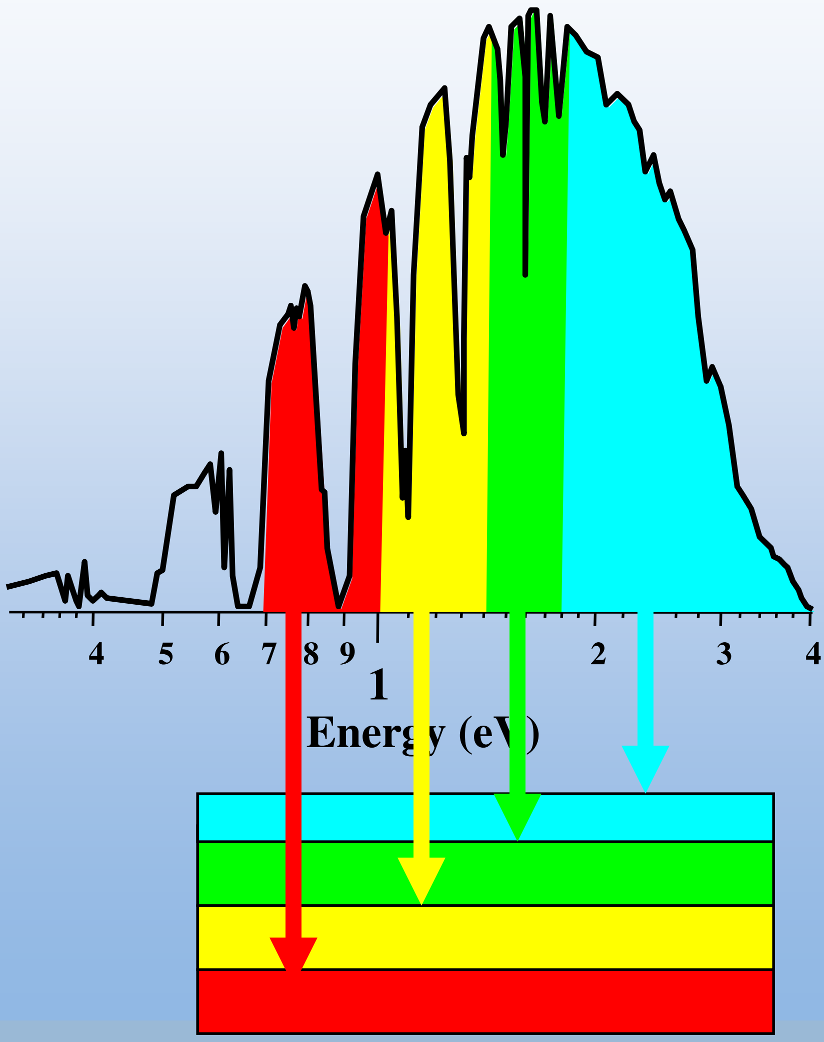
High current,
but low voltage
Excess energy lost to heat



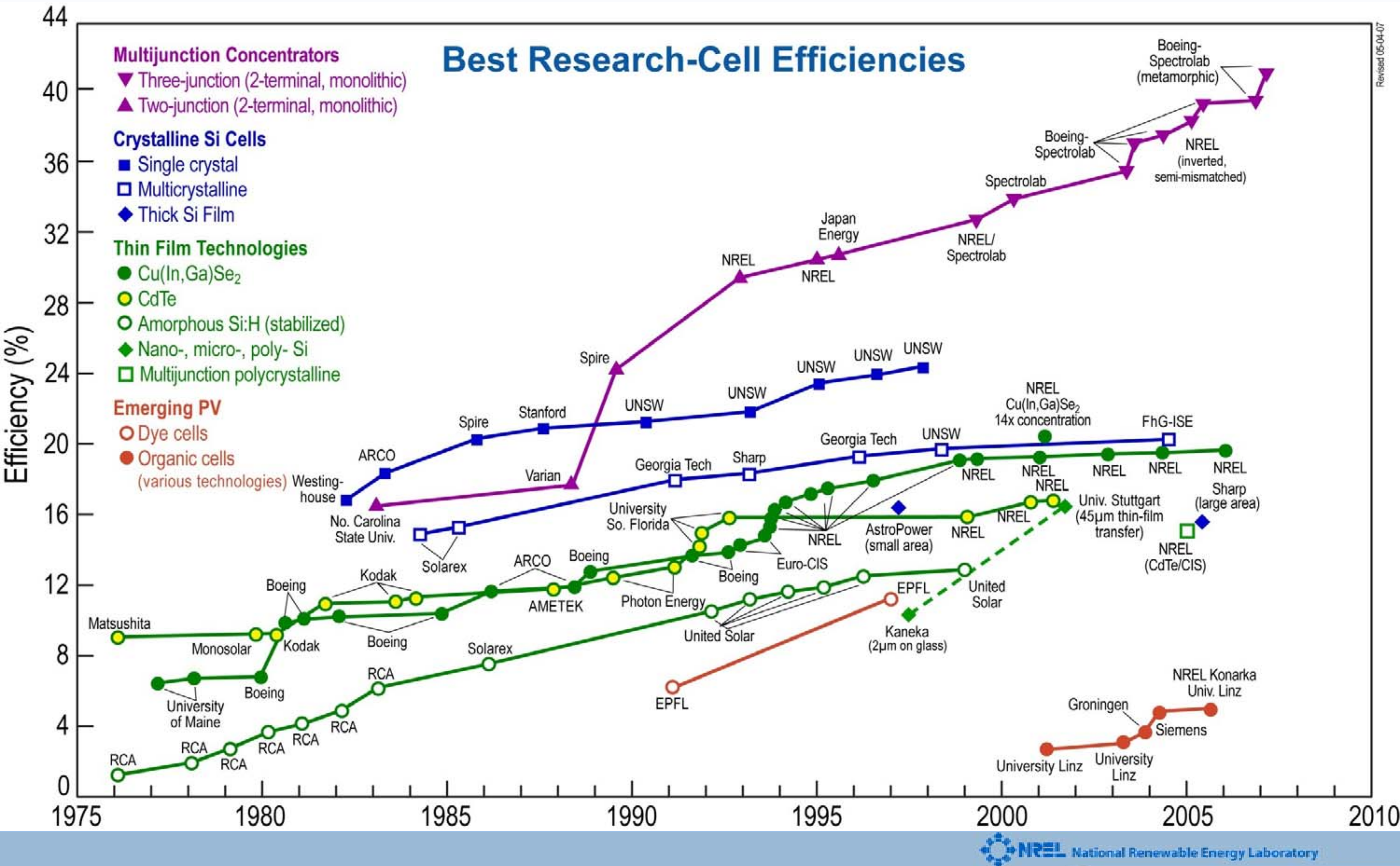
High voltage,
but low current
Subbandgap light is lost

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

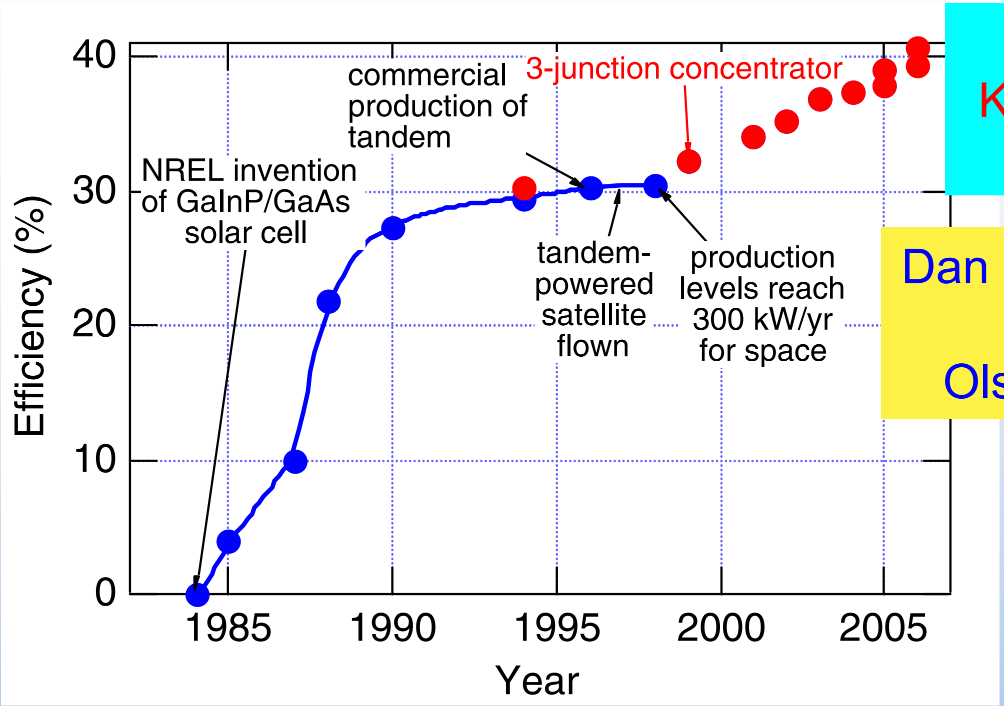
Multijunction cells use multiple materials to match the solar spectrum



Champion solar-cell efficiencies



Success of GaInP/GaAs/Ge cell



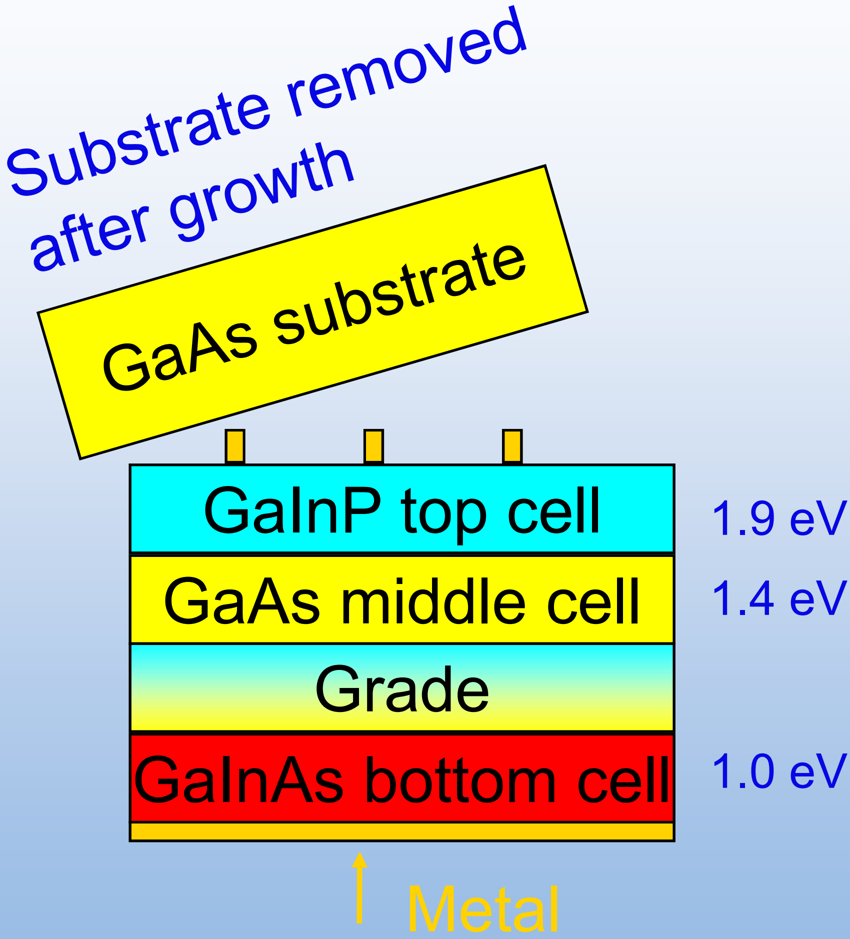
40.7%
King, APL
2007

Dan David Prize
2007
Olson, Kurtz

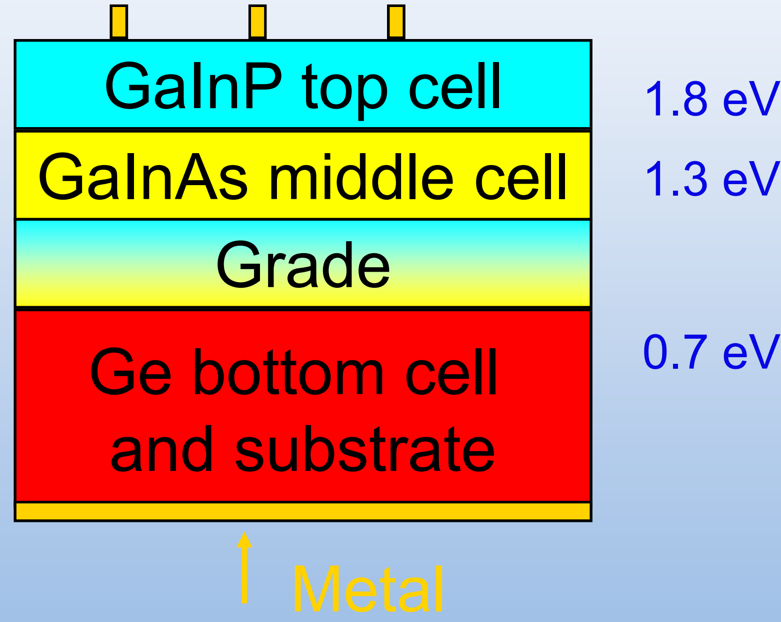
Mars Rover powered by multijunction cells

This very successful space cell is currently being engineered into systems for terrestrial use

High-efficiency mismatched cells



38.9% @ 80 suns
Geisz, 2007



40.7% King, 2006

New research: from 40% to 50%

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  - PV - high concentration (low T, uniformity)
  - PV - low concentration (high acceptance angle, reliability)

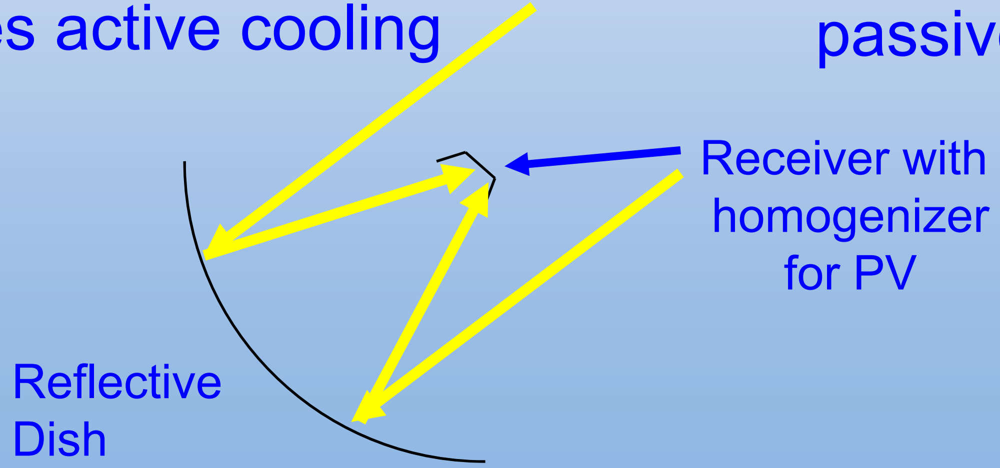
Key issues for optical design

- Low cost
- High efficiency over broad spectral range
- Large acceptance angle for easy alignment and use of diffuse radiation
- Soiling (maintenance)

Reflective optical designs

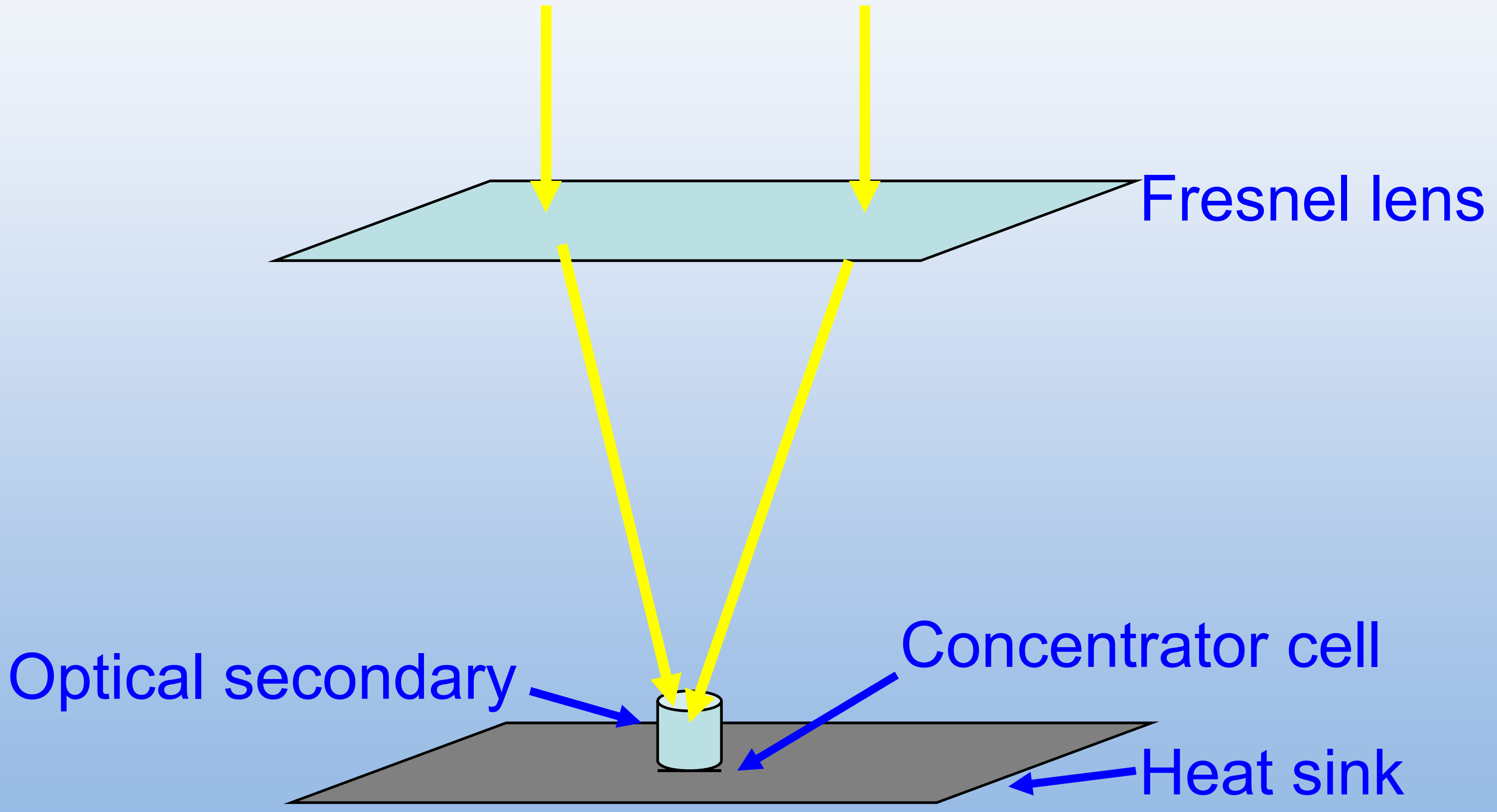
Large dish: Stirling engine; PV requires active cooling

Microdishes can be passively cooled



Reflective optical designs - troughs

Refractive designs for PV - large Fresnel

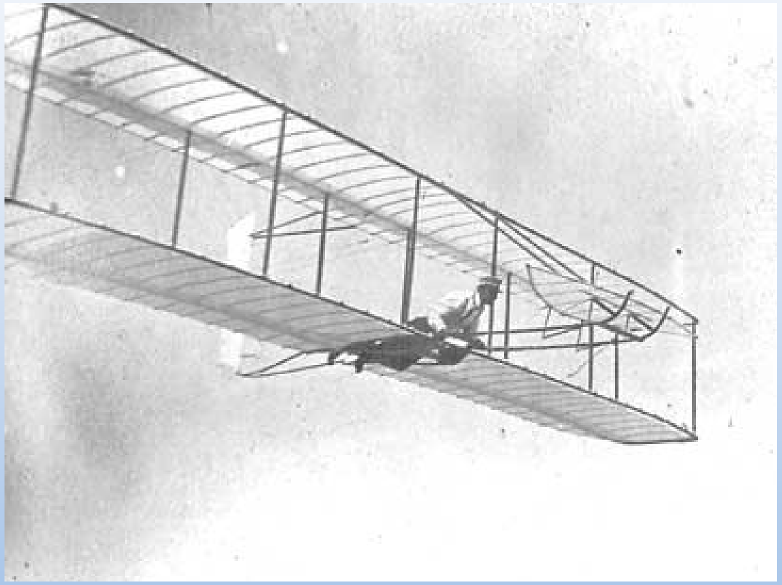


Refractive optical designs

Fresnel lenses focus light on small cells
Passive cooling

Small lenses and small cells can lead to thin designs and "flat-plate" cooling

What will concentrators look like in the future?



Could we have predicted 100 years ago what airplanes look like today?

Innovation

Optics for solar thermal

- Solar thermal
  - Trough - convenient transport of working fluid
  - Dish or tower - higher temperatures
- Guidelines
  - Hit the target
  - Energy is all that counts

Uses for optics for solar

- Concentrating PV
  - High concentration enables use of high-efficiency cells
  - Any concentration reduces use of semiconductor material
- Guidelines differ for PV
  - Keep temperature low (lose 0.2-0.4%/° C)
  - Uniformity concerns
  - Chromatic aberrations
  - Don’t care about lowest E light; blue is important

Series connection of cells requires uniformity of light for CPV

100 W can be derived from
1 V @ 100 A
or
100 V @ 1 A

High voltage is always preferred, so connect cells in series

Series-connected cells: current is limited by cell with least light;

Need same light hitting each cell

Uniformity of light is important for CPV, not thermal

Uniformity challenge for CPV

- Dish - need uniform image
- Trough - need clean image (pay attention to shadows for supports and end of image)
- Fresnel - make each cell and lens identical

Low-concentration

Reduce Si usage with low concentration

- Theoretically for non-imaging optics: $C_{max} = n/\sin\theta$
- For point focus 4 X, limit is acceptance angle ~ 45°
- Tracking is now used in many systems
- Efficiency of optics is important
- Use design that is unaffected by soiling
- Small cells may allow for very thin systems with minimal cooling problems
- Historically, low-concentration systems have shown new degradation mechanisms

Summary

- Photovoltaic industry is doubling every two years
- Using concentration may help the solar industry grow even faster
- Multijunction cells provide the path to high efficiency; > 40% and are still increasing
- The optical designs are varied and the requirements differ for solar thermal and PV

Flying high with high efficiency

Cells from Mars rover
may soon provide
electricity on earth

High efficiency, low cost,
ideal for large systems