High-efficiency, multijunction solar cells for large-scale solar electricity generation

Sarah Kurtz

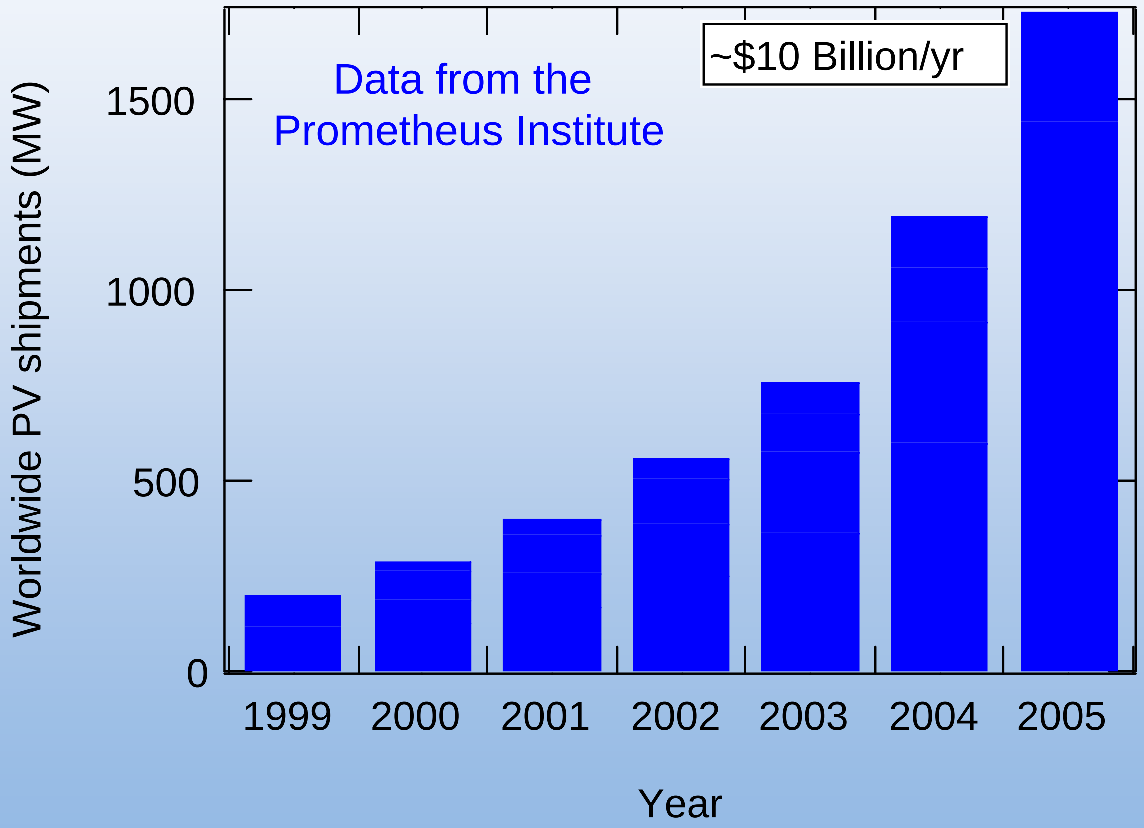
APS March Meeting, 2006

Acknowledge: Jerry Olson, John Geisz, Mark Wanlass, Bill McMahon, Dan Friedman, Scott Ward, Anna Duda, Charlene Kramer, Michelle Young, Alan Kibbler, Aaron Ptak, Jeff Carapella, Scott Feldman, Chris Honsberg (Univ. of Delaware), Allen Barnett (Univ. of Delaware), Richard King (Spectrolab), Paul Sharps (EMCORE)

Outline

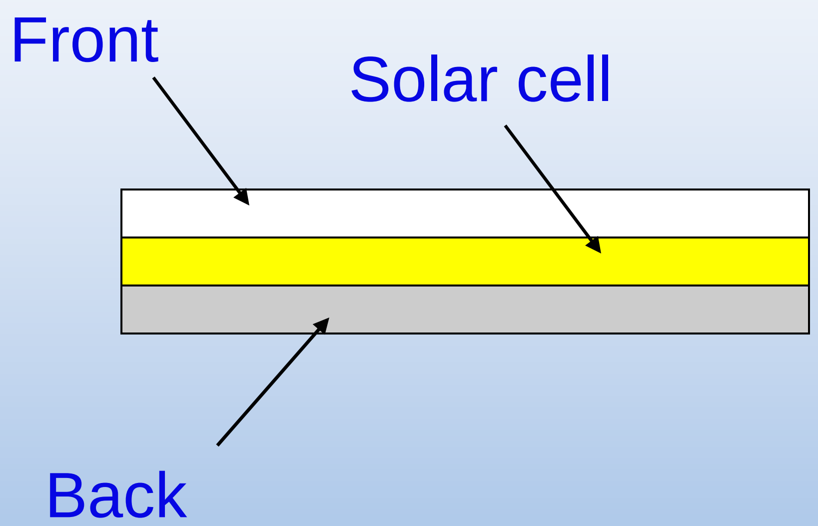
- Motivation - High efficiency adds value
- The essence of high efficiency
  - Choice of materials & quality of materials
  - Success so far - 39%
- Material quality
  - Avoid defects causing non-radiative recombination
- High-efficiency cells for the future
  - Limited only by our creativity to combine high-quality materials
- The promise of concentrator systems

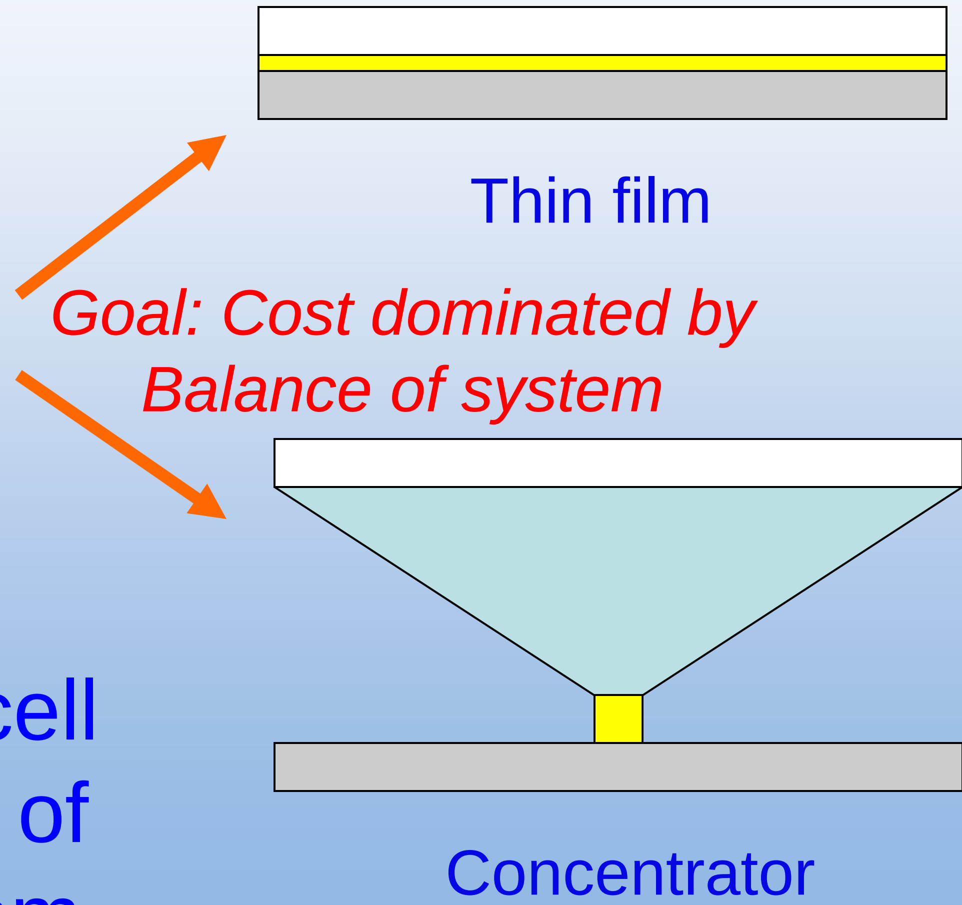
Photovoltaic industry is growing



Growth would be even faster if cost is reduced and availability increased

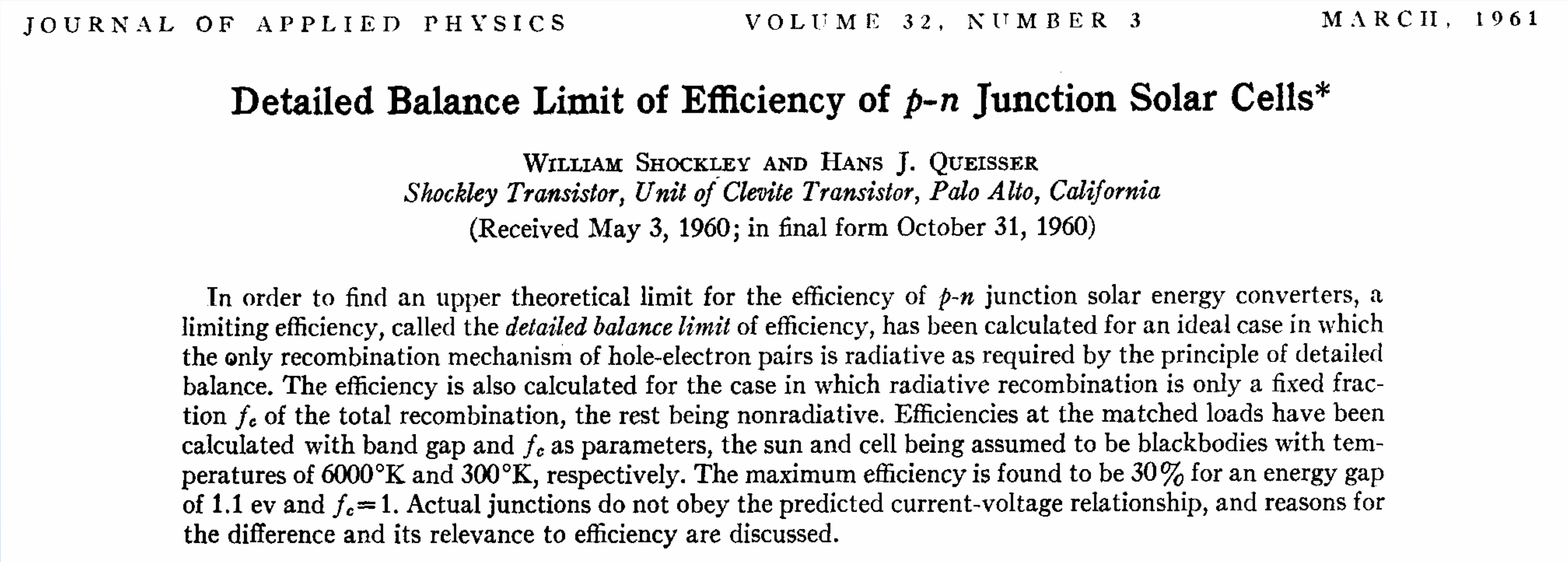
To reduce cost and increase availability: reduce semiconductor material





A higher efficiency cell increases the value of the rest of the system

Detailed balance: Elegant approach for estimating efficiency limit



JOURNAL OF APPLIED PHYSICS VOLUME 32, NUMBER 3 MARCH, 1961

Detailed Balance Limit of Efficiency of *p-n* Junction Solar Cells*

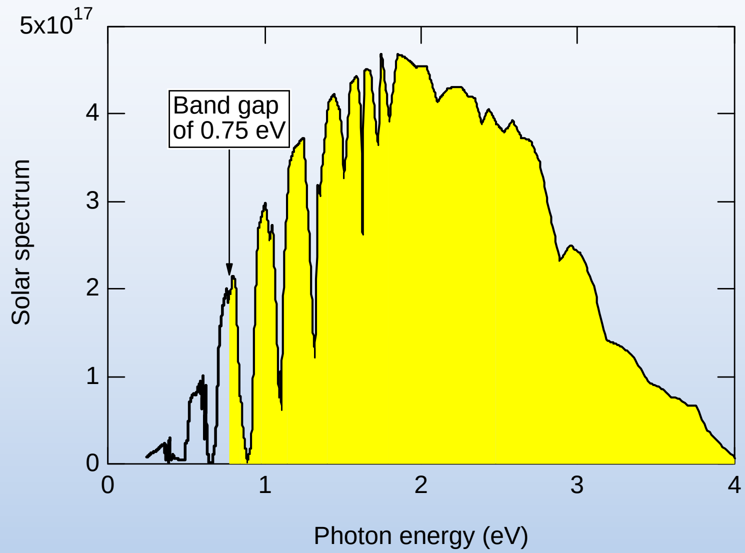
WILLIAM SHOCKLEY AND HANS J. QUEISSER
Shockley Transistor, Unit of Clevite Transistor, Palo Alto, California
(Received May 3, 1960; in final form October 31, 1960)

In order to find an upper theoretical limit for the efficiency of *p-n* junction solar energy converters, a limiting efficiency, called the *detailed balance limit* of efficiency, has been calculated for an ideal case in which the only recombination mechanism of hole-electron pairs is radiative as required by the principle of detailed balance. The efficiency is also calculated for the case in which radiative recombination is only a fixed fraction f_c of the total recombination, the rest being nonradiative. Efficiencies at the matched loads have been calculated with band gap and f_c as parameters, the sun and cell being assumed to be blackbodies with temperatures of 6000°K and 300°K, respectively. The maximum efficiency is found to be 30% for an energy gap of 1.1 ev and $f_c=1$. Actual junctions do not obey the predicted current-voltage relationship, and reasons for the difference and its relevance to efficiency are discussed.

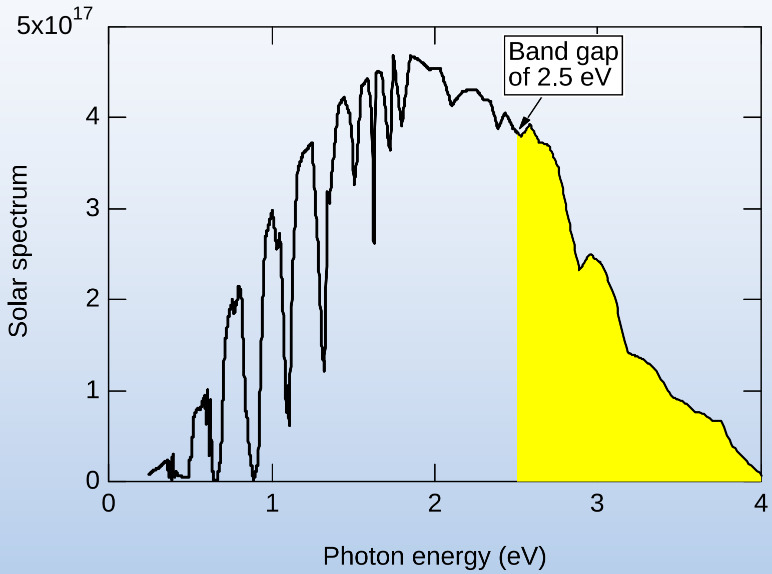
Balances the radiative transfer between the sun (black body) and a solar cell (black body that absorbs $E_{photon} > E_{gap}$), then uses a diode equation to create the current-voltage curve.

Shockley-Queisser limit: 31% (one sun); 41% (~46,200 suns)

Why multijunction?
Power = Current X Voltage



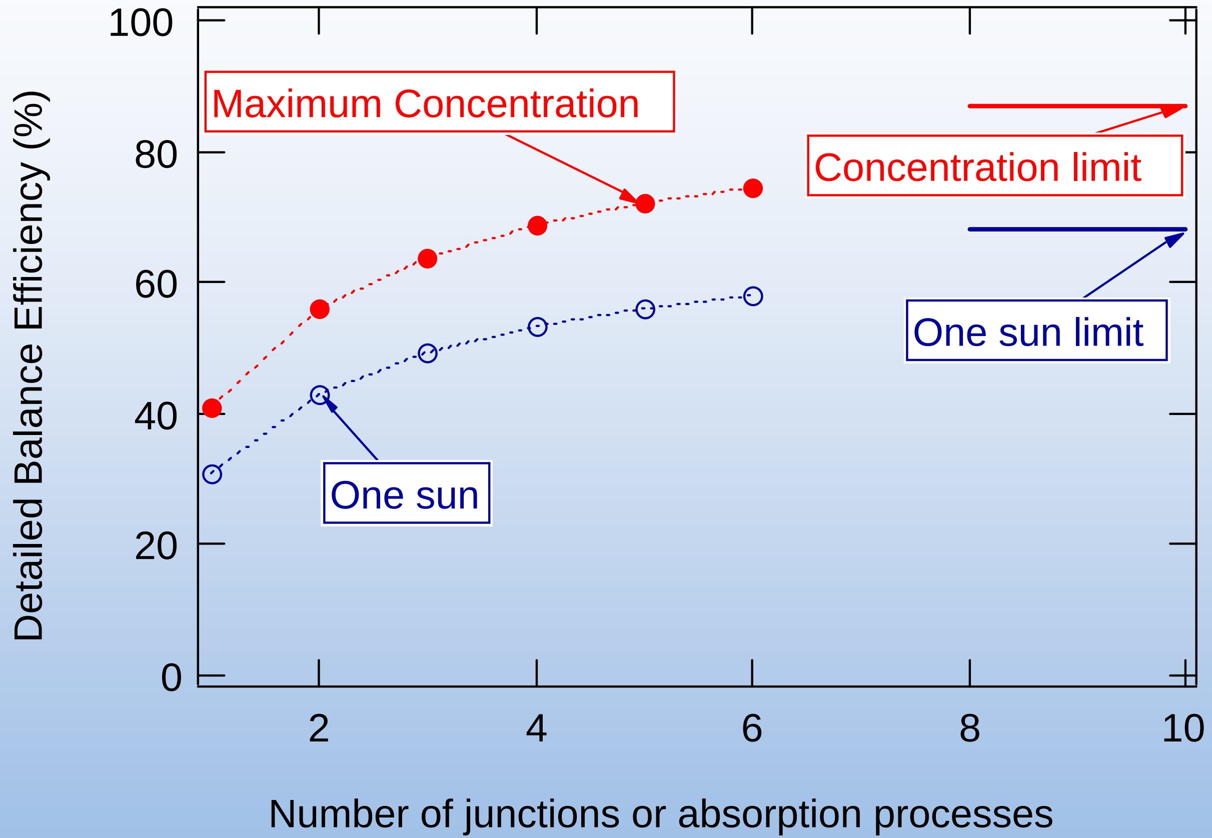
High current,
but low voltage
Excess energy lost to heat



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

Detailed balance for multiple junctions

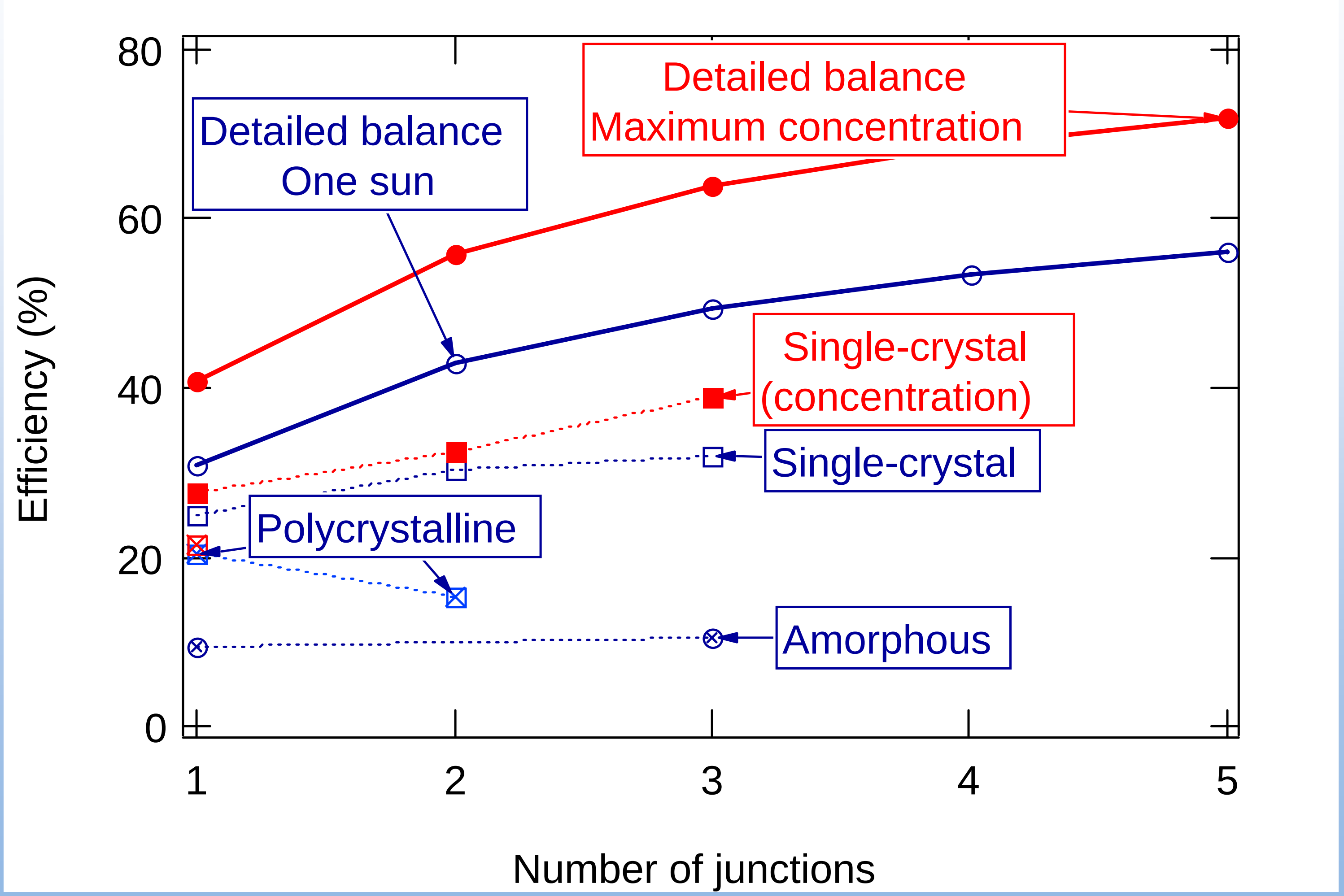


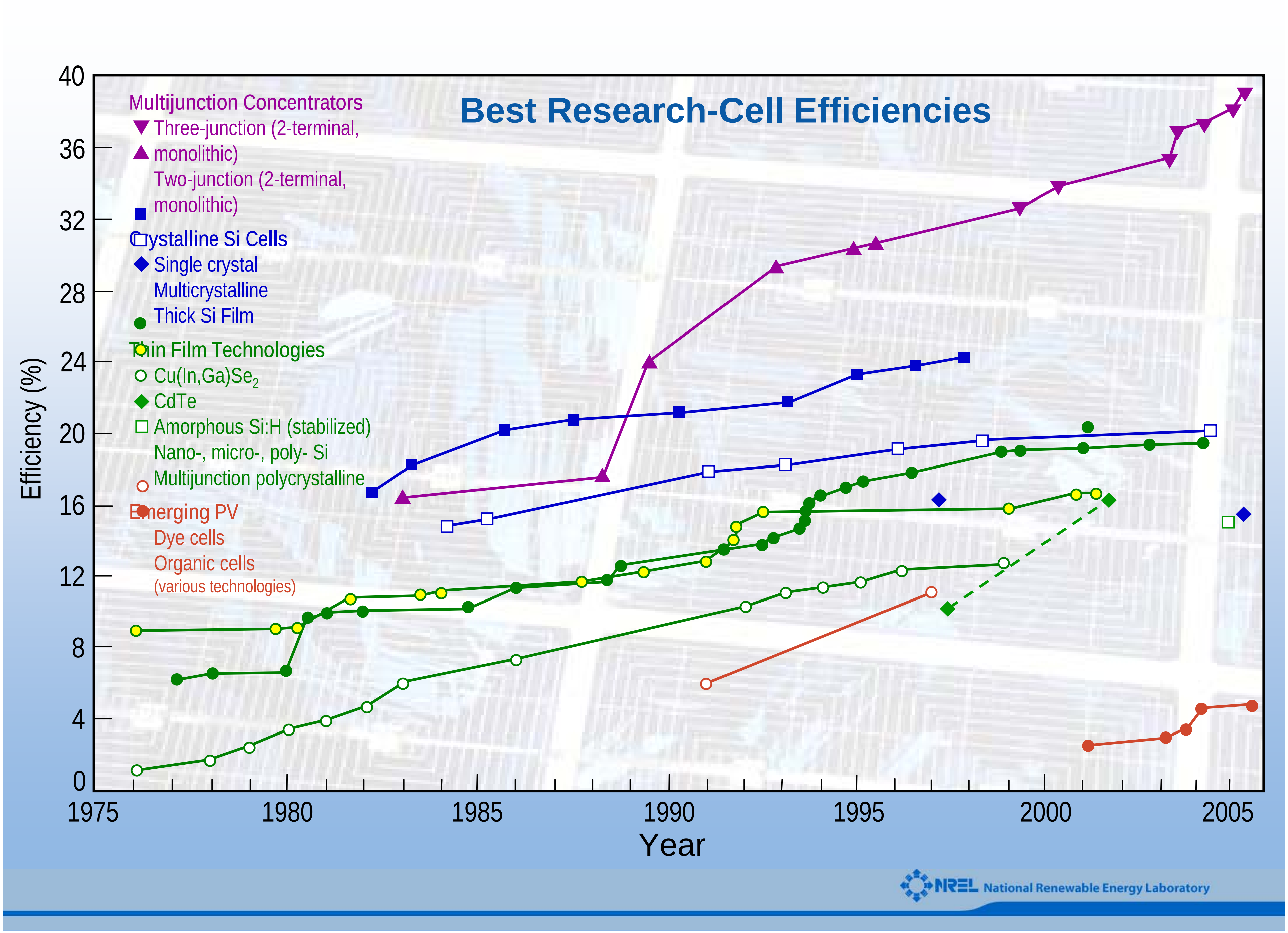
Marti & Araujo 1996 Solar Energy Materials and Solar Cells **43** p. 203

Depends on E_{gap}, solar concentration, & spectrum.

Assumes ideal materials

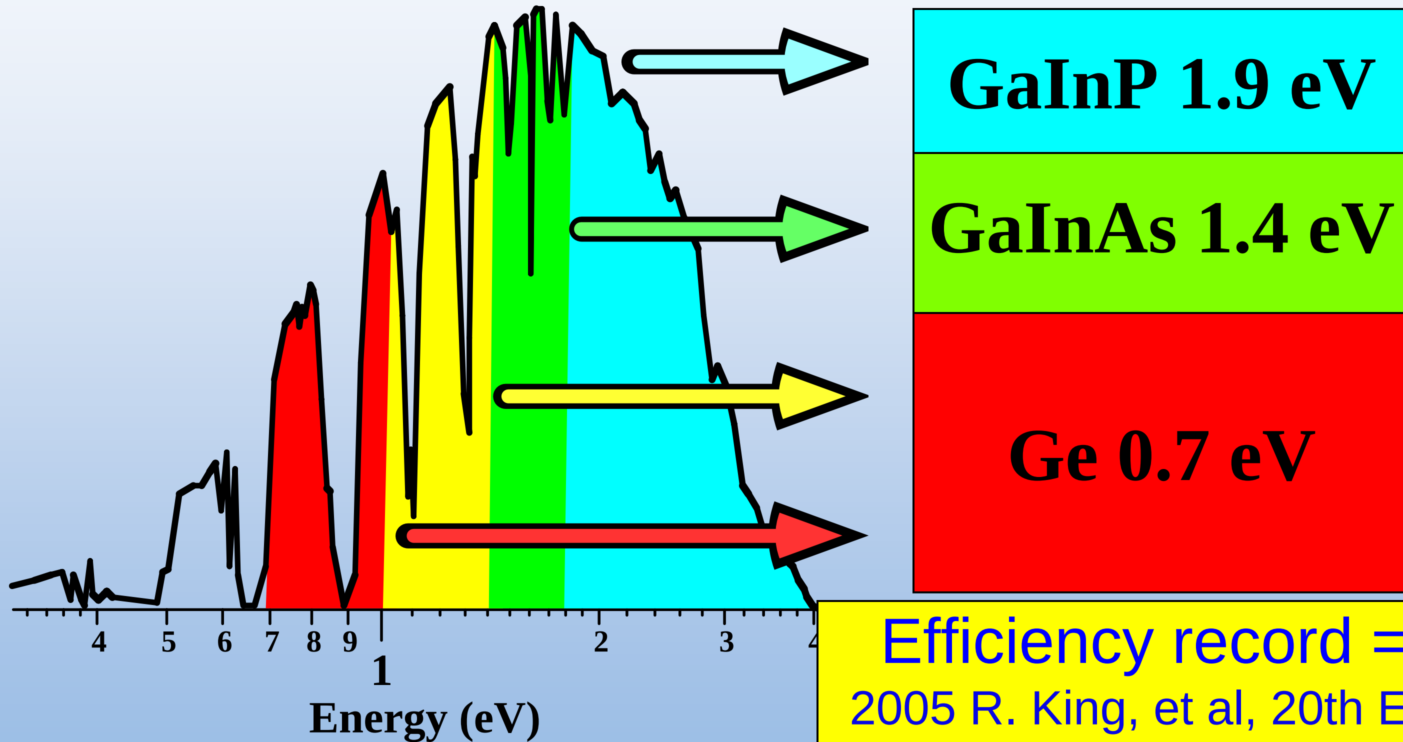
Achieved efficiencies - depend more on material quality





Best Research-Cell Efficiencies
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si Film
Thin Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly- Si
Multijunction polycrystalline
Emerging PV
Dye cells
Organic cells
(various technologies)
Efficiency (%)
0
4
8
12
16
20
24
28
32
36
40
Year
1975
1980
1985
1990
1995
2000
2005
NREL National Renewable Energy Laboratory

Multijunction cells use multiple materials to match the solar spectrum

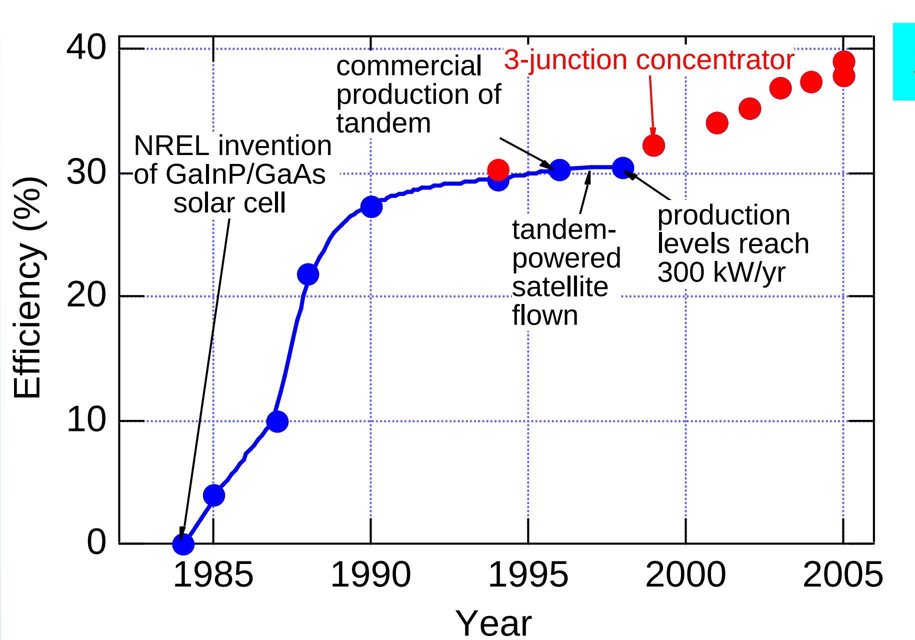


Efficiency record = 39%

2005 R. King, et al, 20th European PVSEC

SPECTROLAB A BOEING COMPANY

Success of GaInP/GaAs/Ge cell



39%!

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

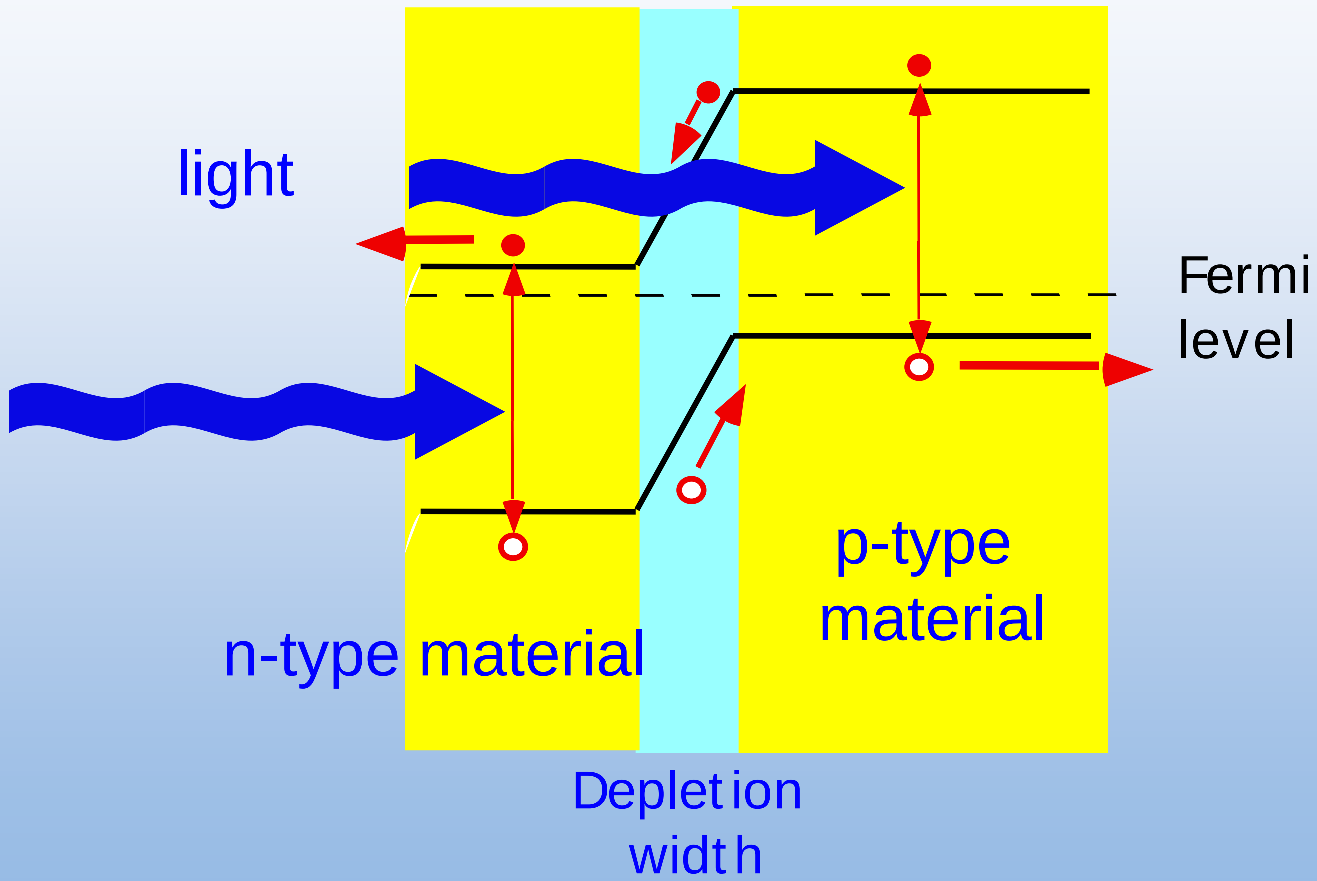
Mars Rover powered by multijunction cells

EMCORE

SPECTROLAB
A BOEING COMPANY

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

Solar cell - diode model

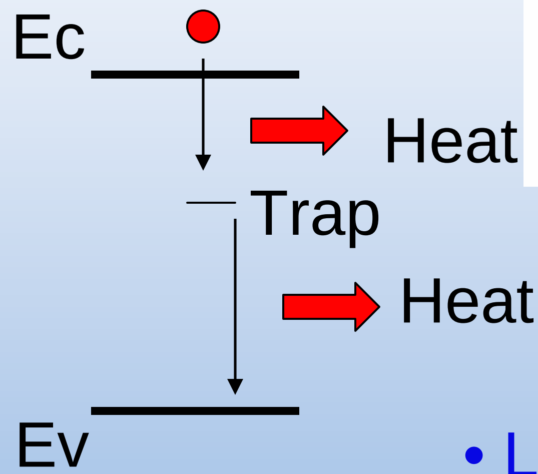


Collect photocarriers at built-in field before they recombine.

Types of recombination

- Auger
- Radiative
- Non-radiative - tied to material quality

Non-radiative recombination generates heat instead of electricity



PHYSICAL REVIEW VOLUME 87, NUMBER 5 SEPTEMBER 1, 1952

Statistics of the Recombinations of Holes and Electrons

W. SHOCKLEY AND W. T. READ, JR.
Bell Telephone Laboratories, Murray Hill, New Jersey

(Received April 29, 1952)

The statistics of the recombination of holes and electrons in semiconductors is analyzed on the basis of a model in which the recombination occurs through the mechanism of trapping. A trap is assumed to have an energy level in the energy gap so that its charge may have either of two values differing by one electronic charge. The dependence of lifetime of injected carriers upon initial conductivity and upon injected carrier density is discussed.

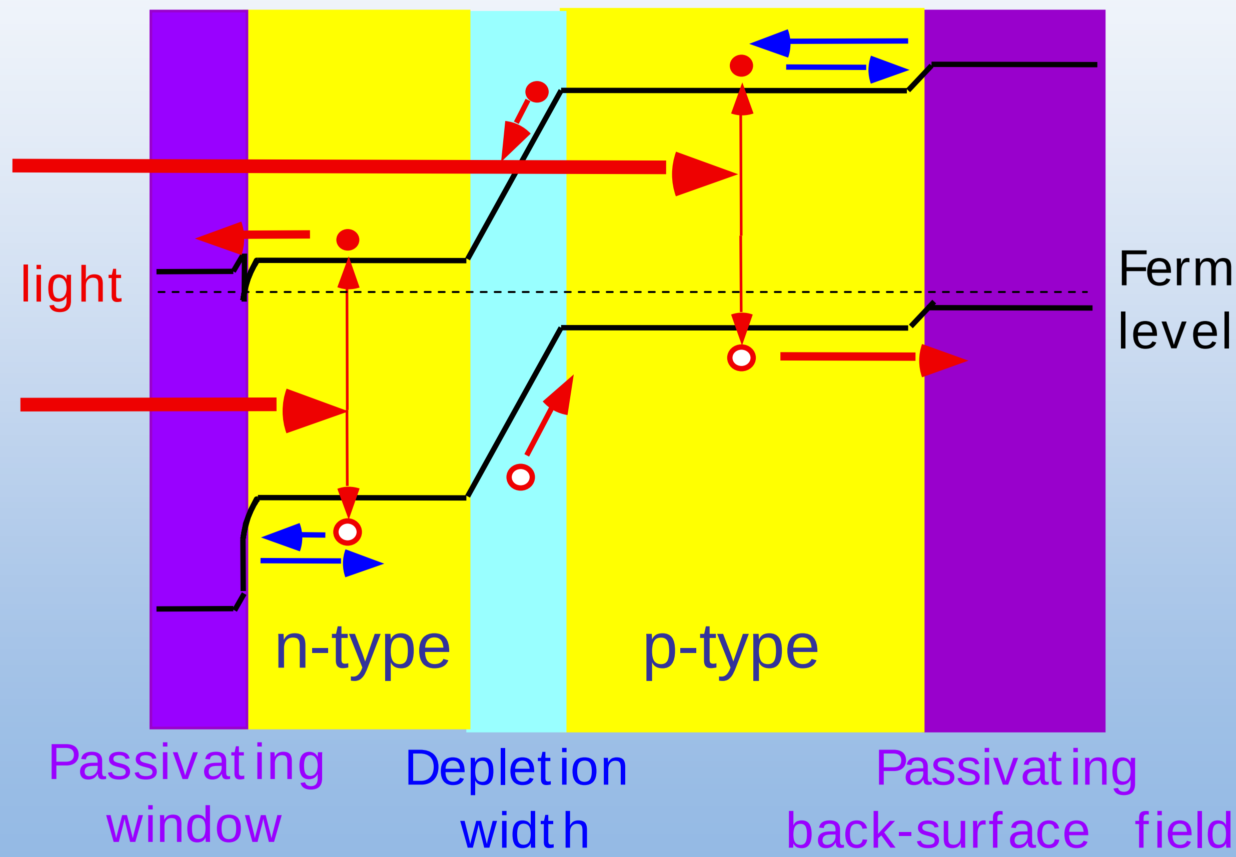
Shockley - Read - Hall recombination

- Large numbers of phonons are required when ΔE is large -- probability of transition decreases exponentially with ΔE
- Trap fills and empties; Fermi level is critical

Defects - problems and solutions

- Defects that cause states near the middle of the gap are the biggest problem
- These tend to be crystallographic defects (dislocations, surfaces, grain boundaries)
  - *use single crystal*
- "Perfect" single-crystal material has defects only at edges
  - *Terminate crystal with a material that forms bonds to avoid unpaired electrons*
  - *Build in a field to repel minority carriers*

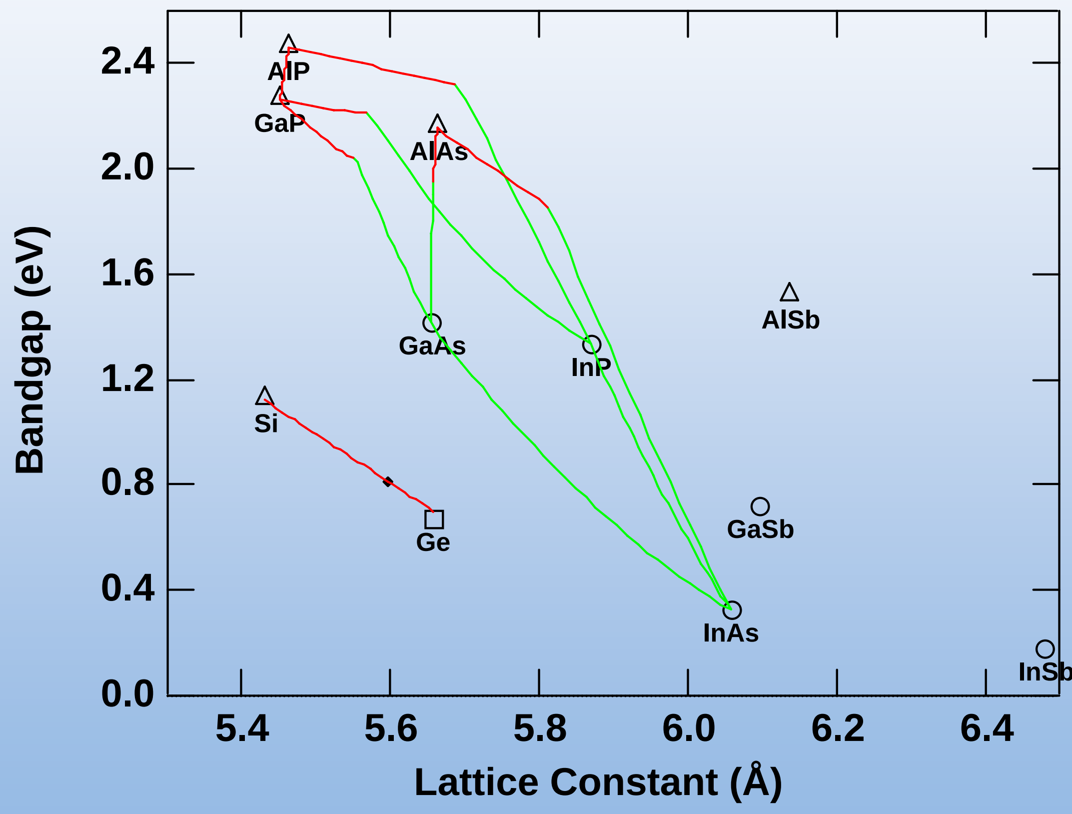
Solar cell schematic to show surface passivation



Summary about high efficiency

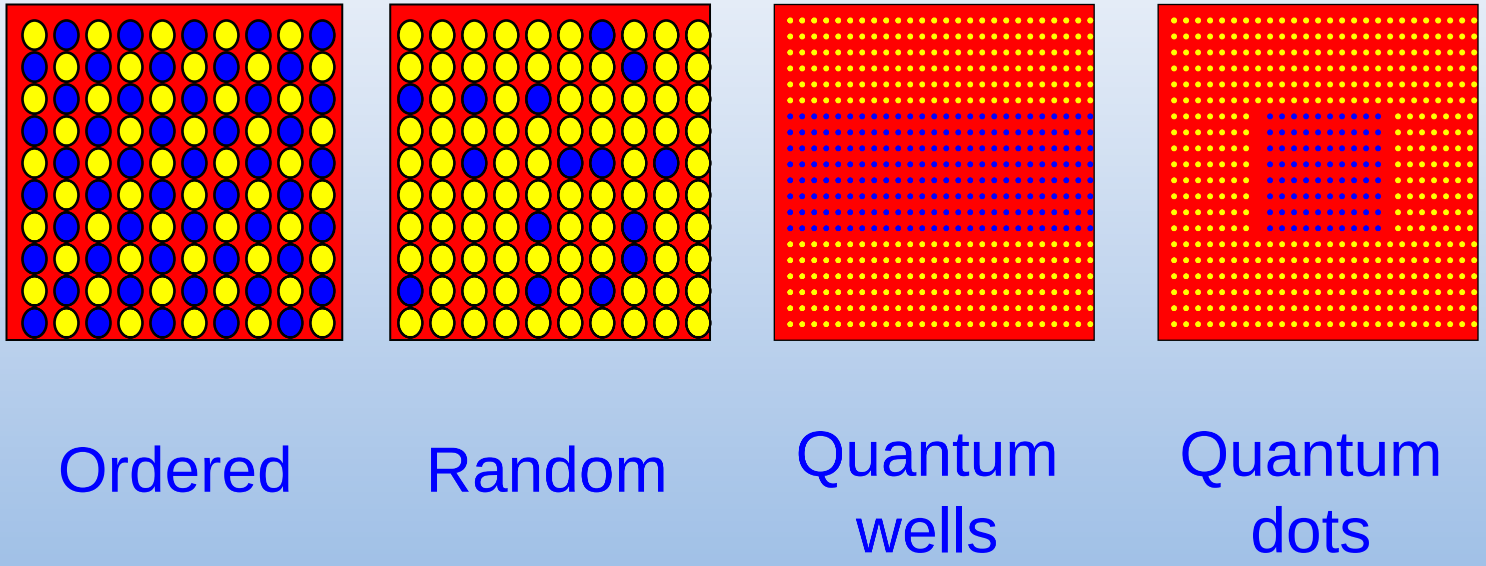
- High efficiency cell makes rest of system more valuable
- Minimize non-radiative recombination
  - Use single crystal
  - “Get rid of” surfaces with passivating layers
- With these ground rules, how do we combine materials? - *Lots of research opportunities*

Many available materials

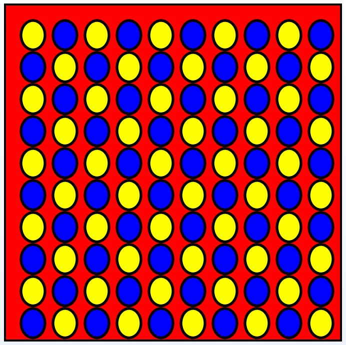


By making alloys, all band gaps can be achieved

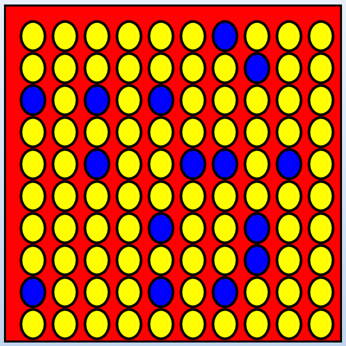
Ways to make a single-crystal alloy



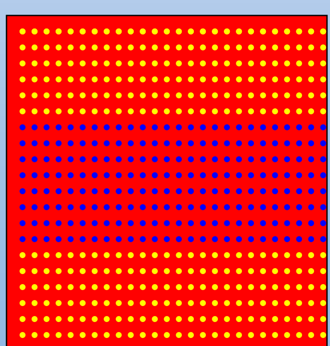
Challenges: • avoid forming defects while controlling structure
• collect photocarriers

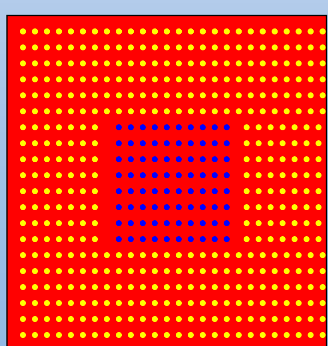


Strain is distributed uniformly
Mobility is determined by band structure
Need driving force for ordering, or growth is impossible

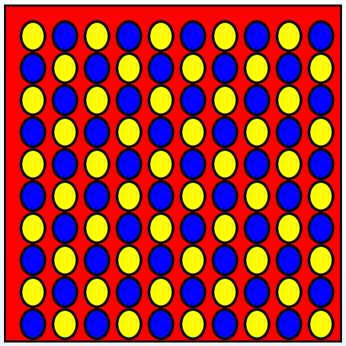


Relatively easy to grow
Alloy scattering is usually small; mobility is decreased slightly





Collection of photocarriers usually requires a built-in electric field
Growth is typically more complex, especially to avoid defects and to control sizes of quantum structures



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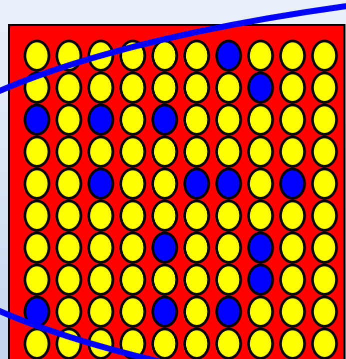

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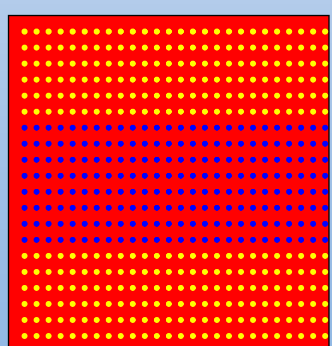

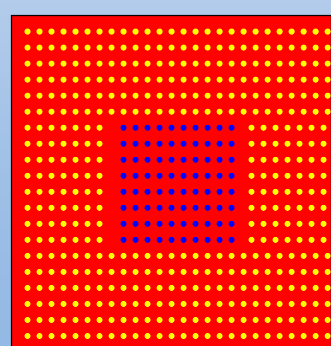

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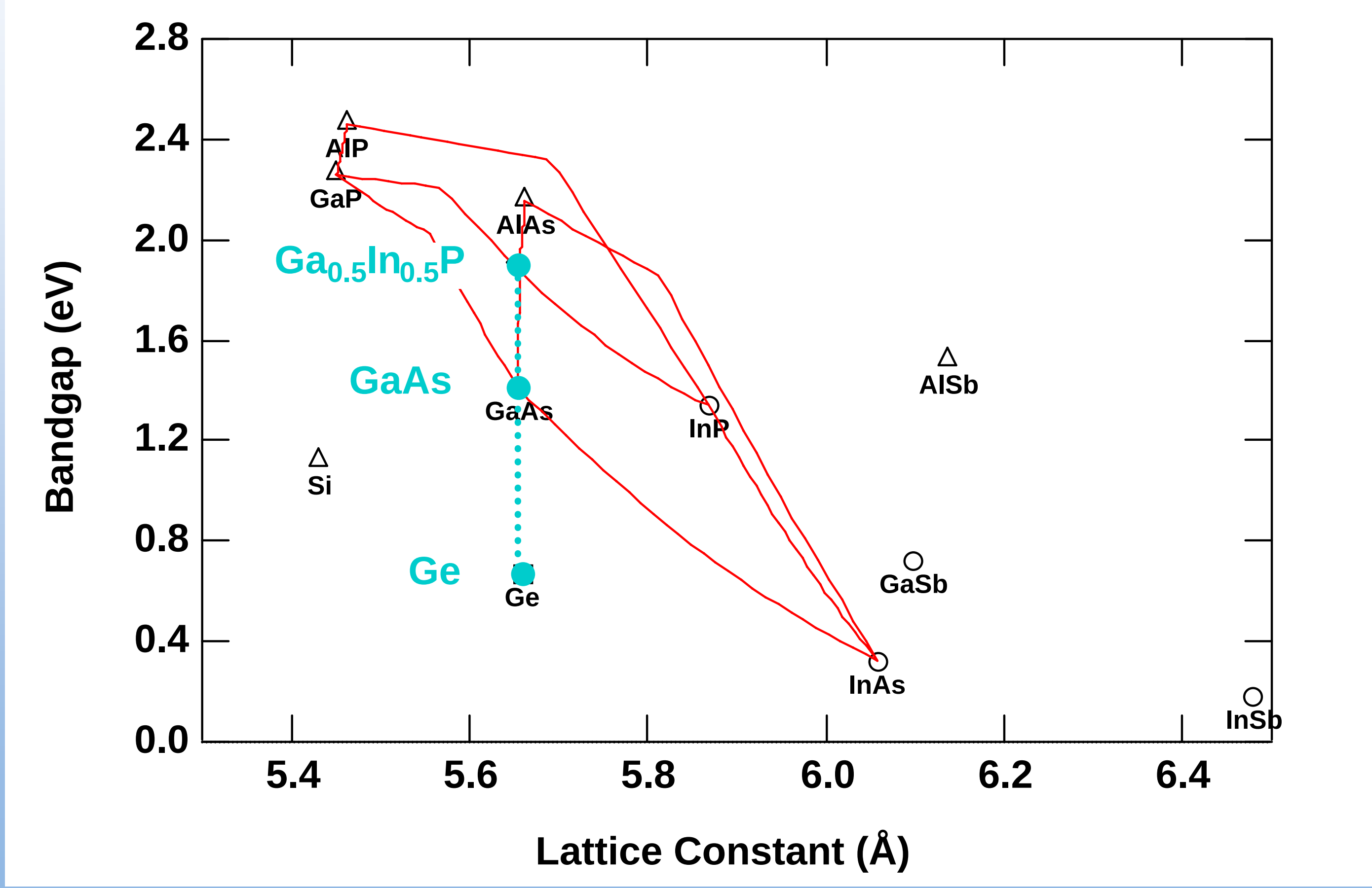
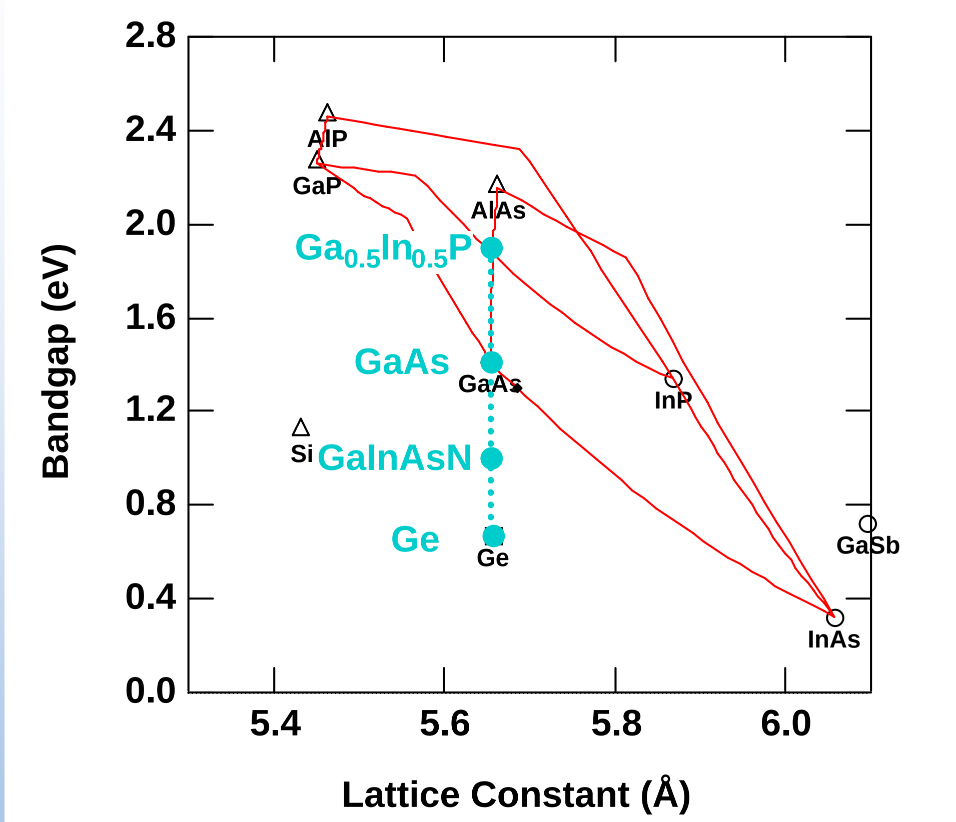
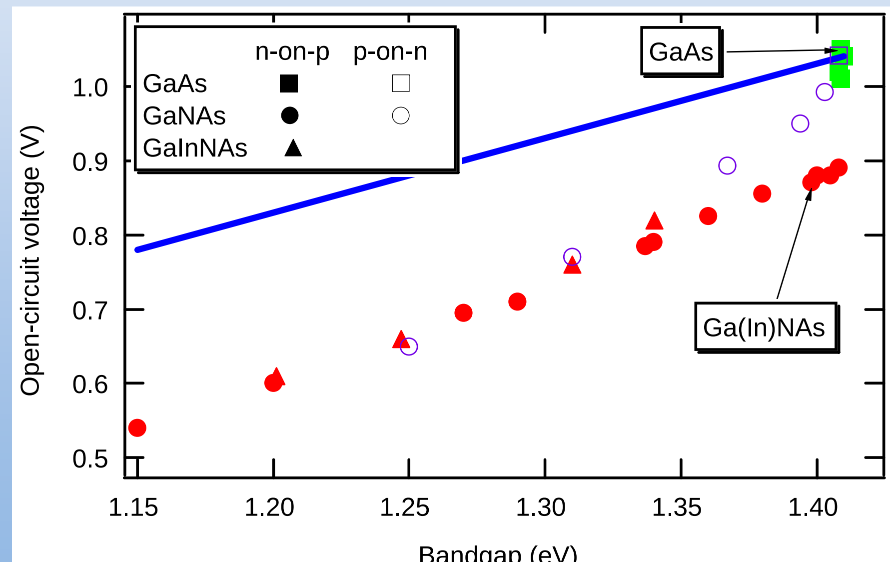
GaInP/GaAs/Ge cell is lattice matched



New lattice matched alloys

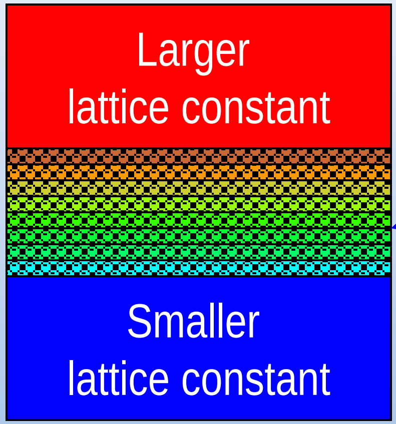


GaInNAs is candidate for 1-eV material, but does not give ideal performance

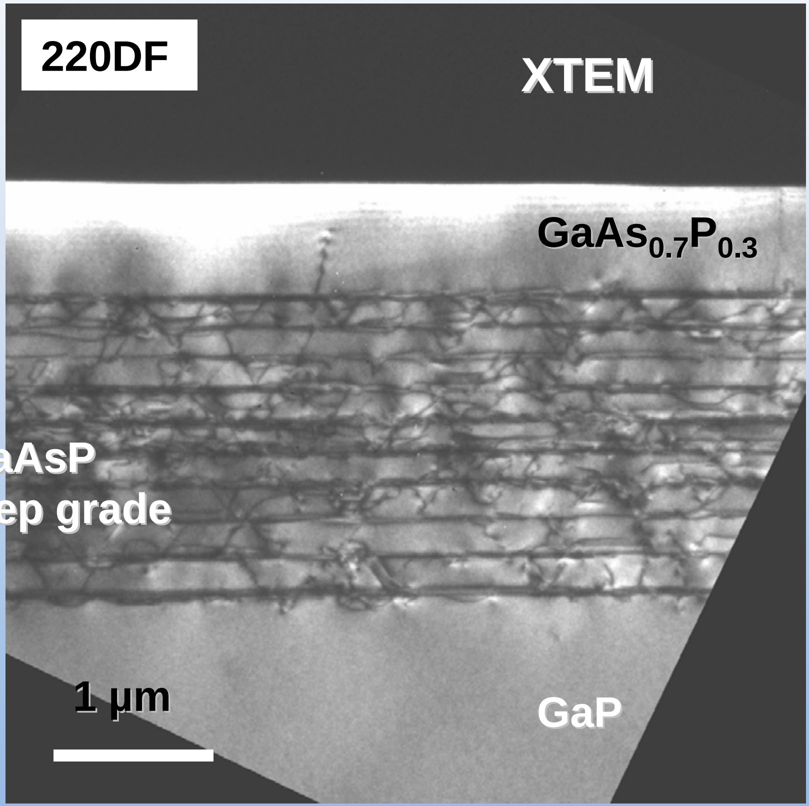


Lattice matched approach is easiest to implement, but is limited in material combinations

Method for growing mismatched alloys

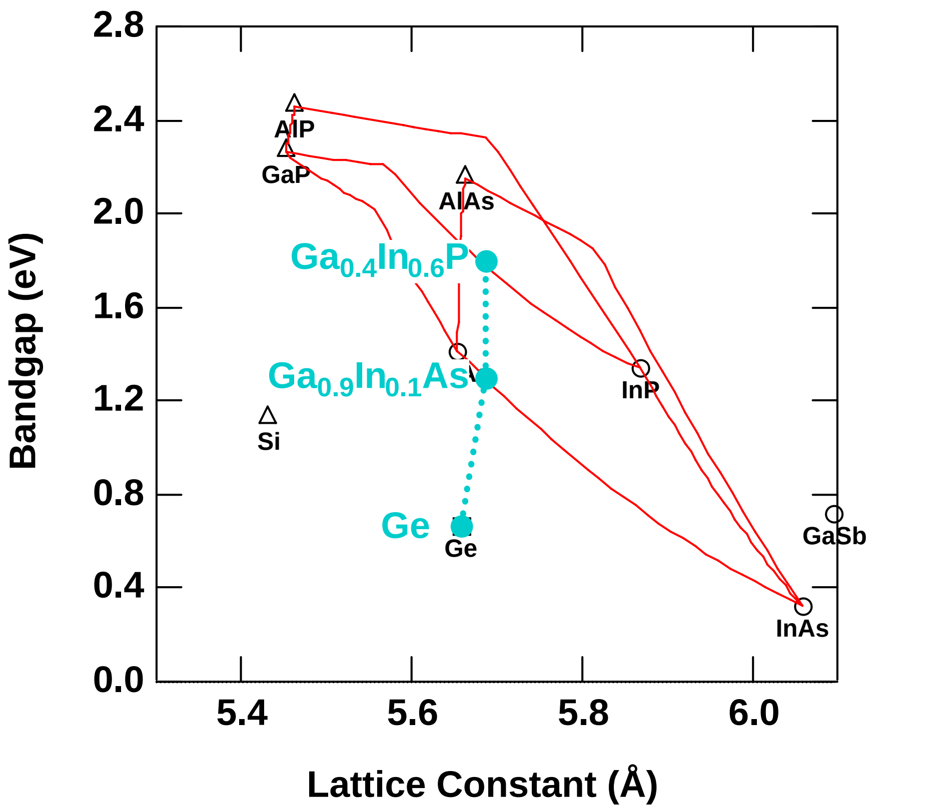


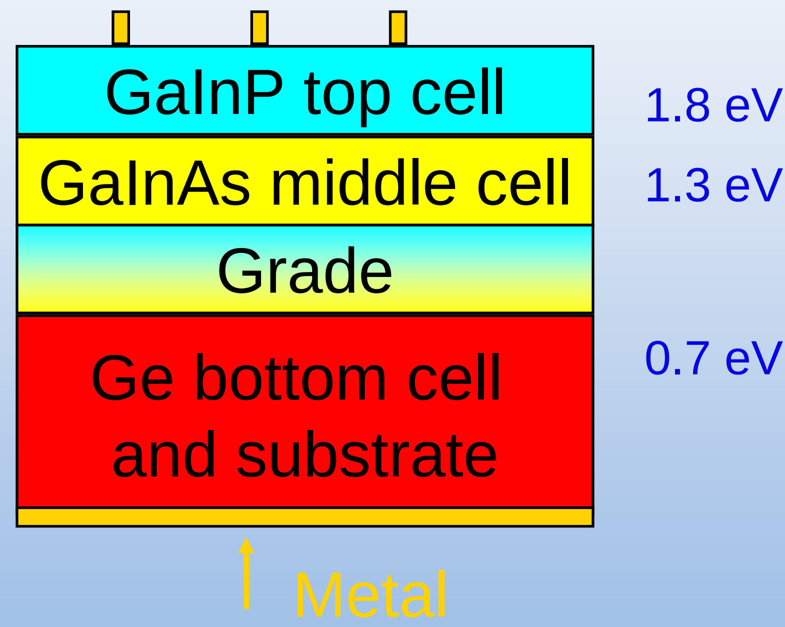
Step grade confines defects



SiGe (majority-carrier) devices are now common, but mismatched epitaxial solar cells are in R&D stage

High-efficiency mismatched cell

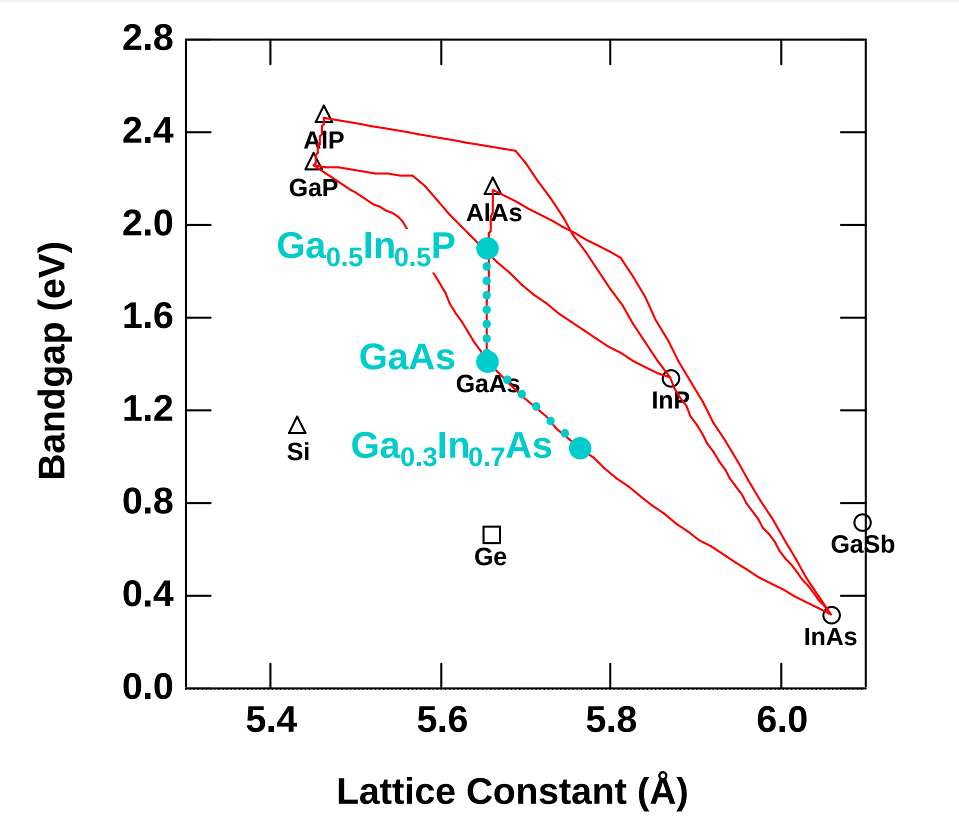


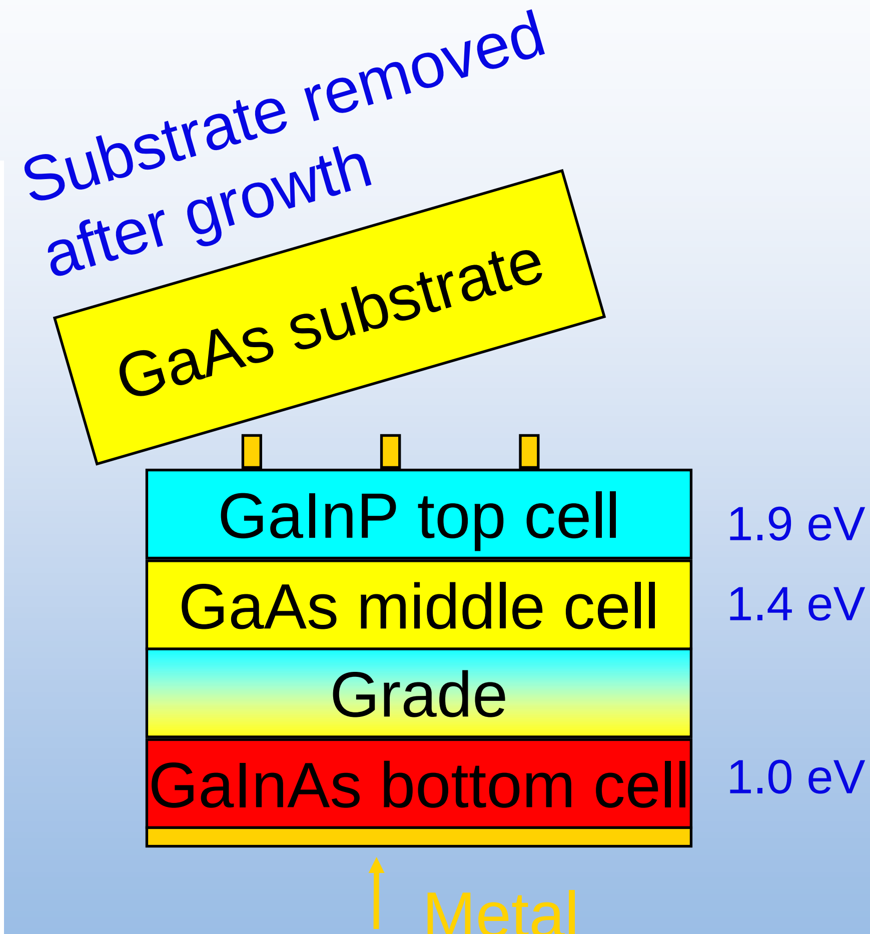


38.8% @ 240 suns

R. King, et al 2005, 20th European PVSEC

Inverted mismatched cell





37.9% @ 10 suns

Mark Wanlass, et al 2005

Mechanical stacks

32.6% efficiency @ 100 suns

1990 L. Fraas, et al 21st PVSC, p. 190

Easier to achieve high efficiency, but more difficult in a system because of heat sinking and 4-terminals

Wafer bonding provides pathway to monolithic structure

A. Fontcuberta I Morral, et al, Appl. Phys. Lett. 83, p. 5413 (2003)

Summary

- Photovoltaic industry is growing > 40%/year
- High efficiency cells may help the solar industry grow even faster
- Detailed balance provides upper bound (>60%) for efficiencies, assuming ideal materials
- Single-crystal solar cells have achieved the highest efficiencies: 39%
- Higher efficiencies will be achieved when ways are found to integrate materials while retaining high crystal quality

Flying high with high efficiency

Cells from Mars rover
may soon provide
electricity on earth

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TIFF (LZW) decompressor
are needed to see this picture.

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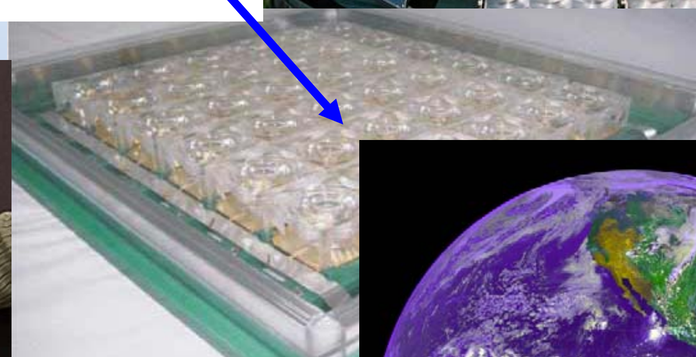
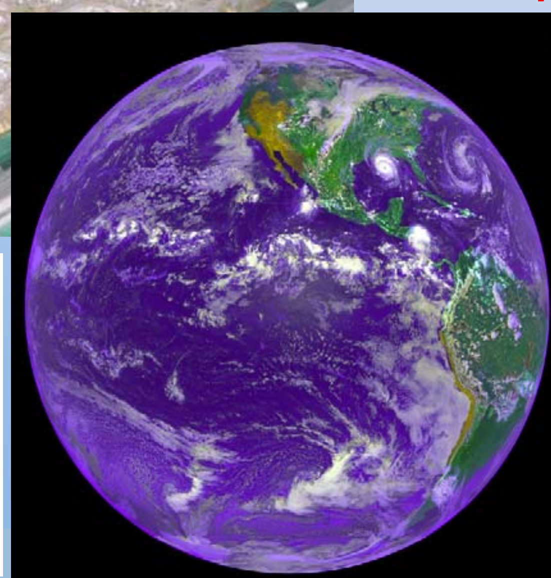
High efficiency, low cost,
ideal for large systems





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