presented at Fermilab, April 17, 2002

# GaInP/GaAs/Ge Ultrahigh-Efficiency Solar Cells

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III-V Materials and Devices Group

National Renewable Energy Laboratory

*NREL

with Spectrolab Inc.

# *NREL – Research Programs

Started in 1977 (as SERI)
1100 staff, mostly in Golden CO

Renewable-energy research:

- basic materials
- photovoltaics
- wind energy
- building technologies
- advanced vehicles
- solar thermal electric
- hydrogen
- superconductivity
- geothermal power
- resource assessment

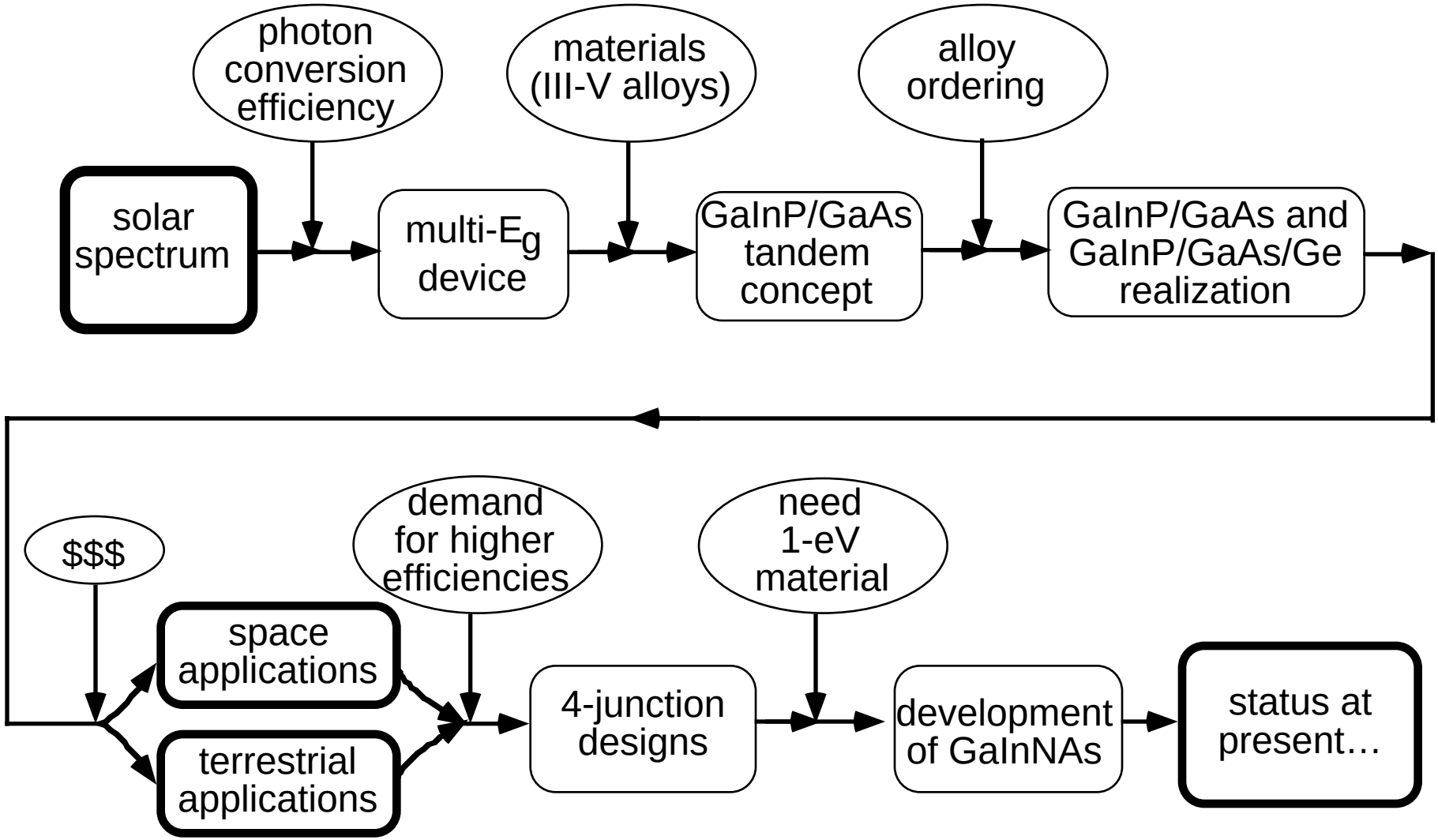
# Solar Cell Technologies

| PARAMETERS | EXAMPLES |
|---|---|
| substrates | glass, crystal wafer |
| materials | silicon, $CuInSe_2$, GaAs |
| amorphous vs crystalline | amorphous silicon vs. GaAs |
| fabrication method | evaporation, MOCVD |

Best one-sun Efficiencies:

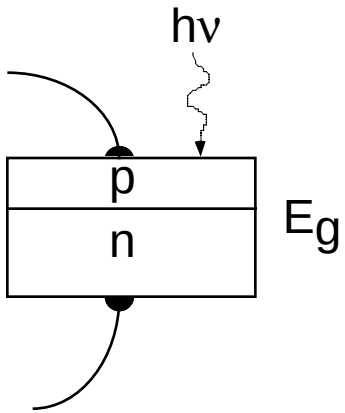
| | |
|---|---|
| amorphous silicon | 13% |
| $CuInSe_2$ | 19% |
| crystalline silicon | 25% |
| GaInP/GaAs/Ge | 31% |

highest efficiency... also most expensive



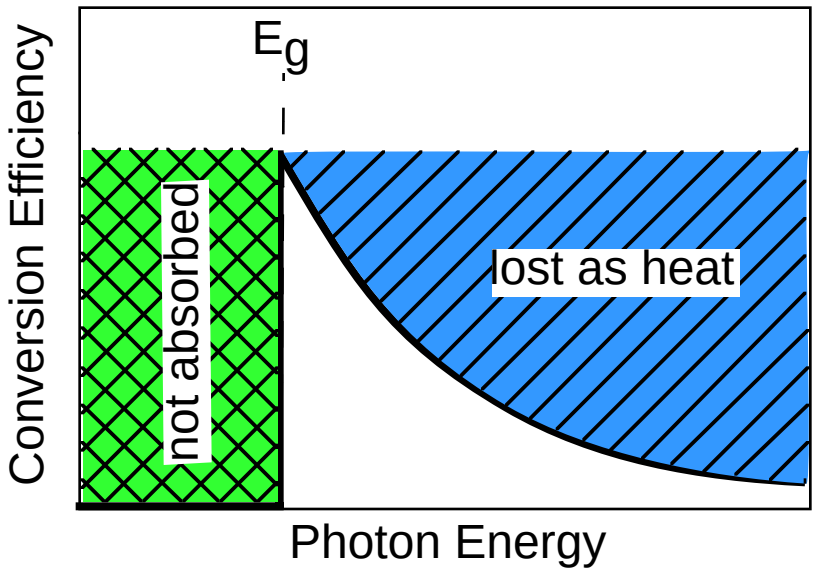

basic materials science — devices — applications

# Photon Conversion Efficiency



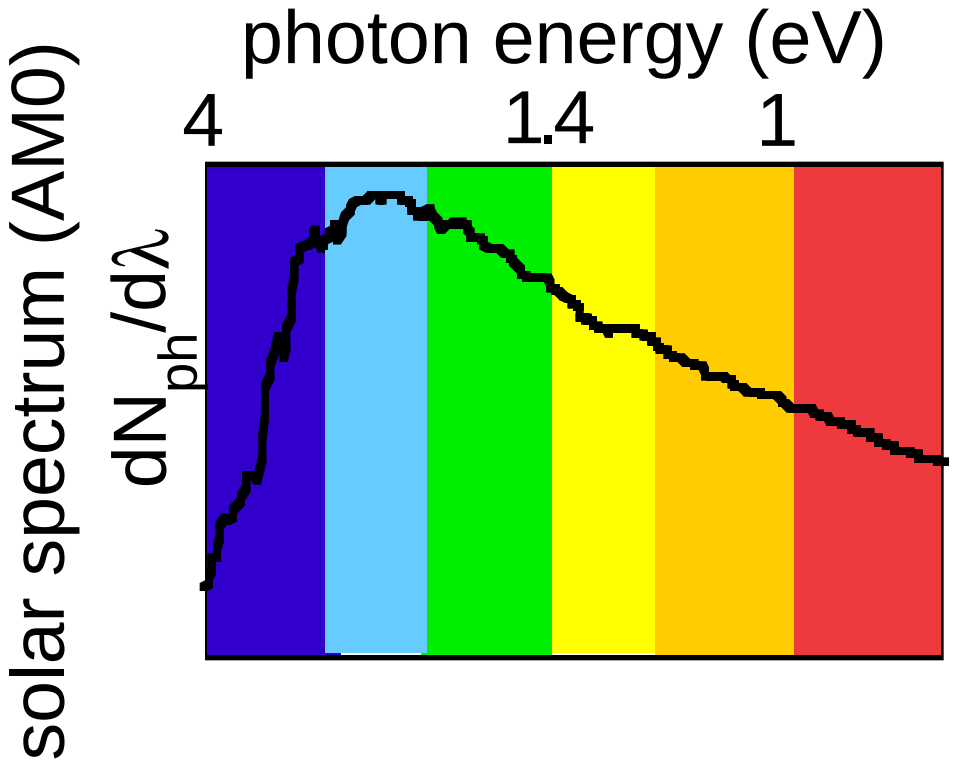

- $h\nu > E_g$: absorbed
  $h\nu - E_g$ wasted (heat)
- $h\nu < E_g$: transmitted

$\Rightarrow$ Conversion to energy ideally efficient only for $h\nu = E_g$



# Solar Spectrum

The sun is not a laser!




color scheme for illustration only!

# Voltage vs. Current Tradeoff

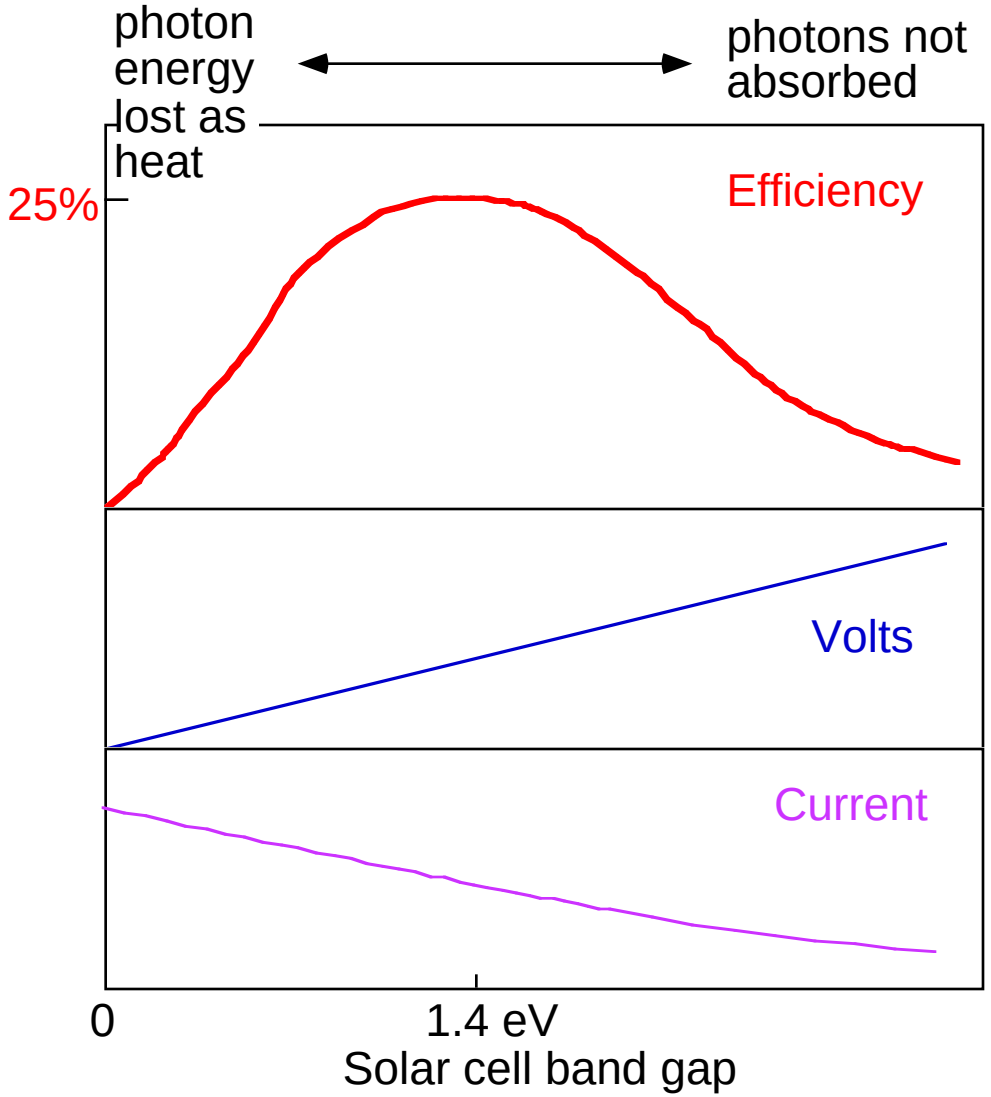
What is the optimal $E_g$ for solar cell?

Power = Volts * Amps

Increasing $E_g \Rightarrow$
- increased voltage
- decreased current

… and vice versa …

inherent limit on single-junction solar cell efficiency

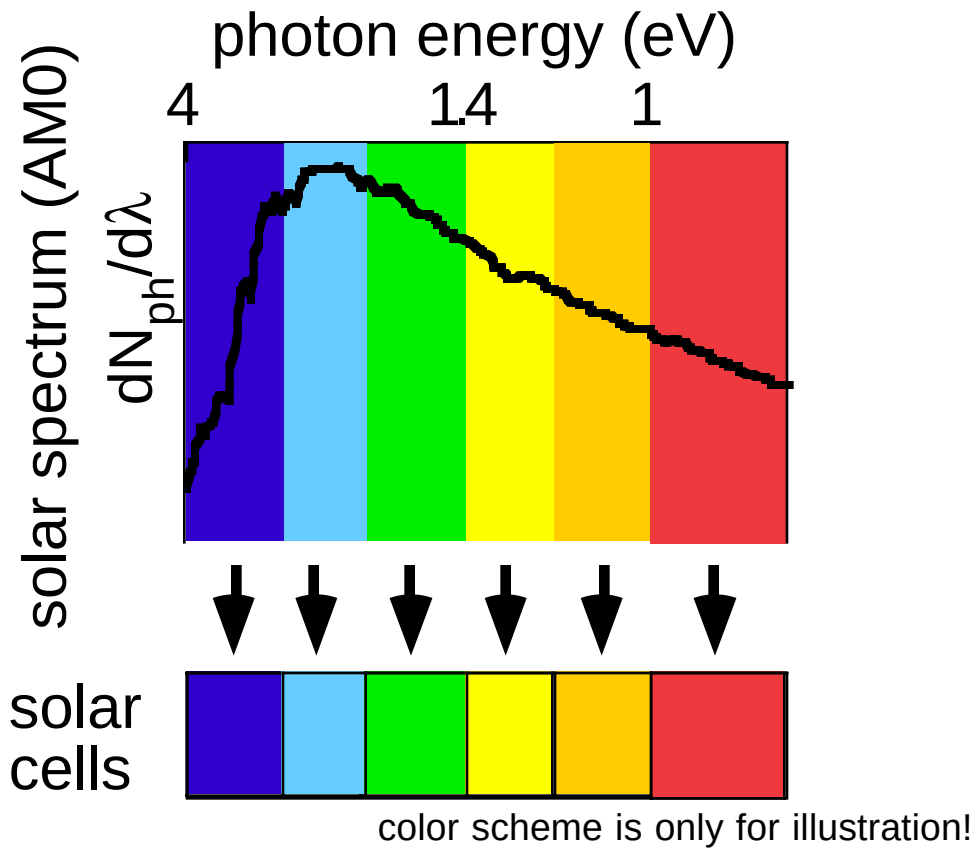


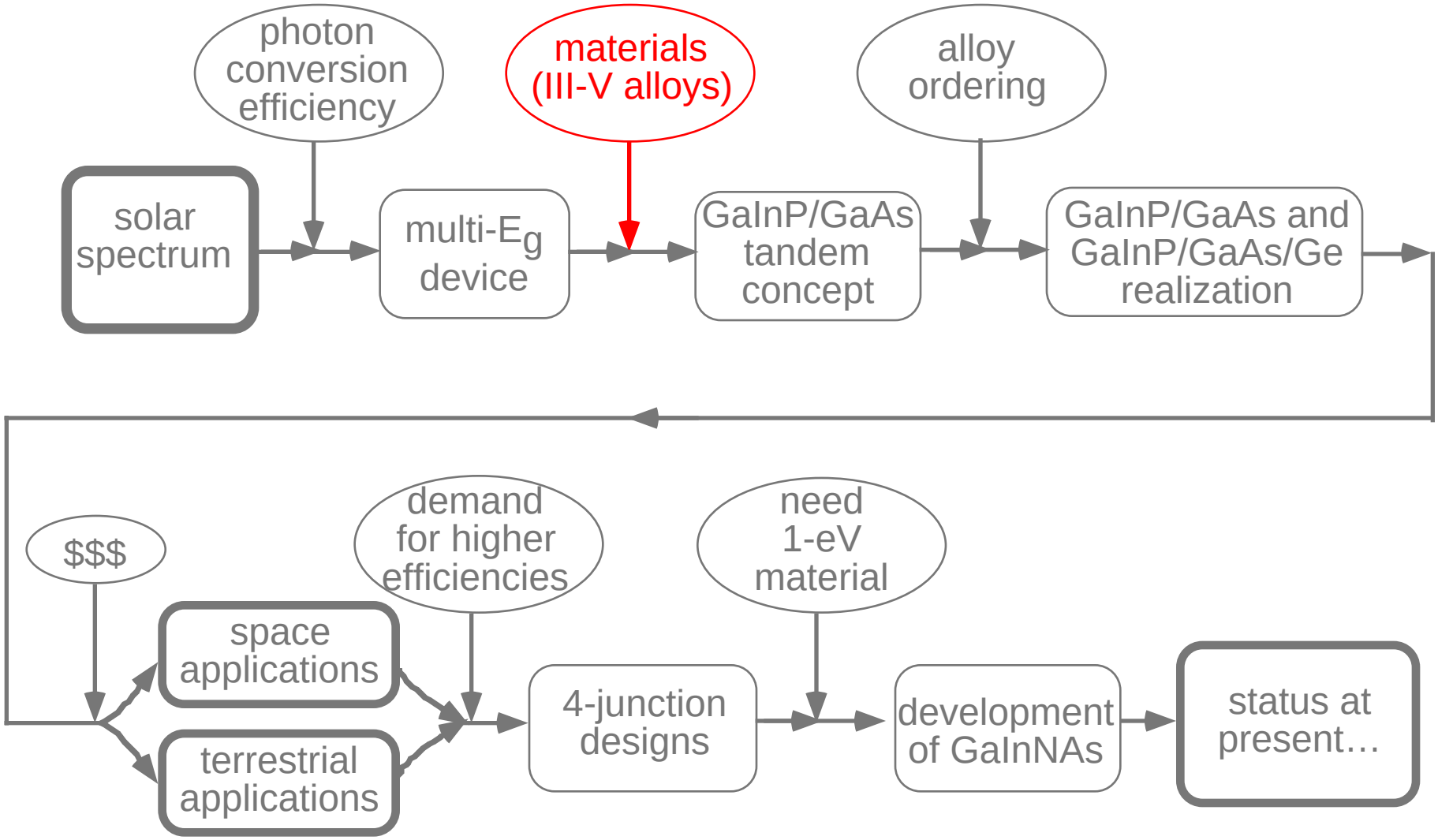
# Solution to Spectrum Problem: Multi-Bandgaps

Divide up spectrum into little regions

Convert each region with a band gap tuned for that region

Sounds great in principle…




photon conversion efficiency
materials (III-V alloys)
alloy ordering
solar spectrum
multi-Eg device
GaInP/GaAs tandem concept
GaInP/GaAs and GaInP/GaAs/Ge realization
$$$
demand for higher efficiencies
need 1-eV material
space applications
terrestrial applications
4-junction designs
development of GaInNAs
status at present…

# Materials Issues

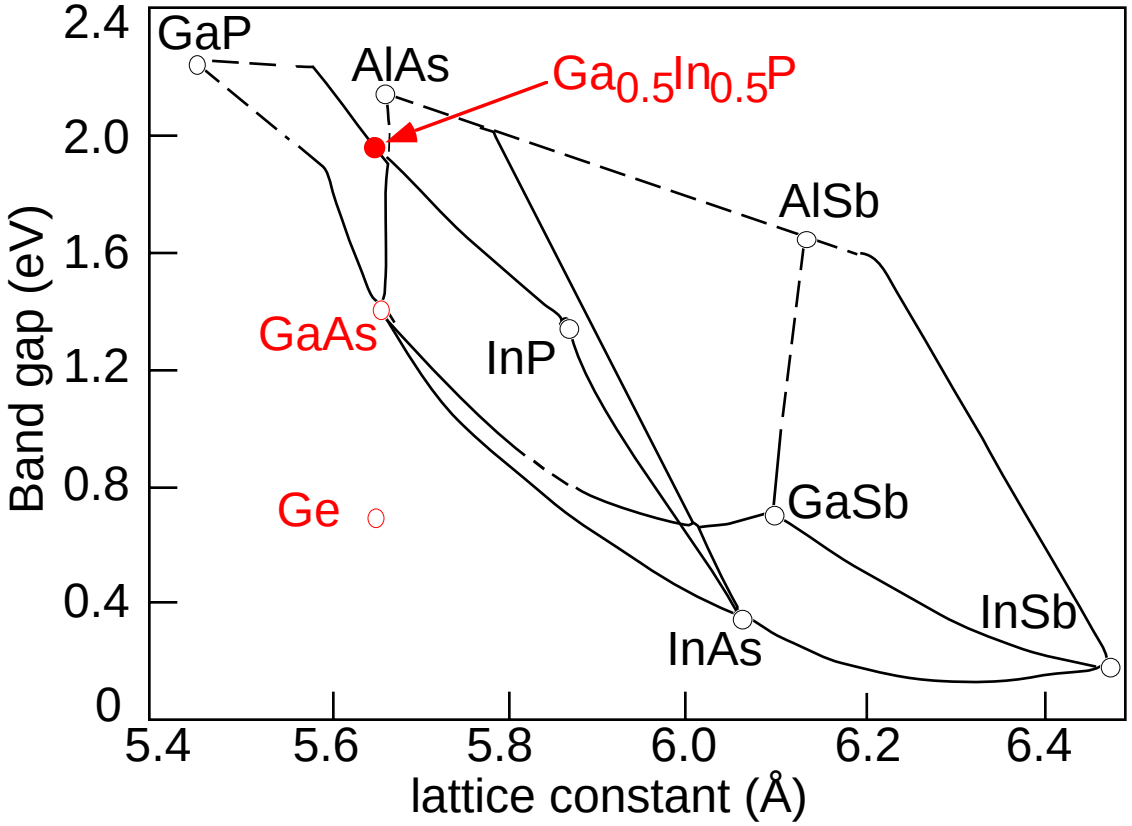
Must work with available materials!

- Band gap
- Lattice constant (if epitaxial)

note - materials like Si, GaAs etc offer limited selection of these

- ease of growth
- materials quality

# III-V Alloys: Band gap and Lattice Constant

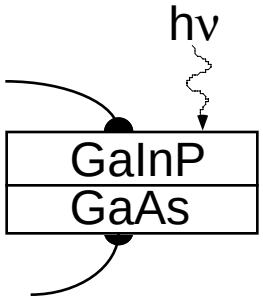


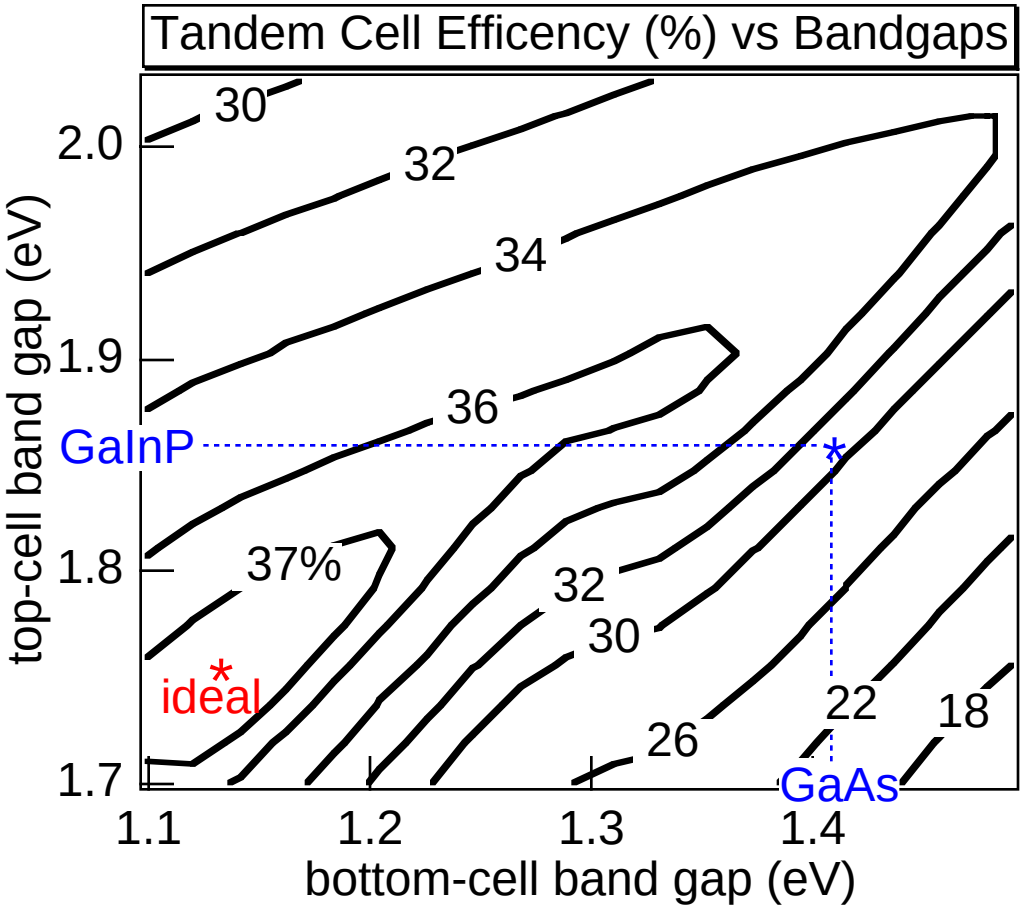

epitaxy: materials must be at or near lattice-matched

# Designing a Realistic Device

- want monolithic two-terminal device
- lattice-matched to standard substrate
- making many-junction device would be very difficult

  Let's look at two junctions:



# Alloy Ordering and Band Gap

III-V epitaxial alloys (GaInP, InGaAs) tend to show cation site ordering

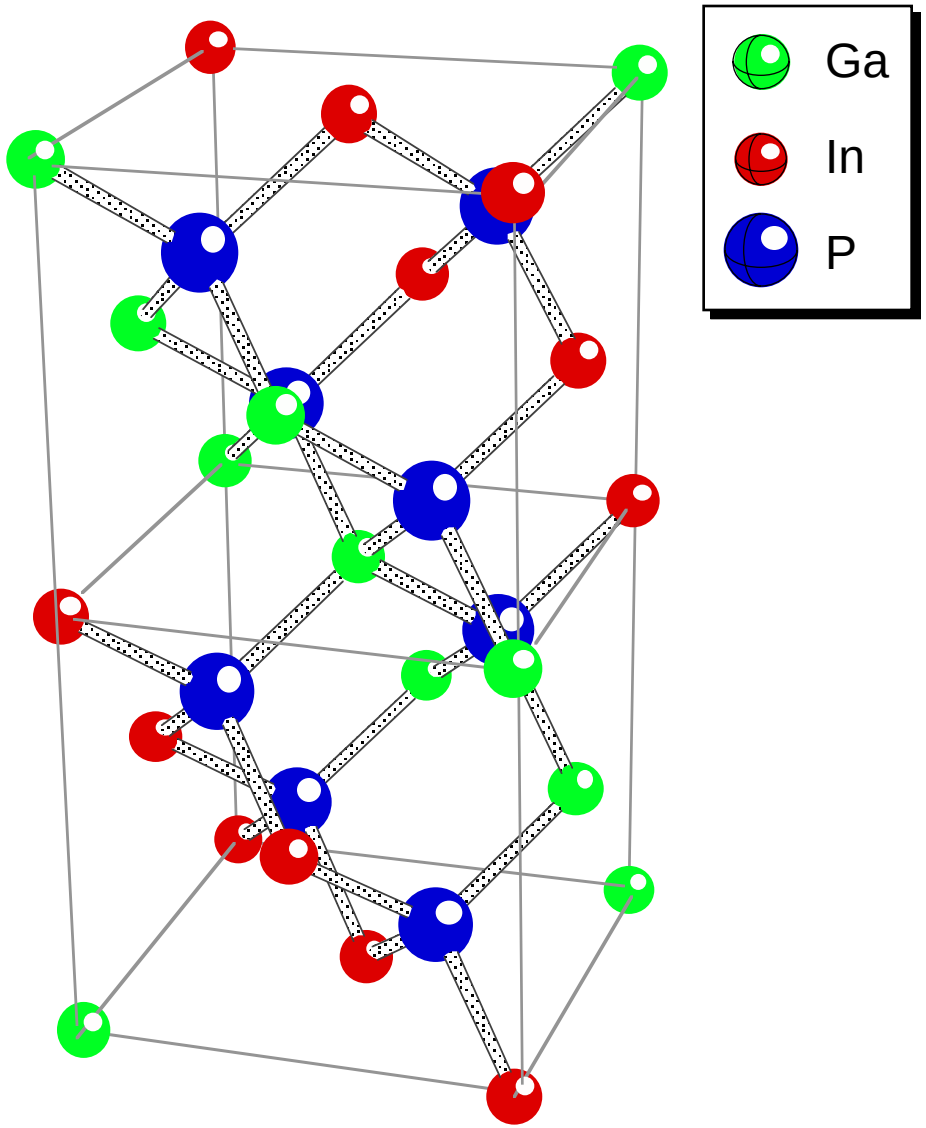
ordering is surface-driven

ordering depends on growth conditions ($T_g$, etc)

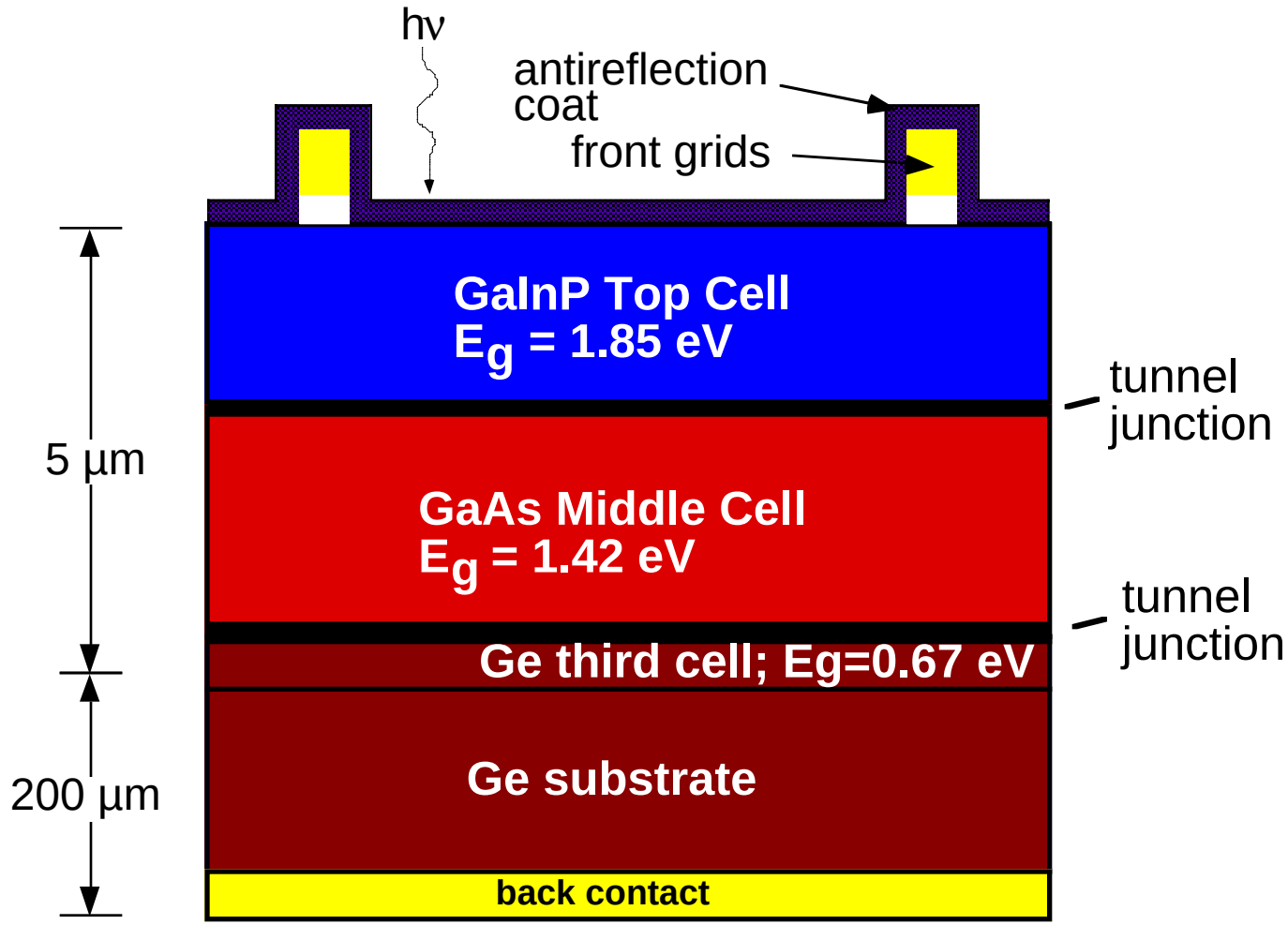
more ordered $\Rightarrow$ lower $E_g$

Can be significant:
>0.1 eV lowering for $Ga_{0.5}In_{0.5}P$

Gives additional degree of freedom in $E_g$ selection

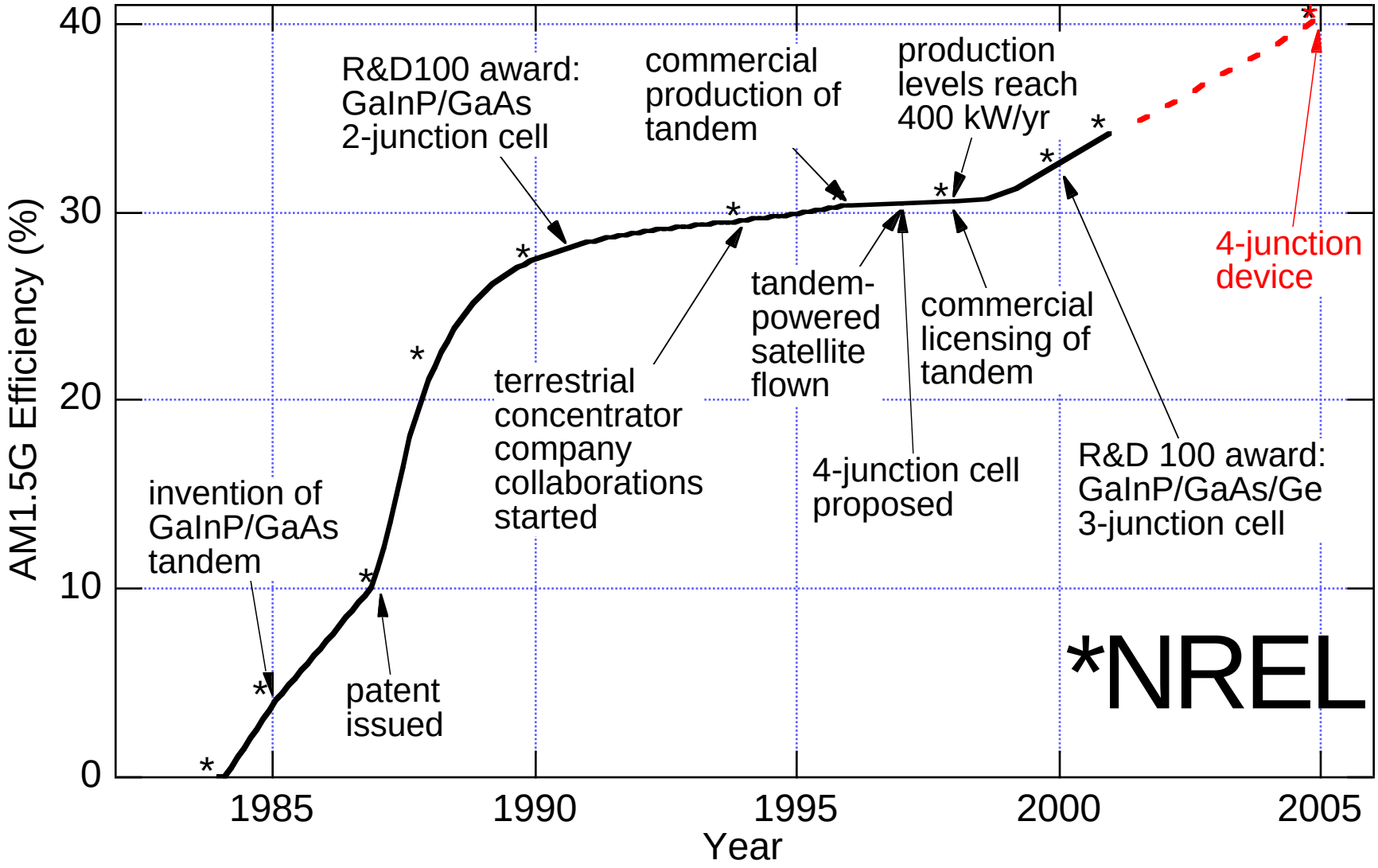


# GaInP/GaAs/Ge Cell Schematic

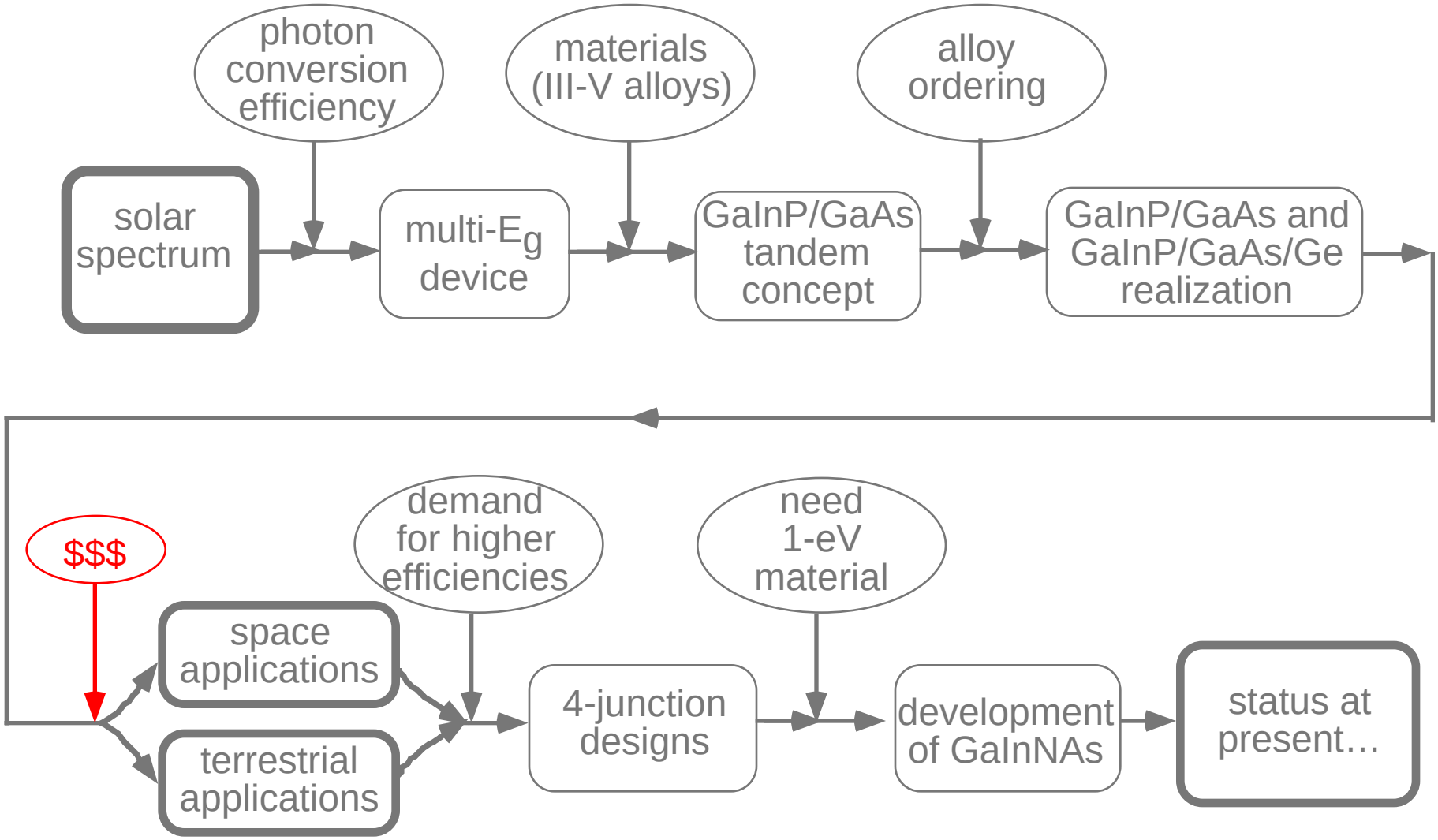



monolithic, two terminals — very important!

# GaInP/GaAs/Ge Cell Development Timeline




several of the most recent record efficiencies were set by Spectrolab Inc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# Economic Considerations: What are the Markets?

- III-V multijunction solar cells are most efficient

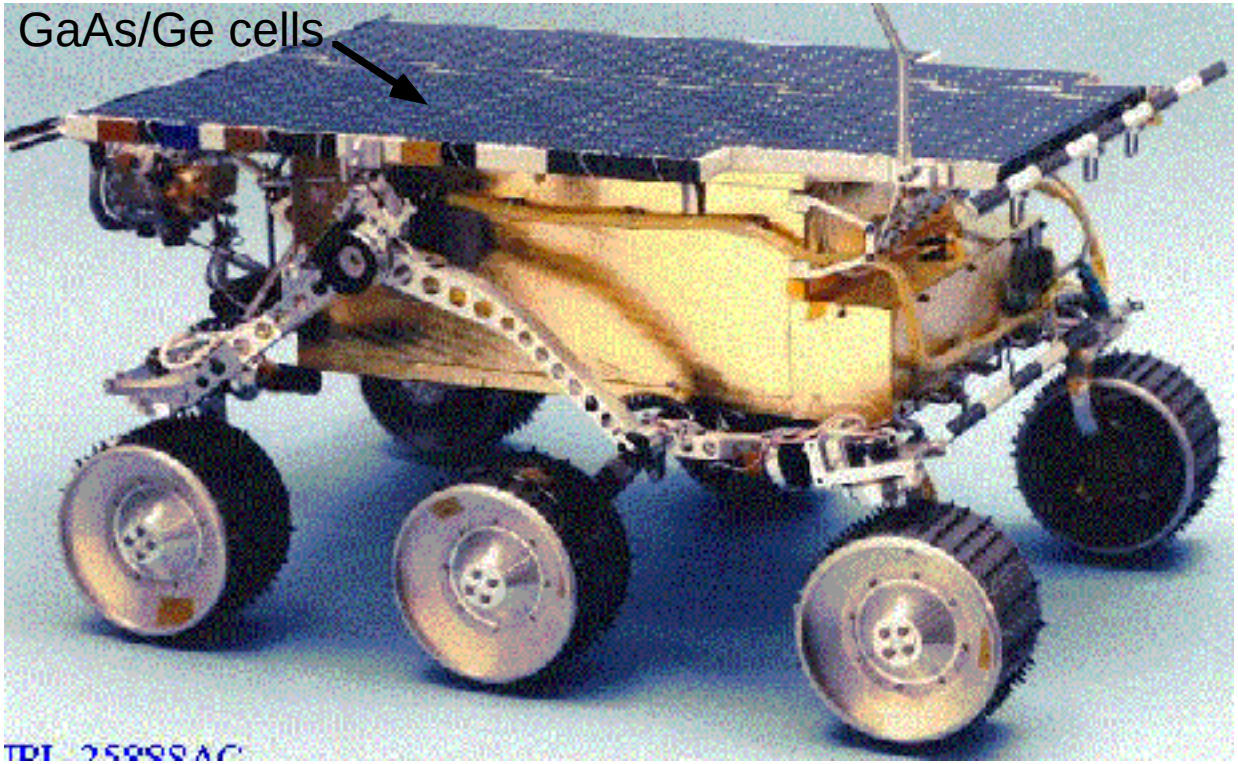
- However, epitaxial III-V technology is very expensive:
  – substrates
  – epitaxy (complex structures)
  – processing

So, useful where the high efficiency is valuable

# Markets: Space / Satellites

High cell efficiency means less weight and smaller size: critical for space applications!

GaInP/GaAs/Ge cell is now the preferred cell for most space applications



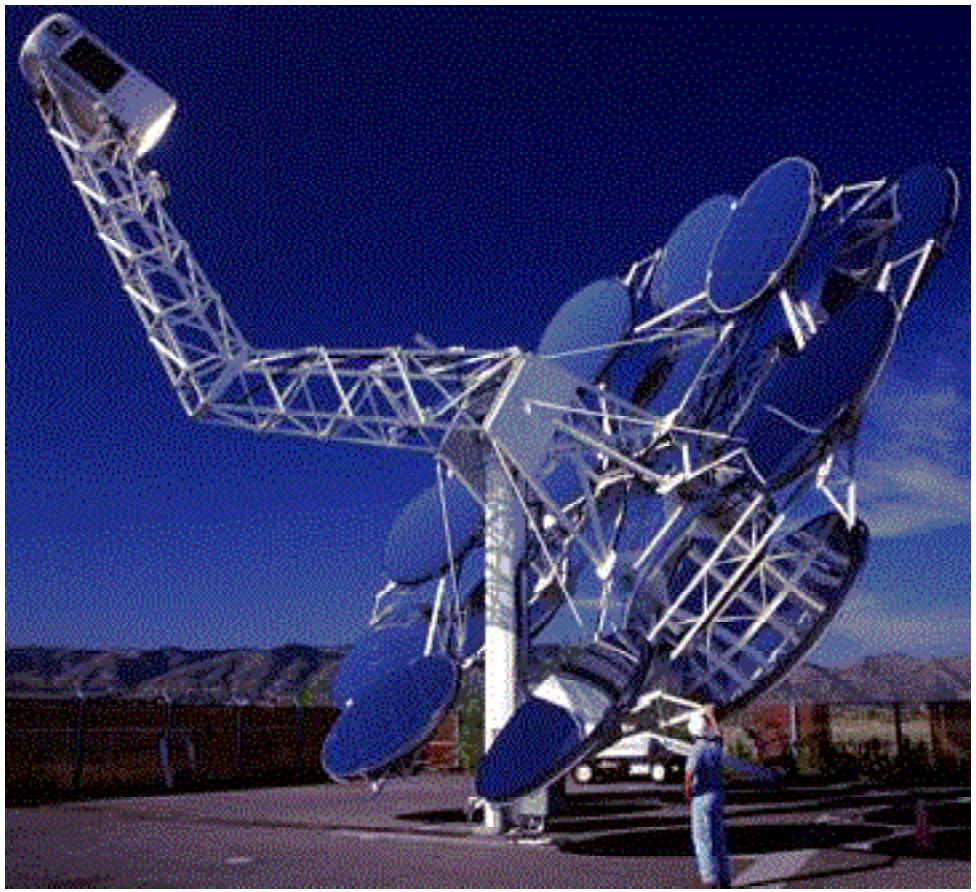

Yearly roduction rate (in the US) is
~300–800 kW/year (~$100–200 million/year)

Production capacity is ~1 MW/year
...might seem like a small number...

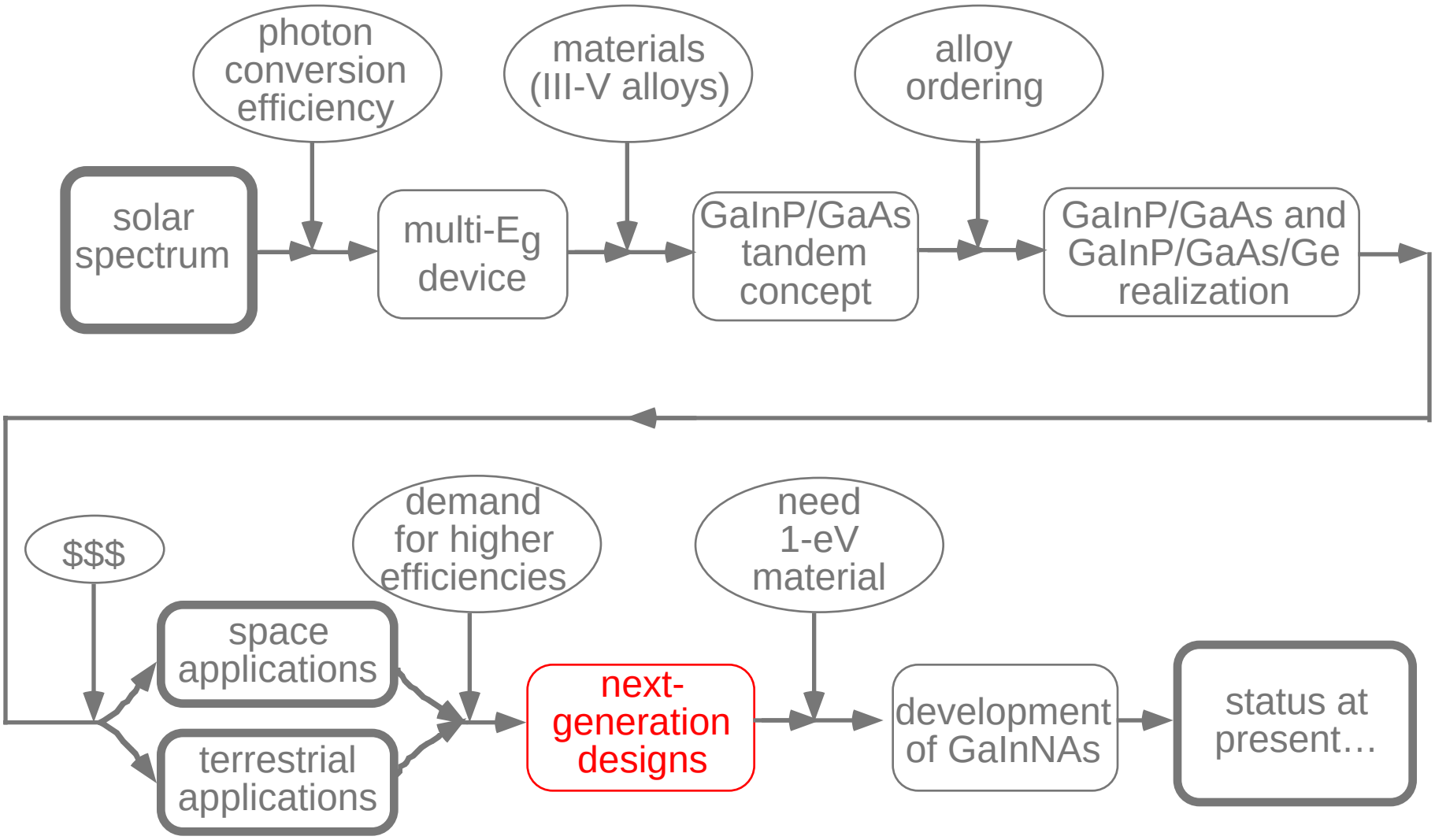
# Terrestrial Applications: Concentrators

Small, efficient, expensive cell + large cheap concentrating optics (lens or mirror)

$\Rightarrow$ potential economic viability for terrestrial applications (in its infancy)



Remember the ~1 MW/yr production capacity?
At 1000x concentration, it corresponds to ~1 GW!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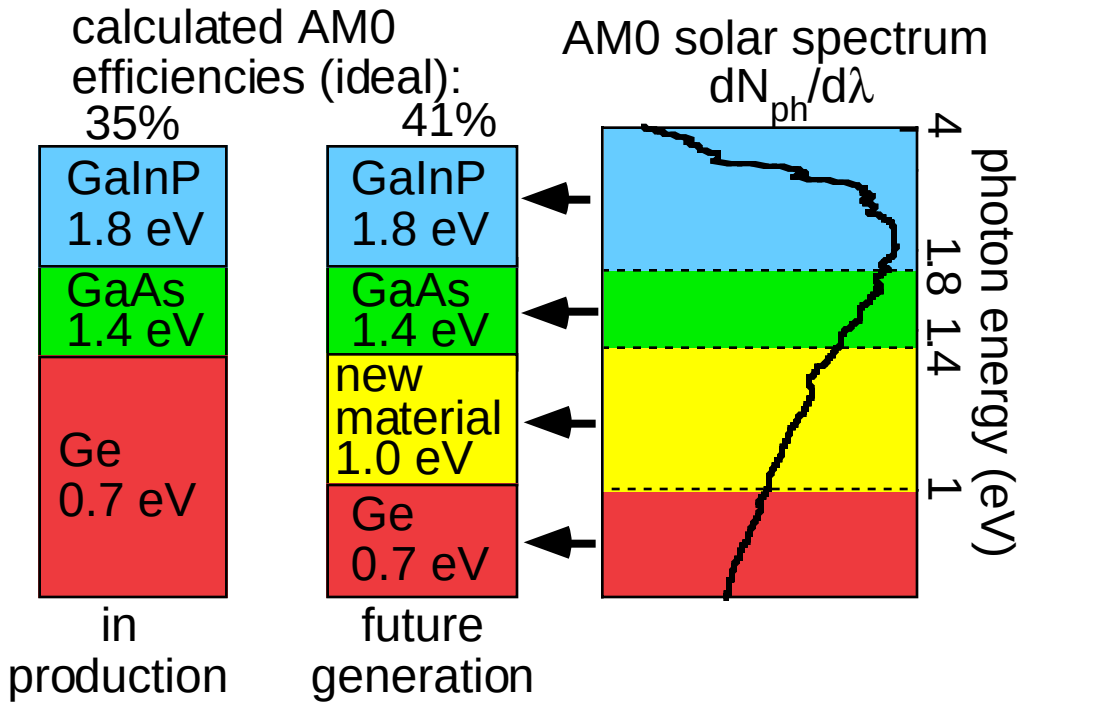
# Next-Generation III-V Solar Cells

Add a fourth junction

Need new material:

- 1 eV
- lattice-matched to GaAs / Ge

- also, good opto-electronic properties

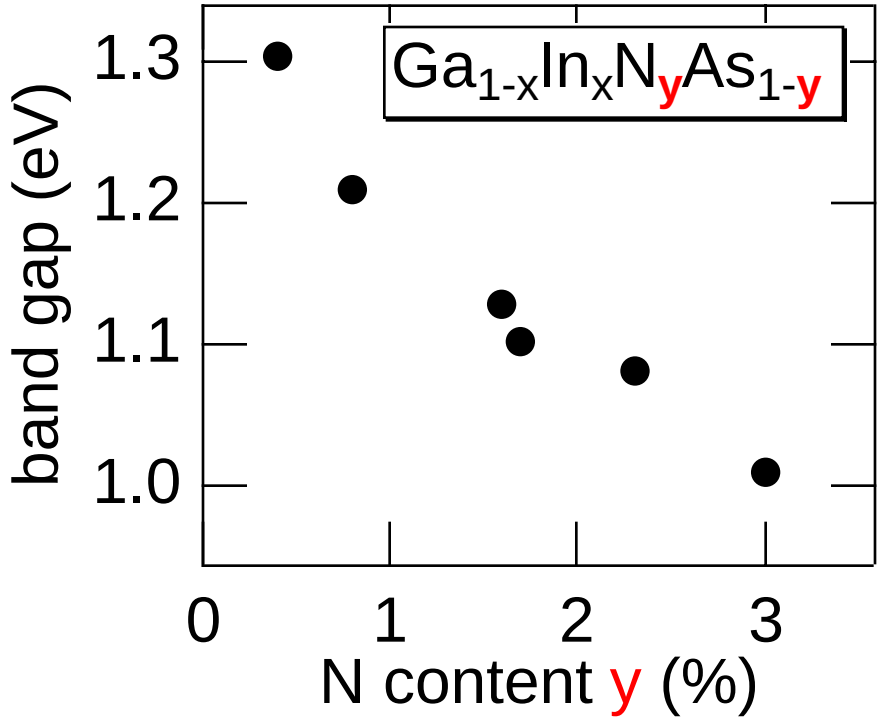


# GaInNAs for 1-eV Junction

Want
- 1-eV band gap
- lattice-matched to GaAs  (for materials quality)

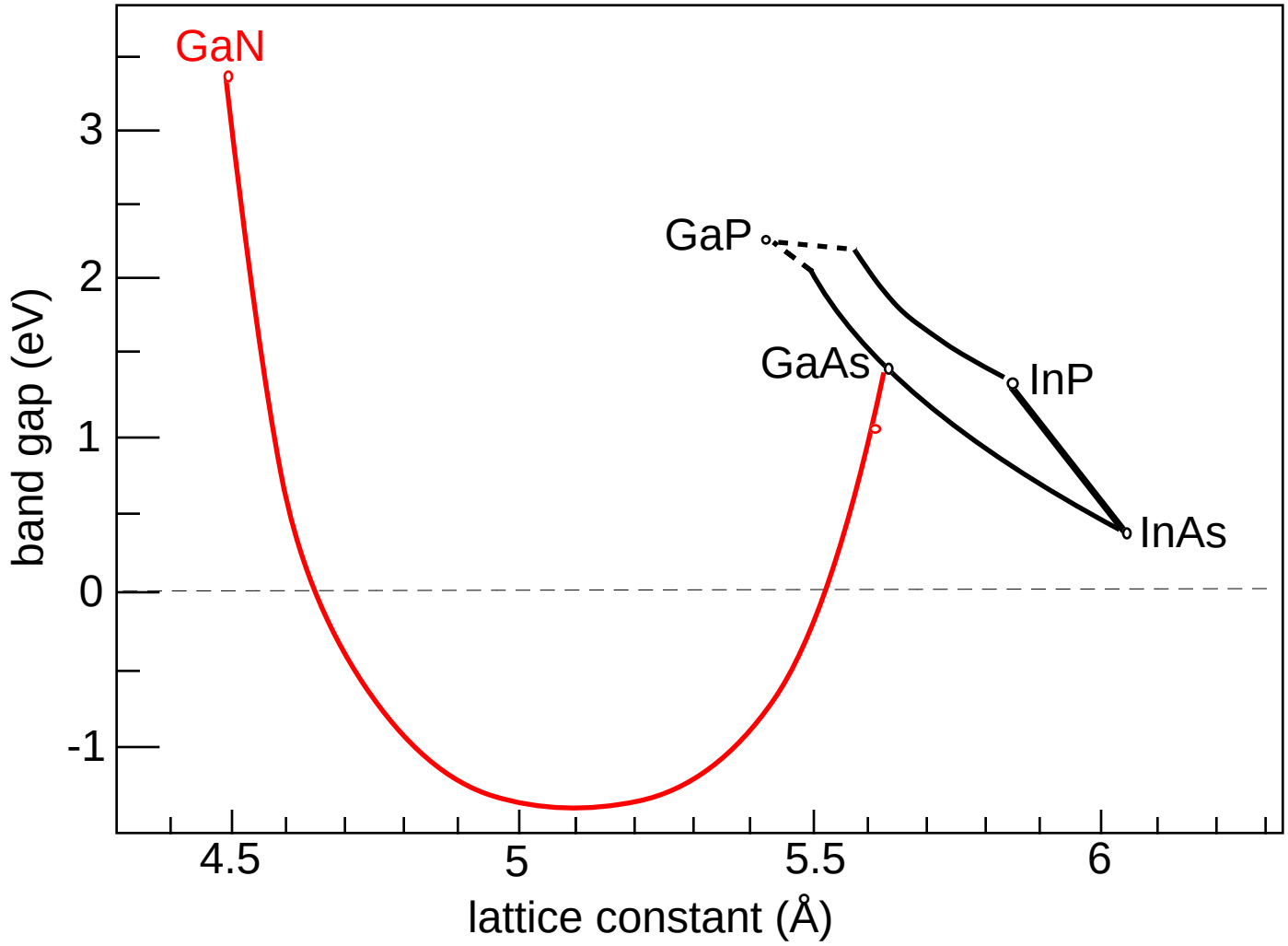
Kondow noted that $Ga_{1-x}In_xN_yAs_{1-y}$ satisfies these criteria (with $x \approx 3y$ and $y \approx 3\%$)

Lots of interest for lasers




For us: obvious candidate for 1-eV junction

# Adding N to the GaInAsP Materials System

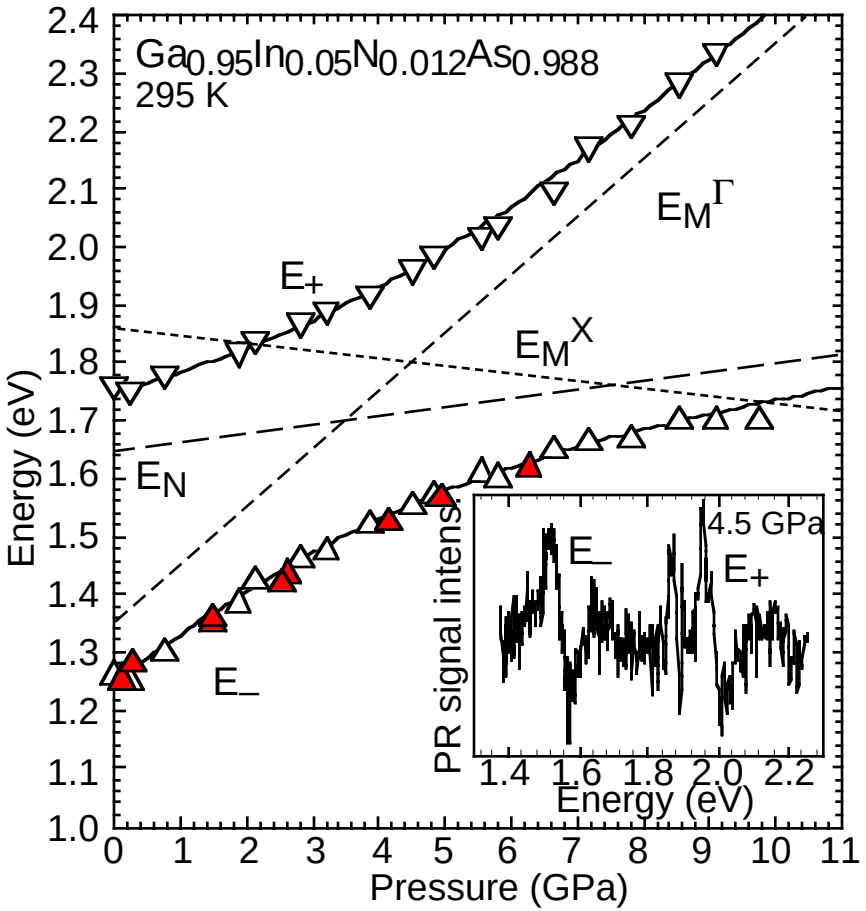


# GaInNAs Electronic Structure: N level

Interaction between conduction band and narrow resonant N-derived state

from: Walukiewicz et al, LBL, Phys. Rev. Lett. **82**, 1221 (1999)

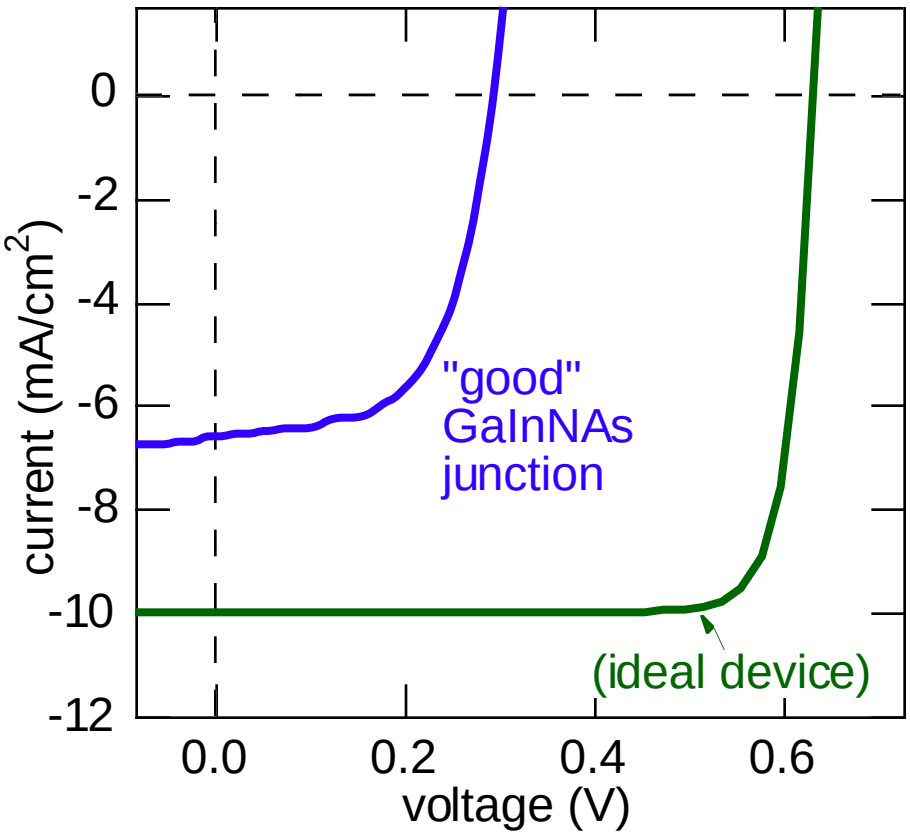
- $E_M$ is energy of GaInAs CB edge
- $E_N$ is energy of N level
- $E_M$ and $E_N$ interact to give observed $E_-$ and $E_+$



# GaInNAs - the Bad News

GaInNAs diffusion lengths are very small
... so why do we care?...

- interesting semiconductor physics question
- need longer diffusion lengths for the solar cell



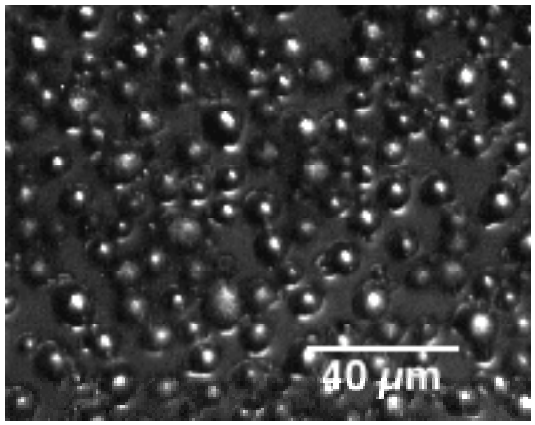
# Possible Causes for Low Diffusion Length

| | |
|---|---|
| Structural? | don't see anything in TEM |
| Impurity? | have tried purifying source, but not conclusive |
| Native defect? | experimental and theoretical evidence for N interstitials |
| electronic structure? | band fluctuations due to GaN clustering? |

# Present Status

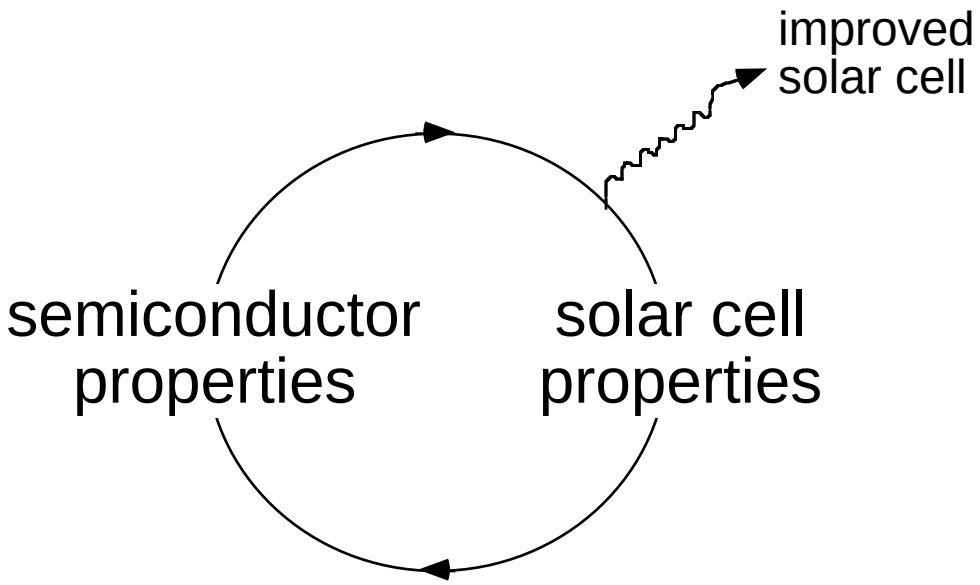
- Studying poor minority-carrier properties of GaInNAs

- Other 1-eV materials?
  e.g. have tried GaTlP… that one made GaInNAs look good!




result of attempting to grow GaTlP

# Summary


improved
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semiconductor
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