GaInAs 4th Junction for Next-Generation Lattice-Mismatched Multijunction Solar Cells

D.J. Friedman, J.F. Geisz, A.G. Norman, M. Wanlass, and S.R. Kurtz

National Renewable Energy Laboratory

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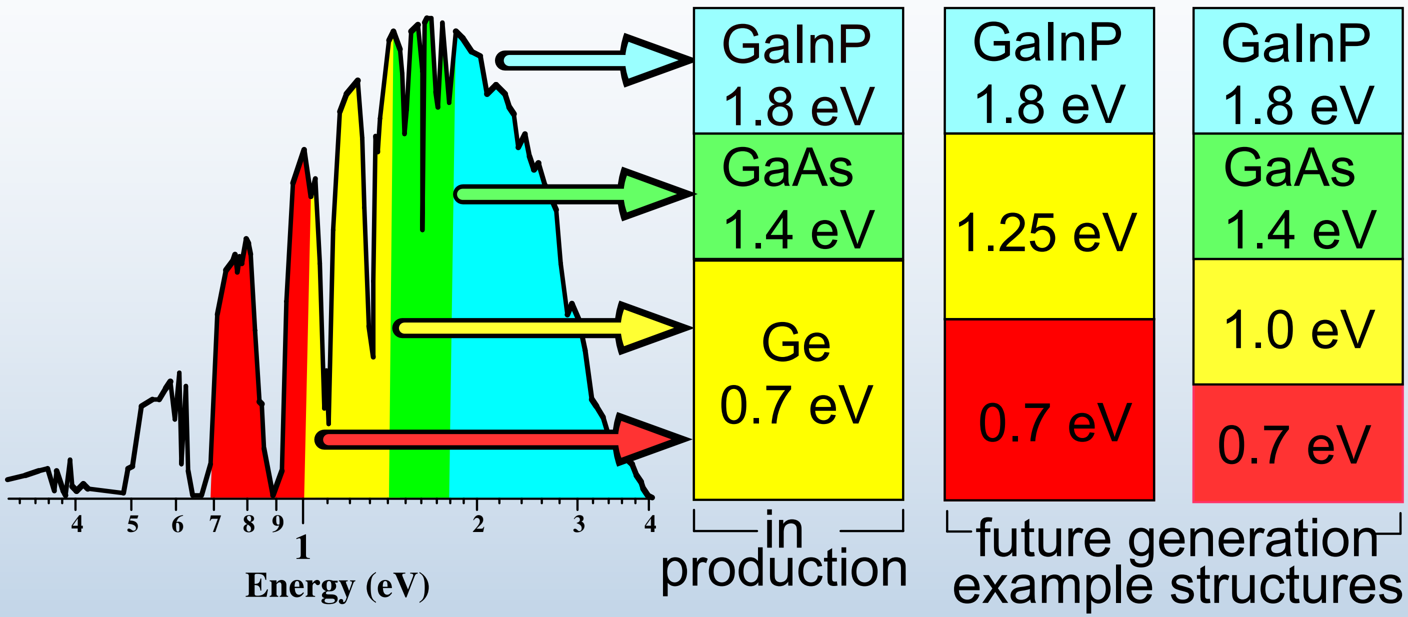
The Fine Print

Evolution of Multijunction Devices

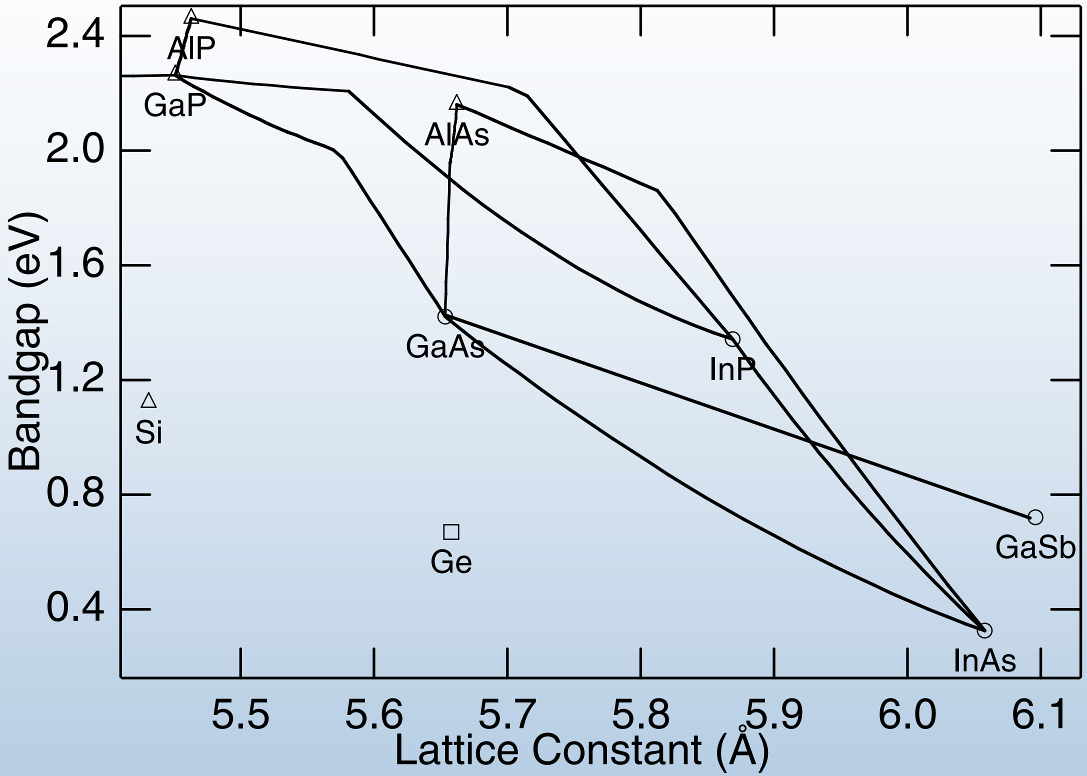


- Need to make better use of spectrum, esp. in 0.7–1.4 eV range
- How to do this…?

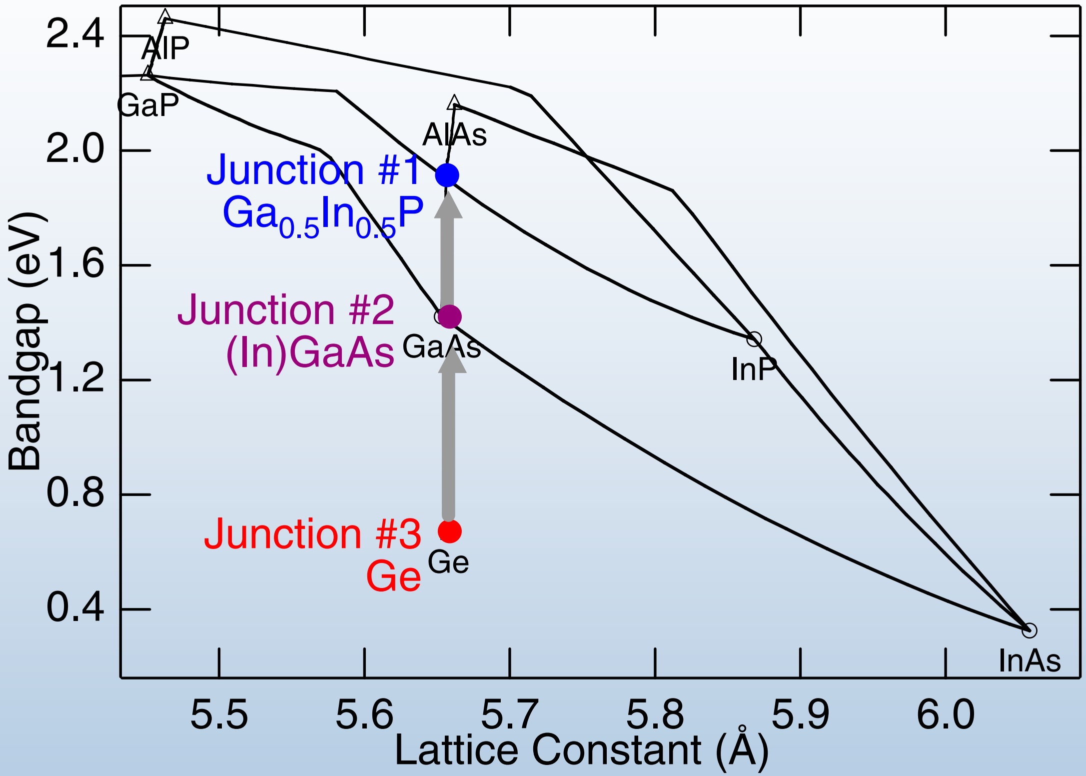
Outline

- Approaches to next-generation high efficiencies: survey of the field
- The inverted mismatched 3-junction cell
- Adding a 4th junction
- Fabrication and testing of 4th junction
- How low a bandgap do we really need?
- Outlook

Our Palette: the III-V Alloys



Lattice-Matched to Ge (and GaAs)



Device structure:

Junction #1

Junction #2

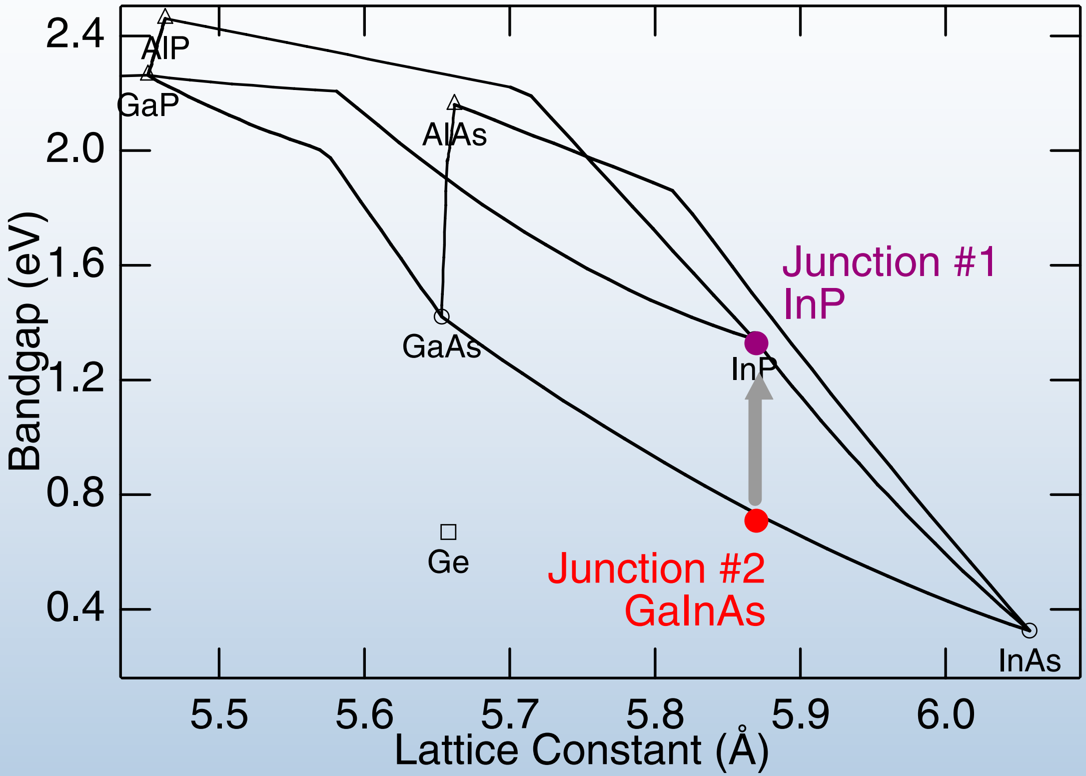
Junction #3

39%@236x by Spectrolab[1]

[1] King et al, 20th Eur.Solar Energy Conf. 2005 p.118

- The "standard" 3-junction device structure
  - Lattice-matched: easy to grow good material… but
  - Restricts available bandgap range

Lattice-Matched to InP



Device structure:

Junction #1
Junction #2

31.8% @ 50x (three-terminal) by NREL[1]

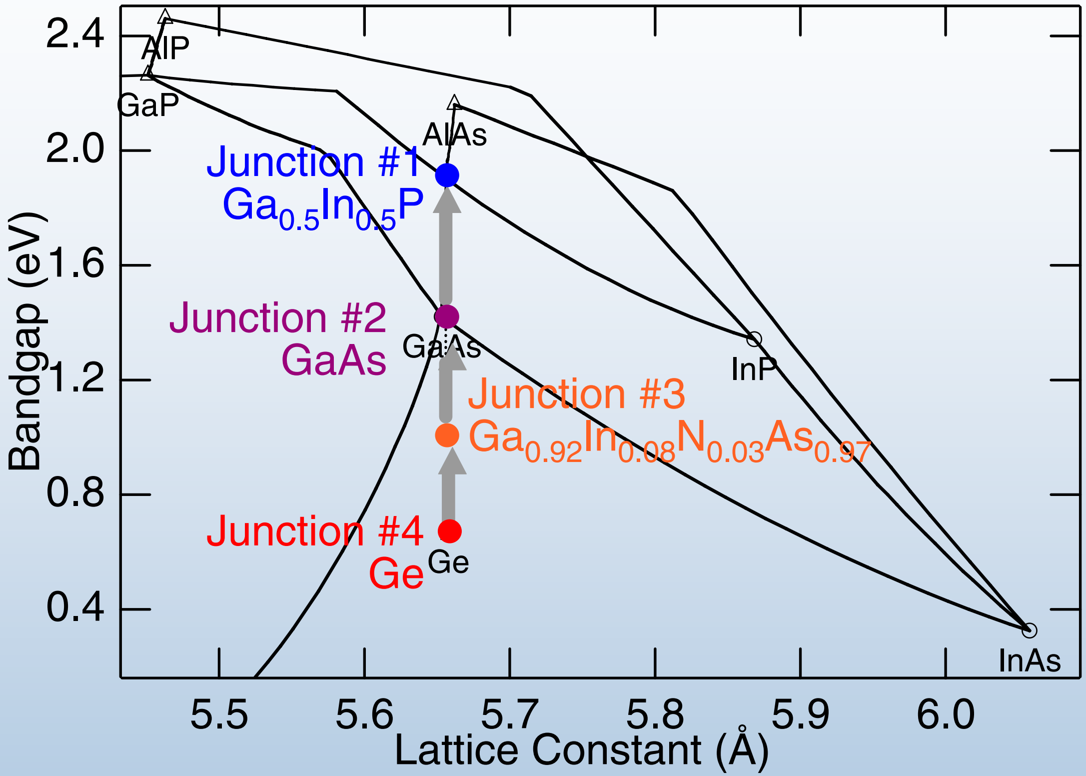
[1] Wanlass et al, 21st PVSC, 1990, p.38

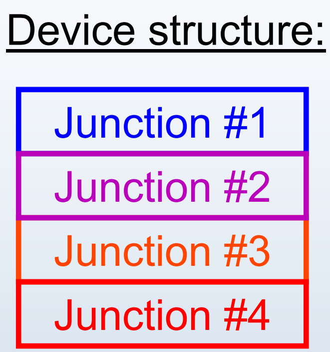
- Another example - lattice matching to InP

Expanding our Range of Bandgap Options

- New materials lattice-matched to GaAs: e.g. GaInNAs
  - Need good PV materials
- Junctions grown separately, then stacked
  - Mechanical stacking
  - Wafer bonding
- Lattice-mismatched epitaxy

New Semiconductor: GaInNAs





[1] Ptak et al, 31st PVSC 2005, p. 603

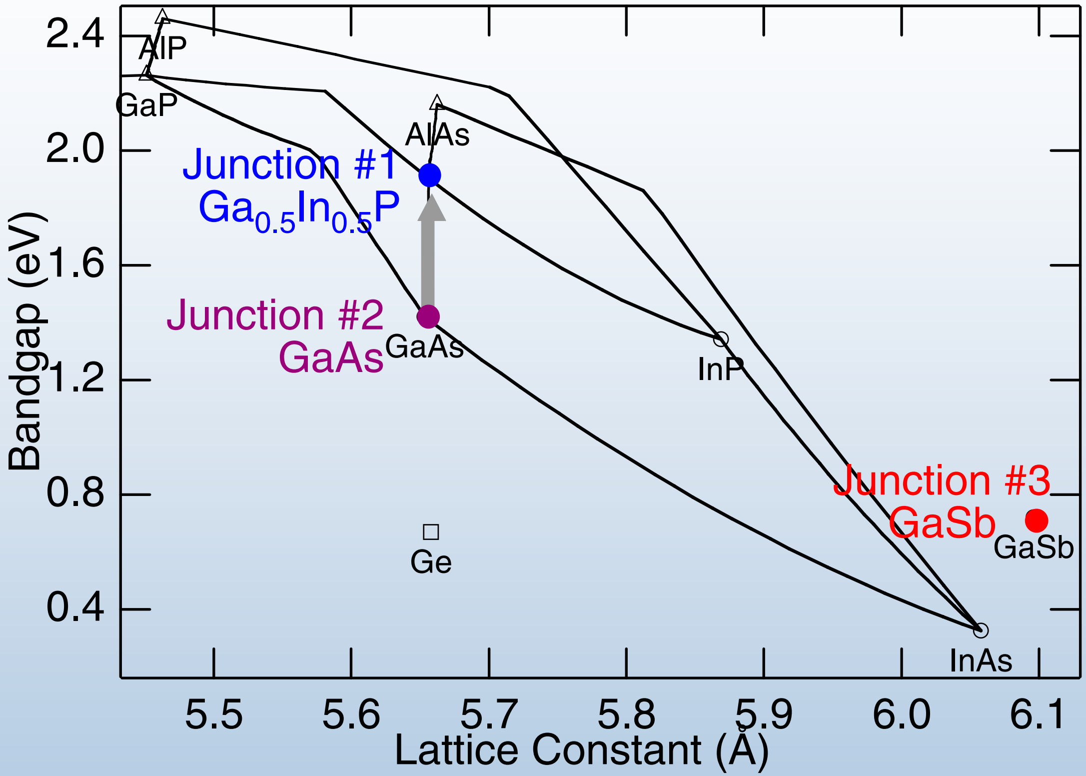
[2] Jackrel et al, this meeting

[3] Meusel et al, 19th Eur.PVSEC 2004 p.3587

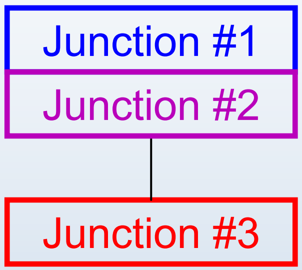
[4] King et al, 19th Eur.PVSEC 2004 p.3581

- GaInNAs: lattice-matched, desired bandgap…
- But: short diffusion lengths >> poor device performance
- MBE may help growth[1,2]
- 5- or 6-junction structures may work around problems[3,4]

Mechanically Stacked Junctions



Device structure:

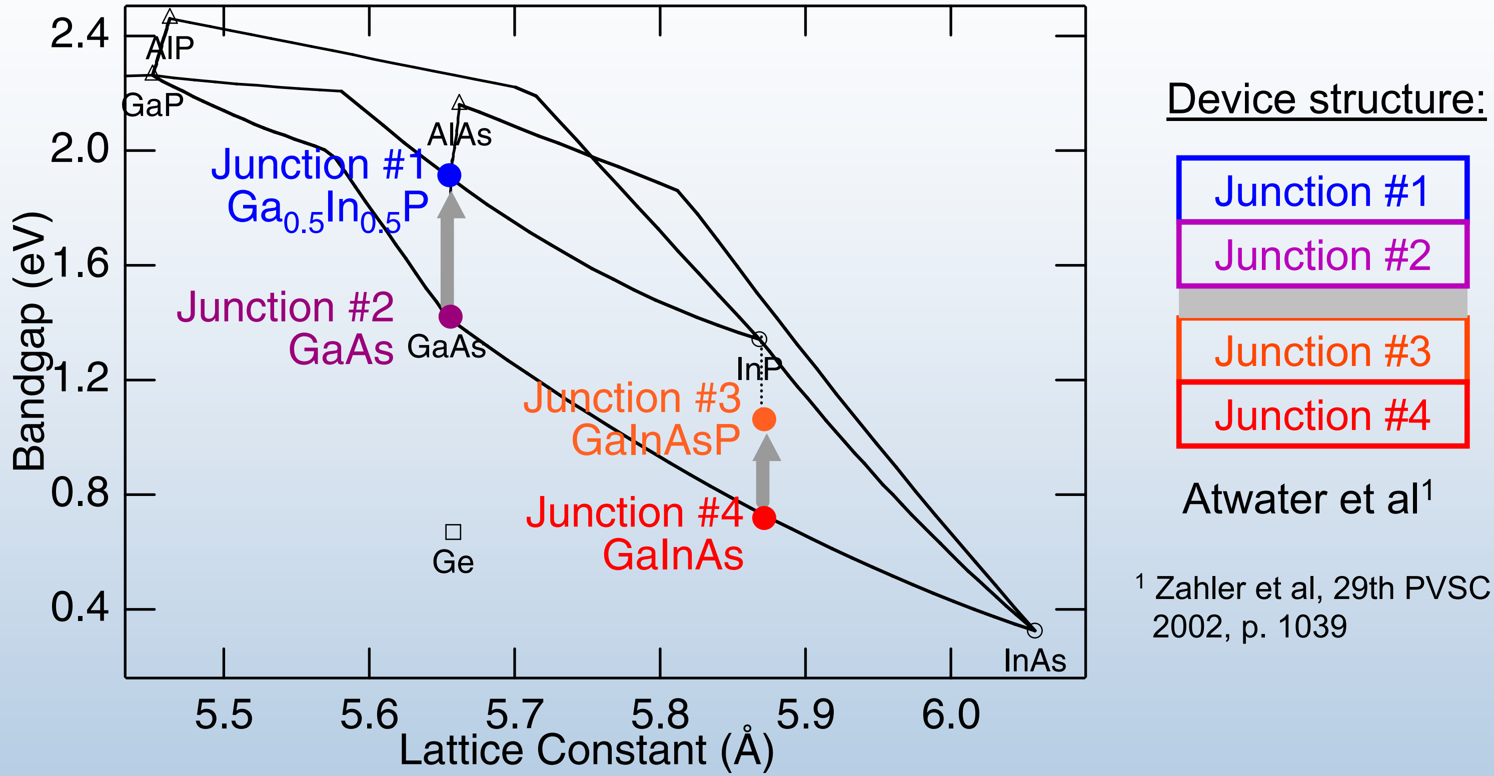


Fraas,[1,2]
Fraunhofer ISE
(33.5%@308x)[3]

- Extremely wide range of materials/bandgaps accessible: high efficiencies; e.g. 32.6% for GaAs/GaSb back in 1990[1]
- Not a single chip; multiple growths required

[1] Fraas et al, 21st PVSC 1990, p. 190
[2] Fraas et al, 31st PVSC 2005, p. 751
[3] Bett et al, 17th Eur.Solar Energy Conf. 2001 p.84

Wafer-bonded Stacked Junctions

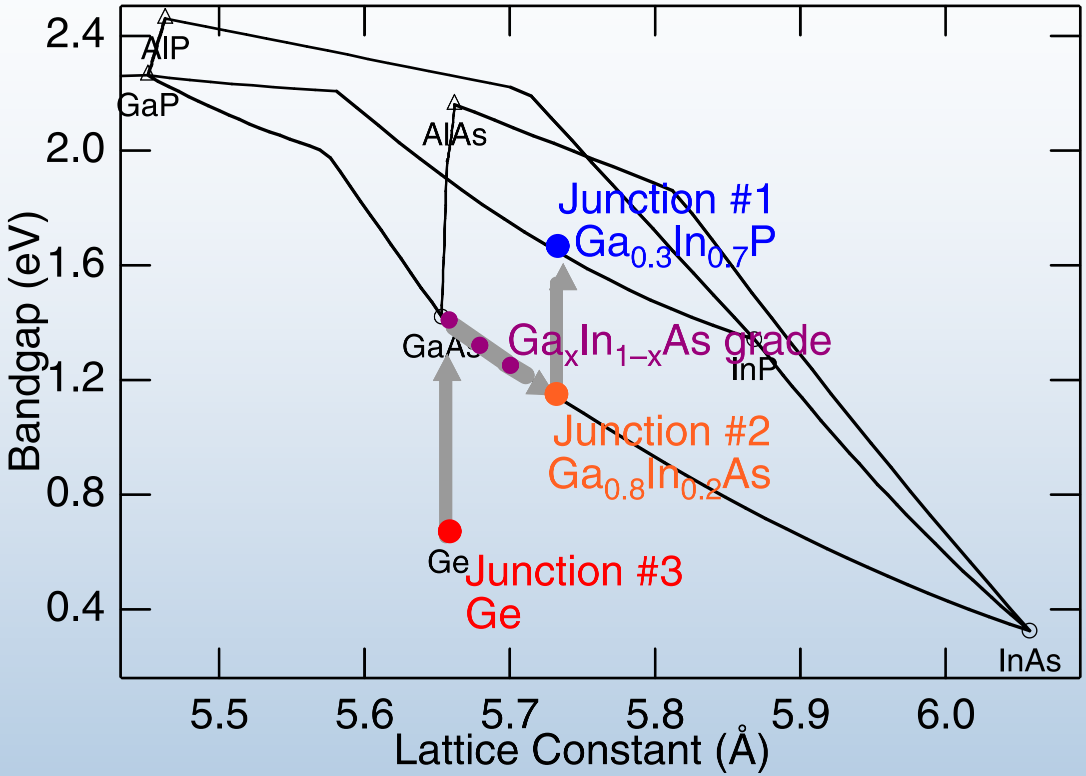


Atwater et al[1]

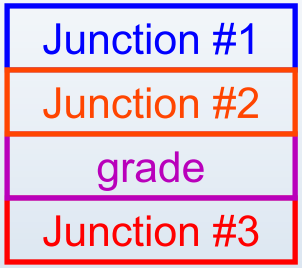
[1] Zahler et al, 29th PVSC 2002, p. 1039

- Wide range of materials/bandgaps accessible
- single chip / III-V integration with Si
- Multiple growths required; requires transparent conductive bond

Lattice-mismatched ("metamorphic") 3J



Device structure:



Spectrolab[1], Fraunhofer ISE[2] EMCore[3]

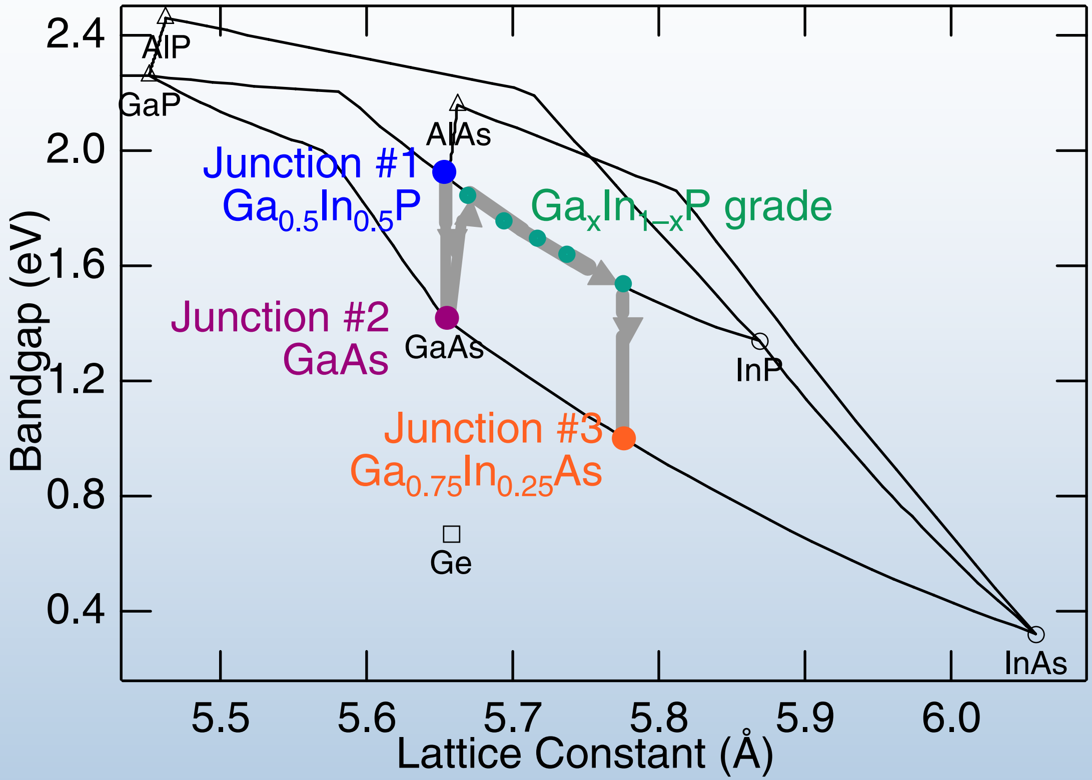
[1] Law et al, 31st PVSC, 2005, p.575

[2] Dimroth et al, Prog. Photovolt. **9**, 2005, p.165

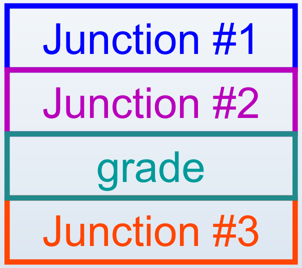
[3] Stan et al, 31st PVSC, 2005, p. 770

- Promising approach, competitive with lattice-matched
- Challenge is to maintain materials quality of junctions grown after grade

<u>Inverted</u> Lattice-Mismatched Structure



Device structure:

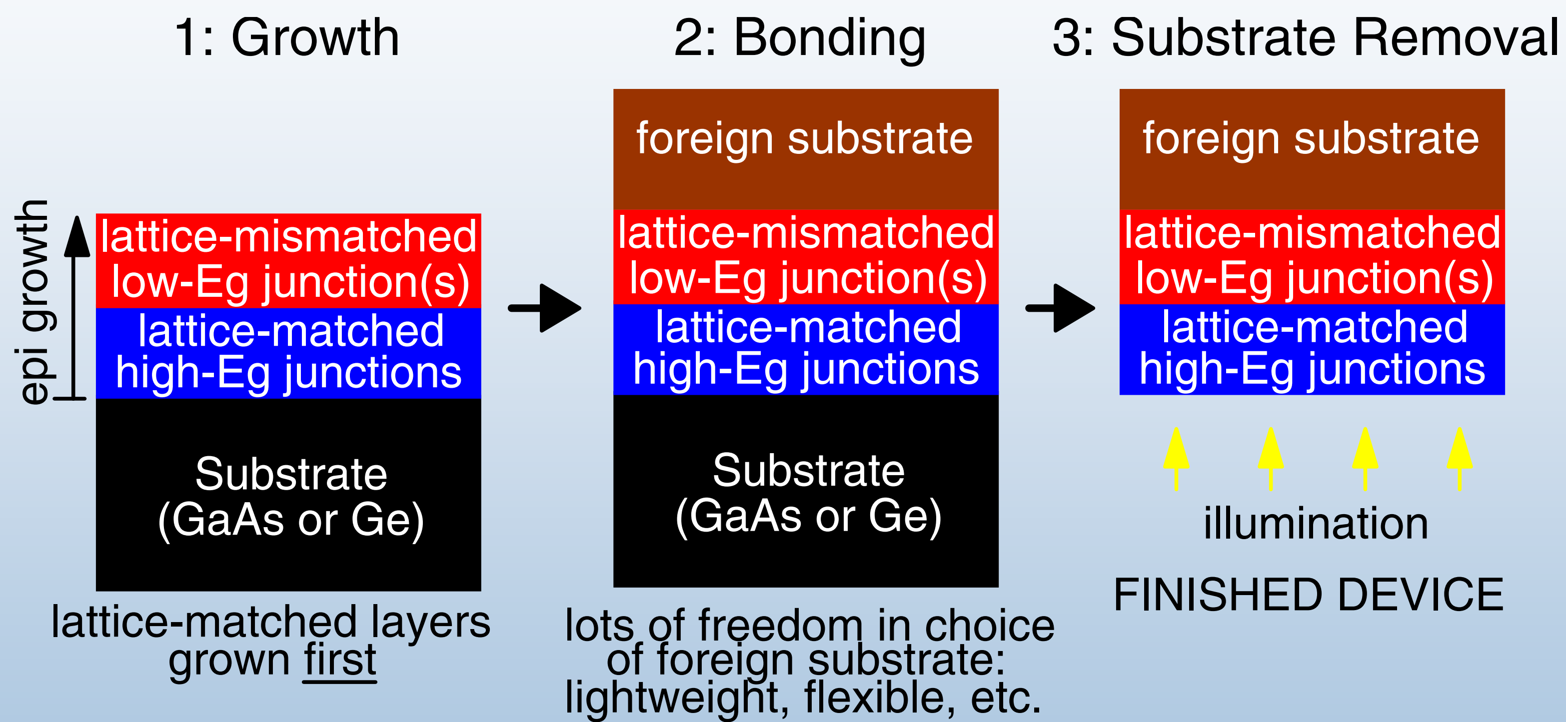


Wanlass et al[1,2]

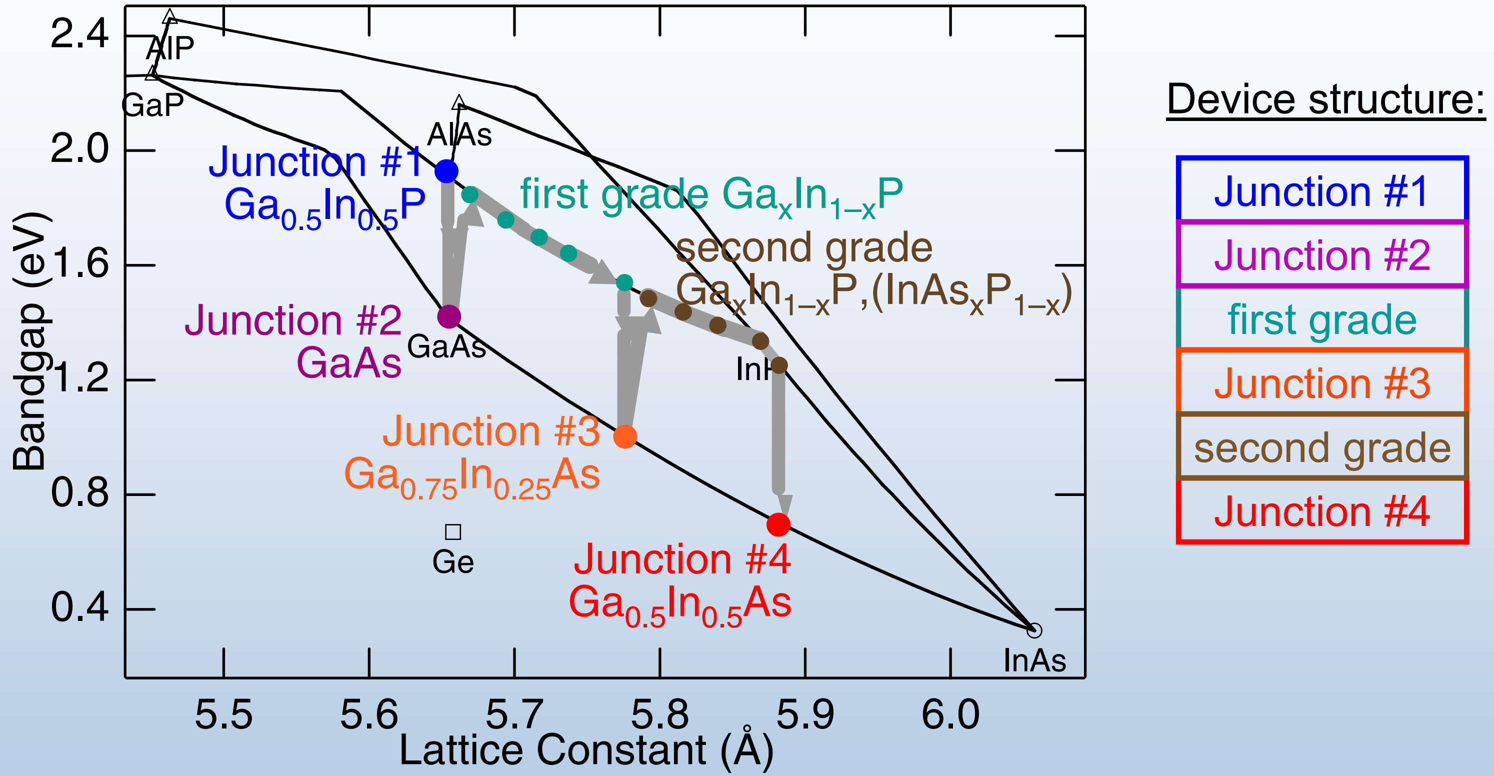
[1] Wanlass et al, 31st PVSC 2005, p. 530
[2] Wanlass et al,this meeting
[3] Schultz et al, 21st PVSC 1990, p. 148

- Only the bottom junction is grown mismatched
  - Similar philosophy to Varian GaInP/GaAs/substrate/GaInAs design[3]
- Potential for very high efficiencies (38% achieved w.o. optimization)
- Some complexities but also opportunities in the processing…

Processing of Inverted Structure



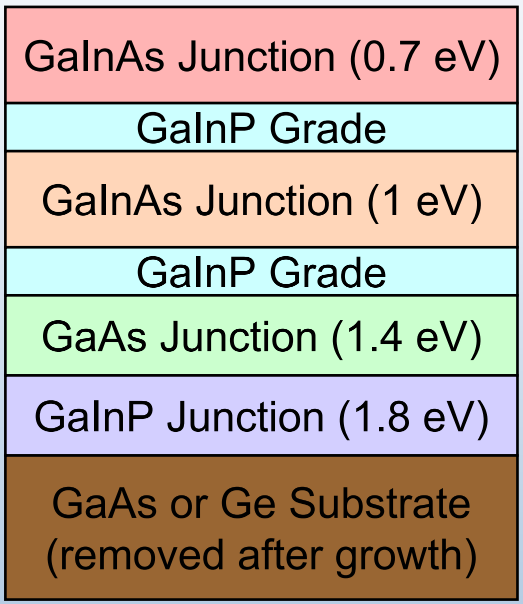
Inverted LMM: Adding a 4th Junction



- Extend advantages of inverted 3-junction structure to higher efficiencies
- But: how far can we grade? How far do we need to grade?

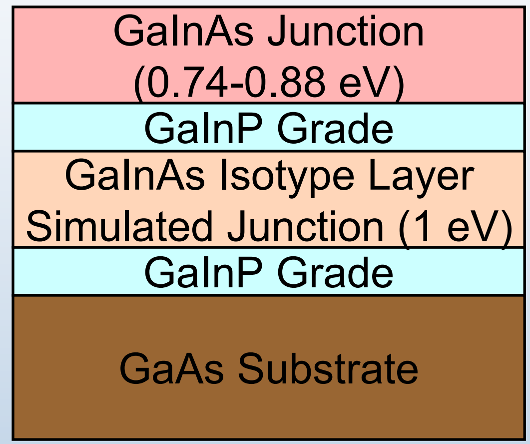
4th Junction: Test Structure

Inverted 4 Junction Design:



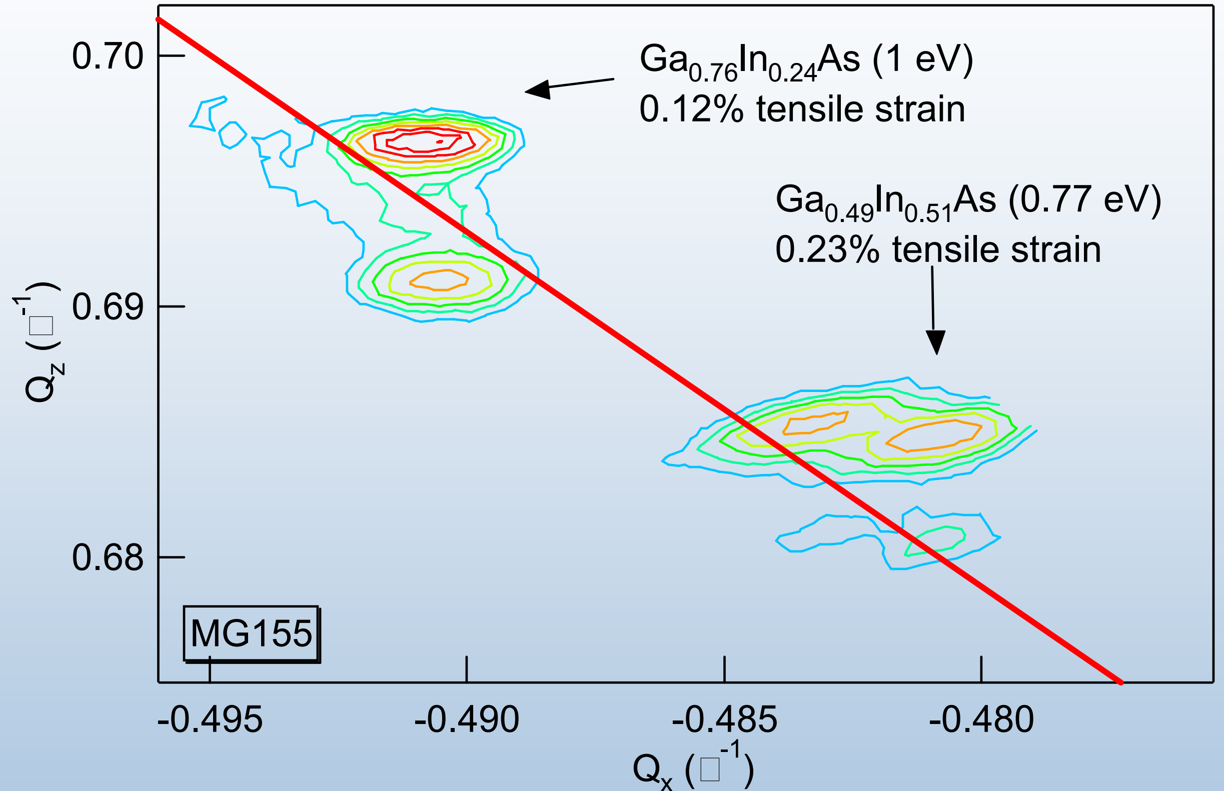
not to scale

4th Junction Test Structure:



- Accounts for effect of lattice-mismatched growth
- Bypasses complexities of growth and especially of measurement of the other three junctions
- Tried bandgaps from 0.88–0.74 eV

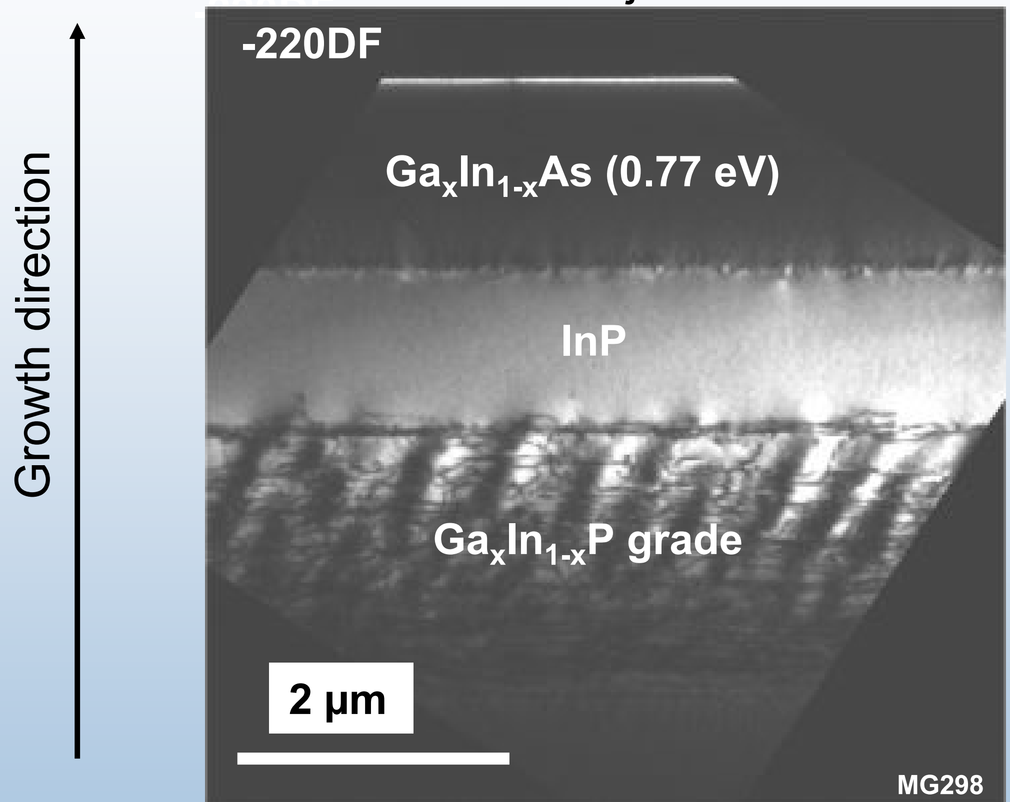
X-ray Characterization of Strained Layers



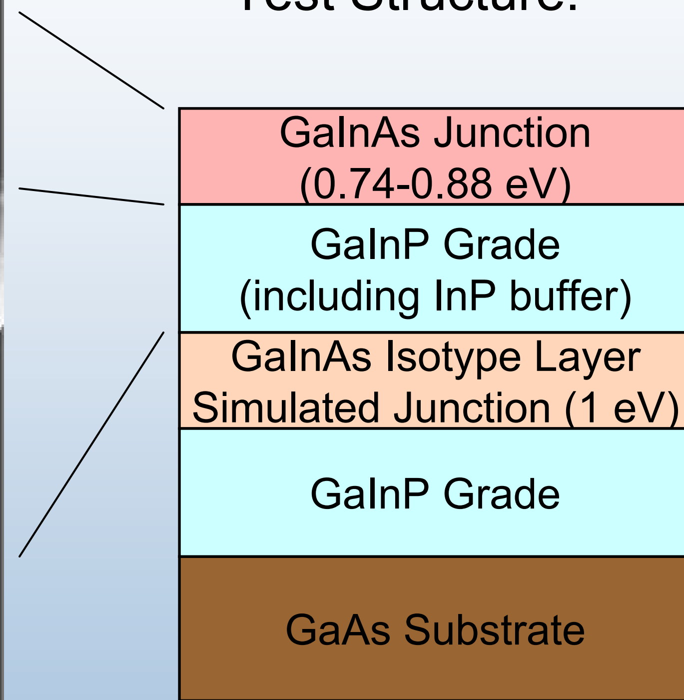
- XRD analysis critical to getting the compositions correct

TEM Characterization: 4th Junction

0.77 eV 4th junction



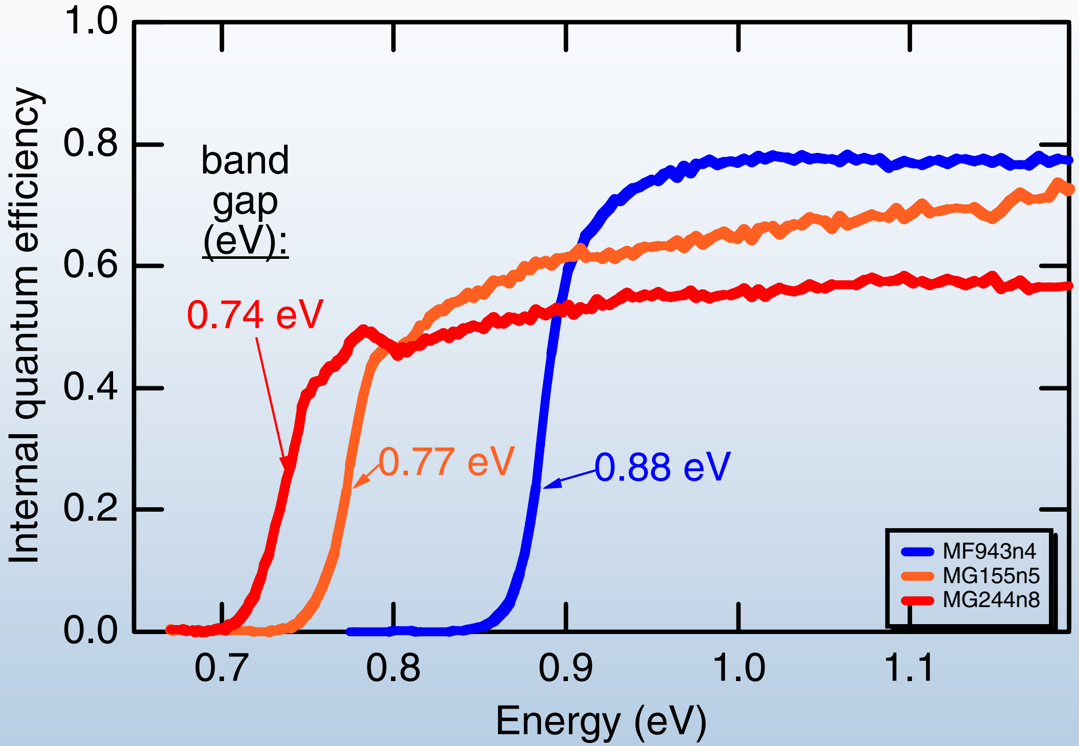
4th Junction Test Structure:



not to scale

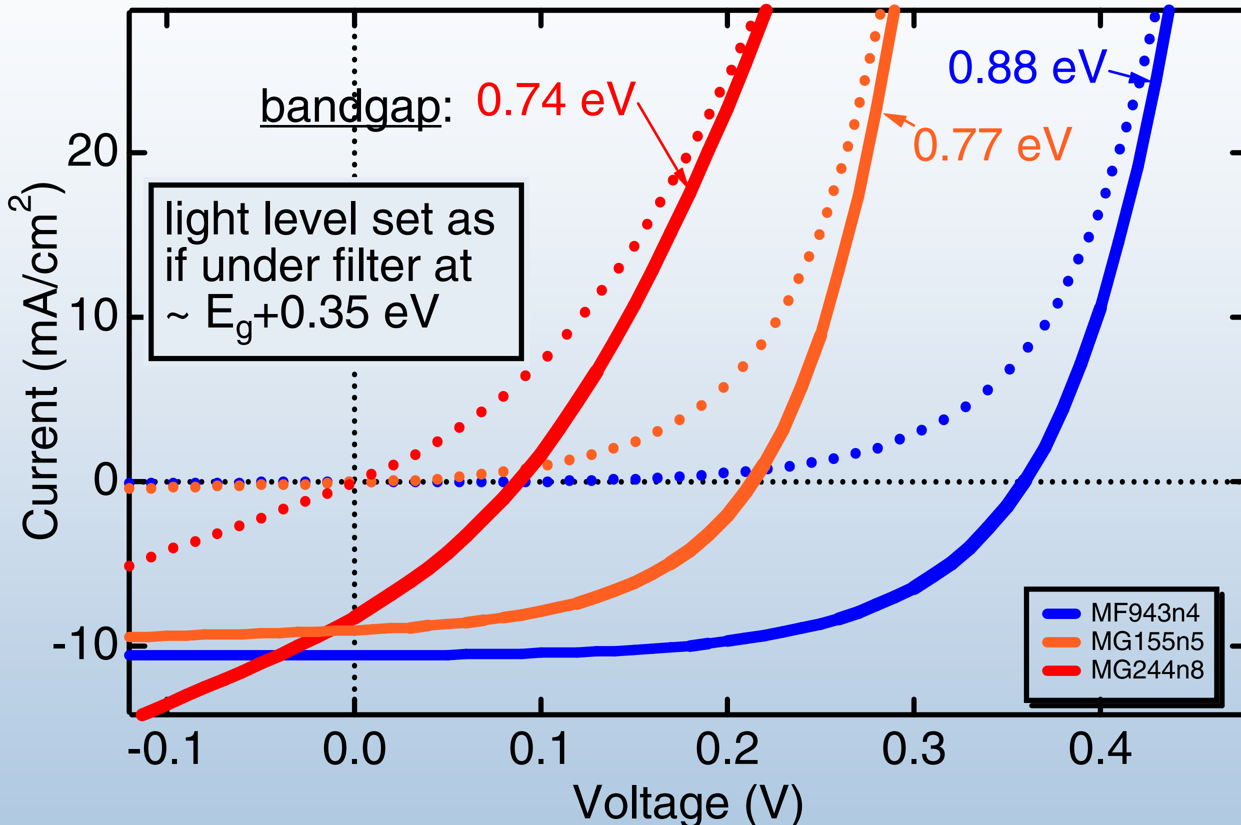
- Dislocations largely confined to grade

Quantum Efficiency



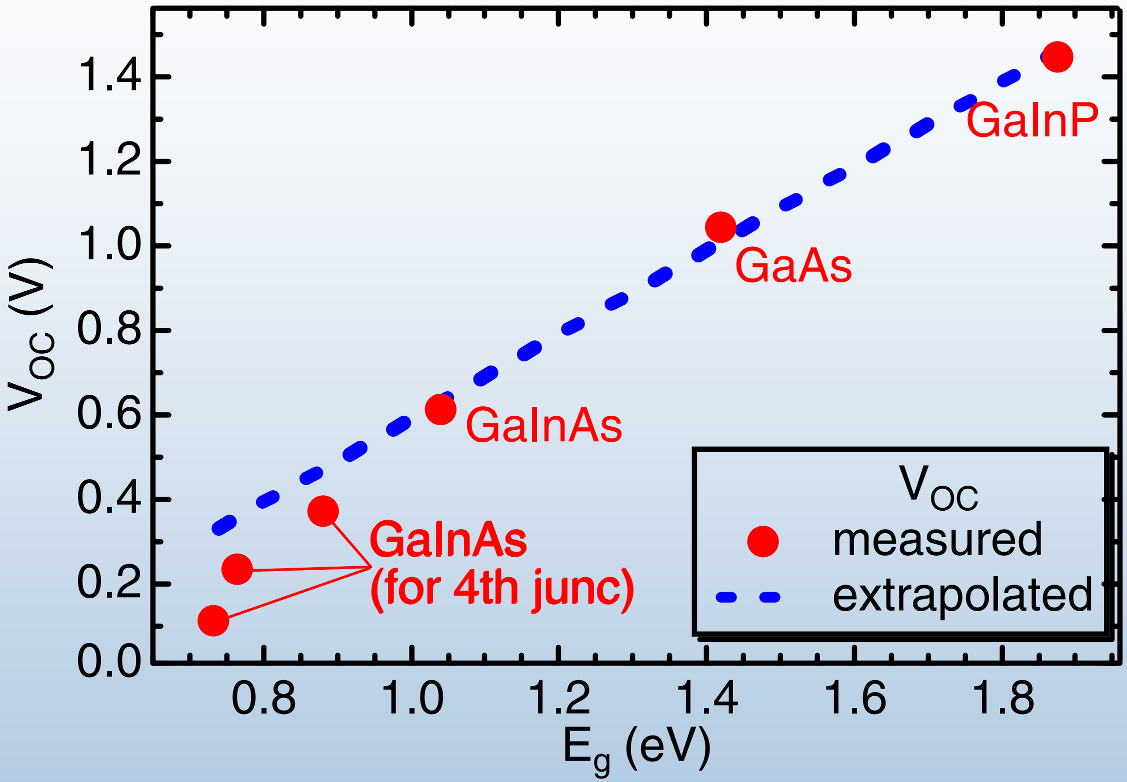
- QE degrades with increasing mismatch (decreasing Eg) (note -- still room for improvement in these devices)
- QE of 0.88 eV device approaches performance required (note -- QE achieved without significant depletion region)

Current-Voltage Characteristics



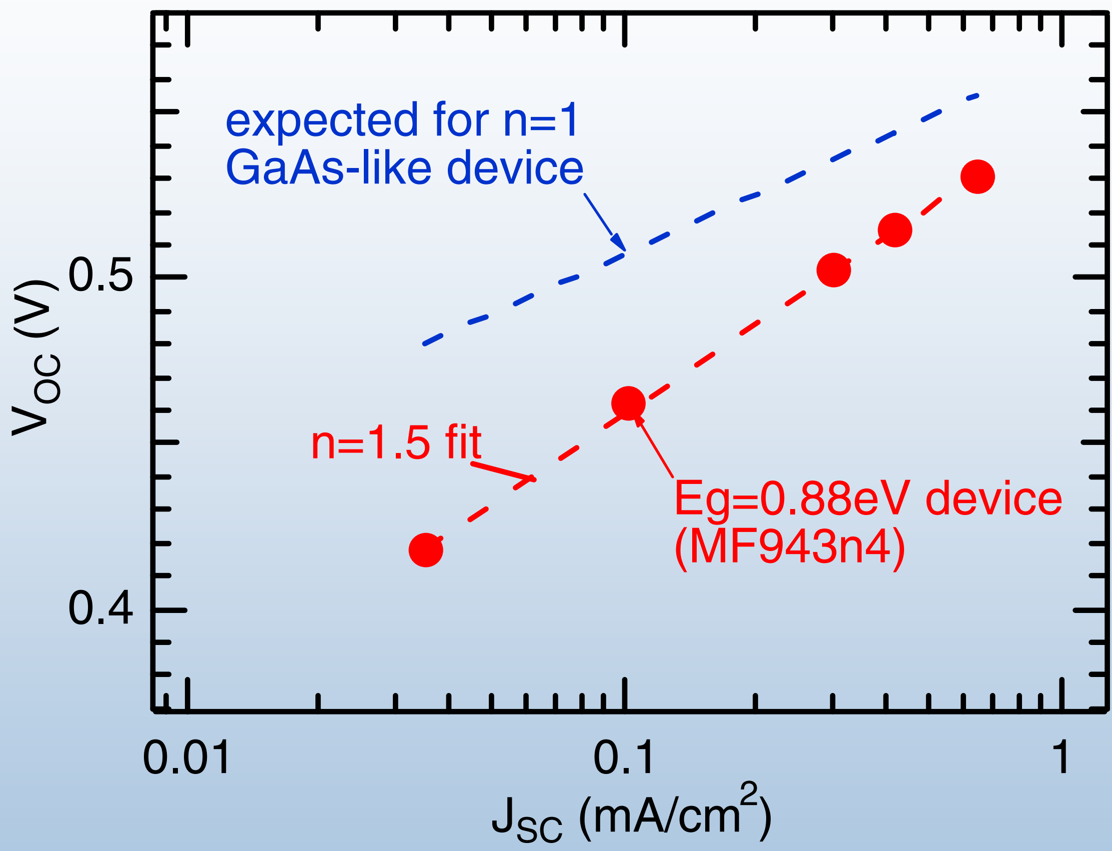
- Eg=0.74eV junction leaky, others good

Dependence of V_{OC} on Band Gap



- Lowest-Eg junction degraded
- Higher-Eg junctions better
  (and should get closer to GaAs-like with concentration)

Improvement of Voc with Concentration

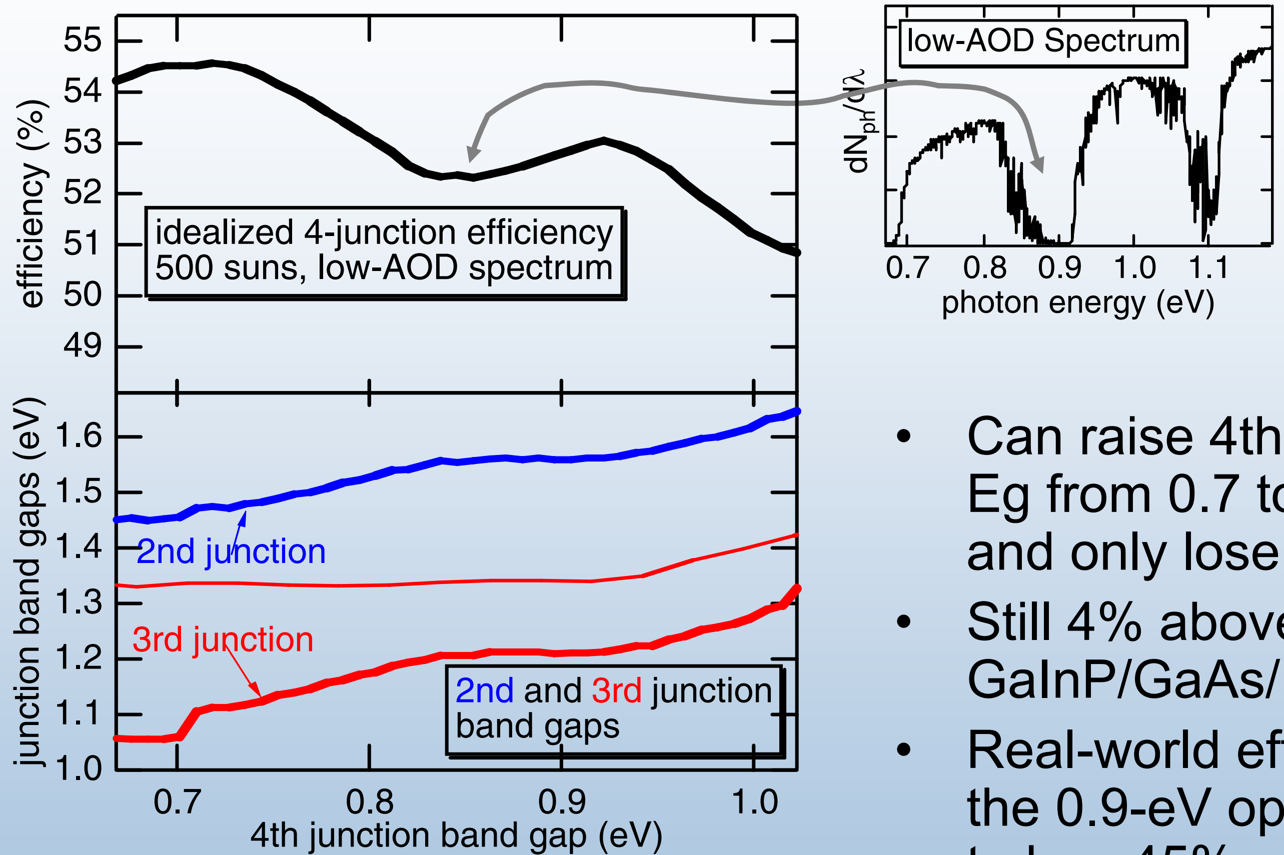


- Voc does get closer to GaAs-like with concentration, as expected

4th-Junction Eg - is 0.7 eV Necessary?

- Good devices increasingly challenging as band gap decreases (i.e.mismatch increases)
- Can we get away with a higher 4th junction band gap?

Allowing Band Gap to Vary



- Can raise 4th junction Eg from 0.7 to 0.9 eV and only lose 1.6% eff.
- Still 4% above GaInP/GaAs/1-eV 3j
- Real-world efficiency for the 0.9-eV option likely to be ~45%

Device with 4th Junction Eg=0.9 eV

Why consider this over the 0.7-eV option:

- High-quality 0.9-eV junction easier to make
- Efficiencies:
  - Only lose 1.6% efficiency compared to 0.7-eV option
  - Still 4% above the 1.85/1.41/1.0eV 3-junction efficiency
- Grade layers can be thinner:
  - Less time to grow
  - Less source material used
  - Less strain/wafer bowing

Concerns:

- 1.6 eV junction needed: can it be as good as GaAs?
- Tunnel junctions need to be demonstrated

Outlook

- A cornucopia of promising approaches to next-generation high efficiencies
  - may be places for more than one, in different cost-performance niches
- Inverted multijunction approach
  - Extending to 4 junctions likely to boost efficiencies by several %, to ~45%
  - 4-junction structure likely to use an 0.9-eV bottom junction

A Golden Age for Multijunctions!