



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

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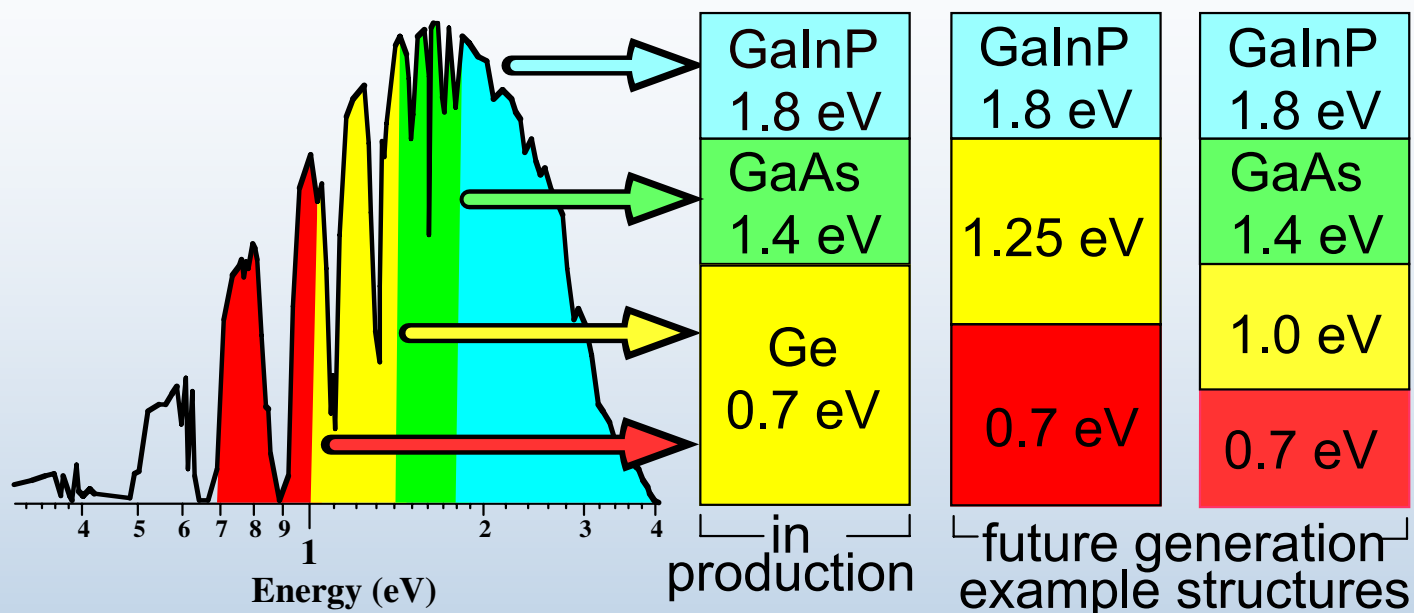
The Fine Print

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Evolution of Multijunction Devices

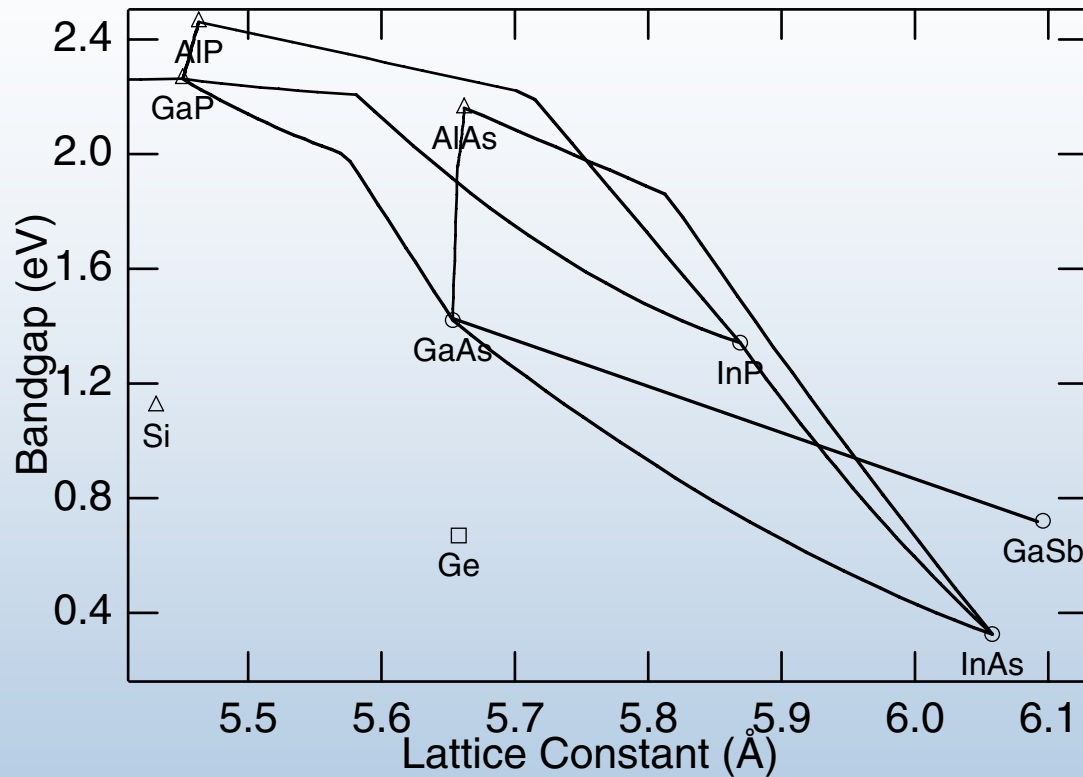


- Need to make better use of spectrum, esp. in 0.7–1.4 eV range
- How to do this...?

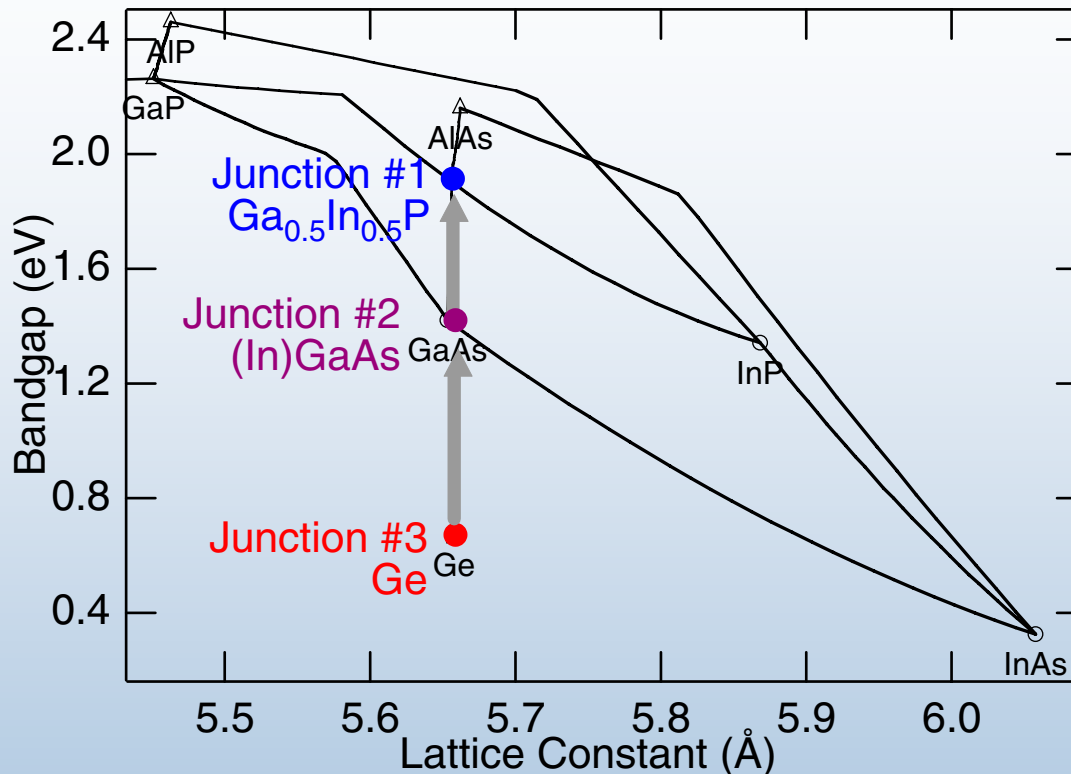
Outline

- 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:

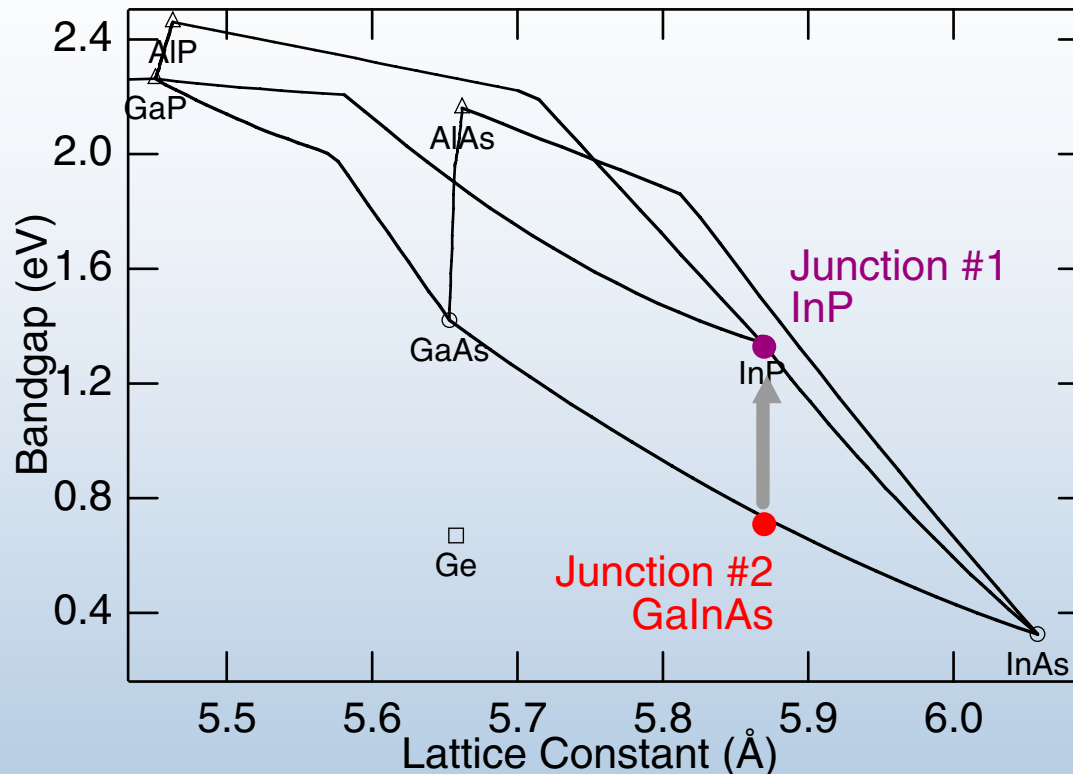


39%@236x by Spectrolab¹

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 NREL¹

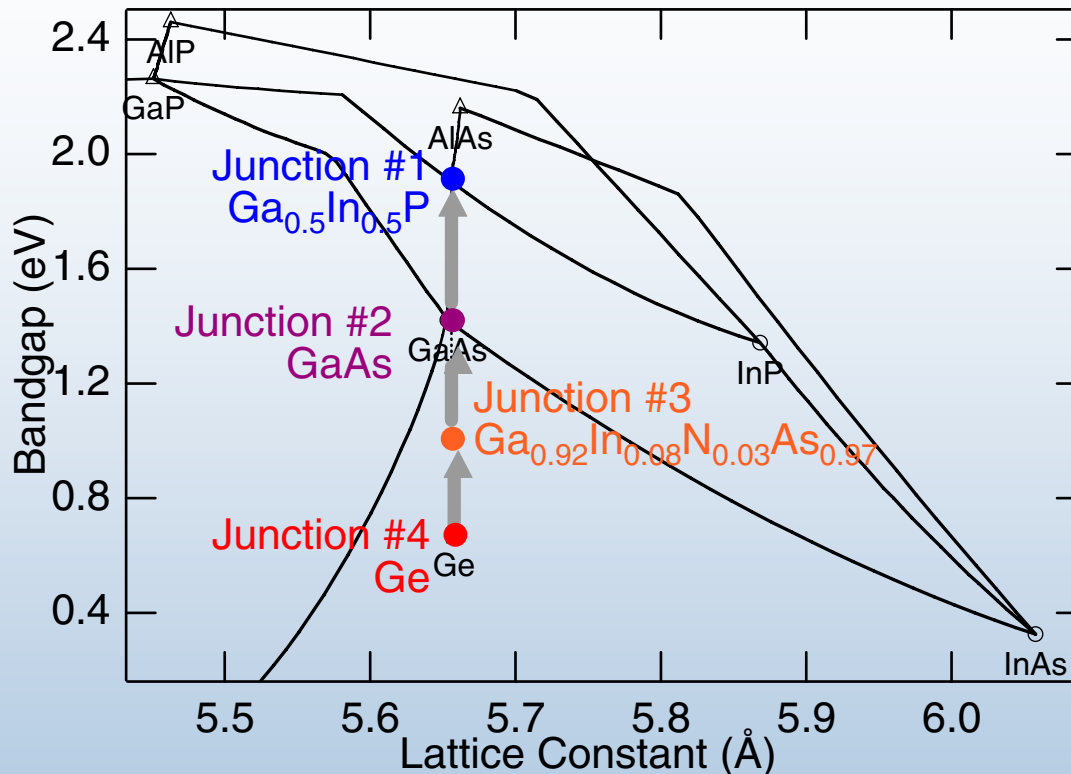
¹ Wanlass et al, 21st PVSC,
1990, p.38

- Another example - lattice matching to InP

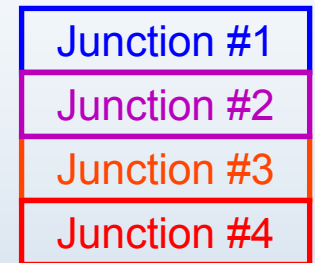
Expanding our Range of Bandgap Options

- 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



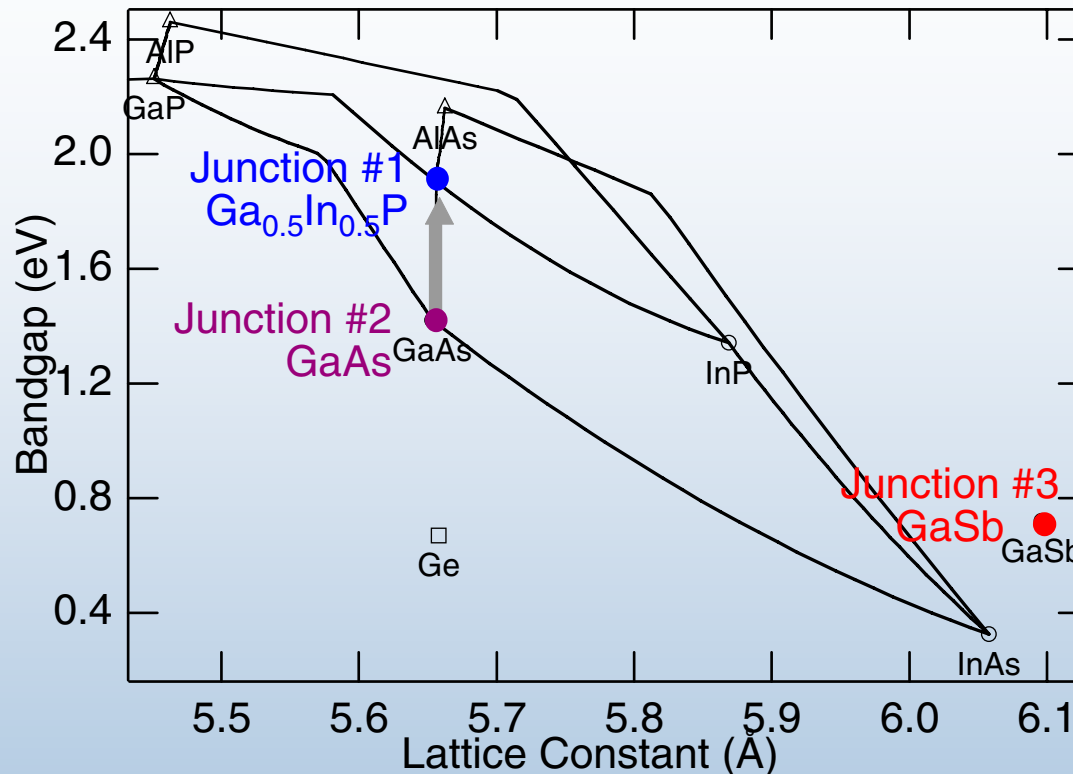
Device structure:



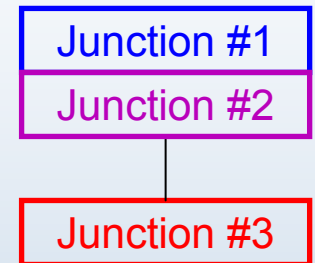
- ¹ Ptak et al, 31st PVSC 2005, p. 603
² Jackrel et al, this meeting
³ Meusel et al, 19th Eur.PVSEC 2004 p.3587
⁴ King et al, 19th Eur.PVSEC 2004 p.3581

- 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

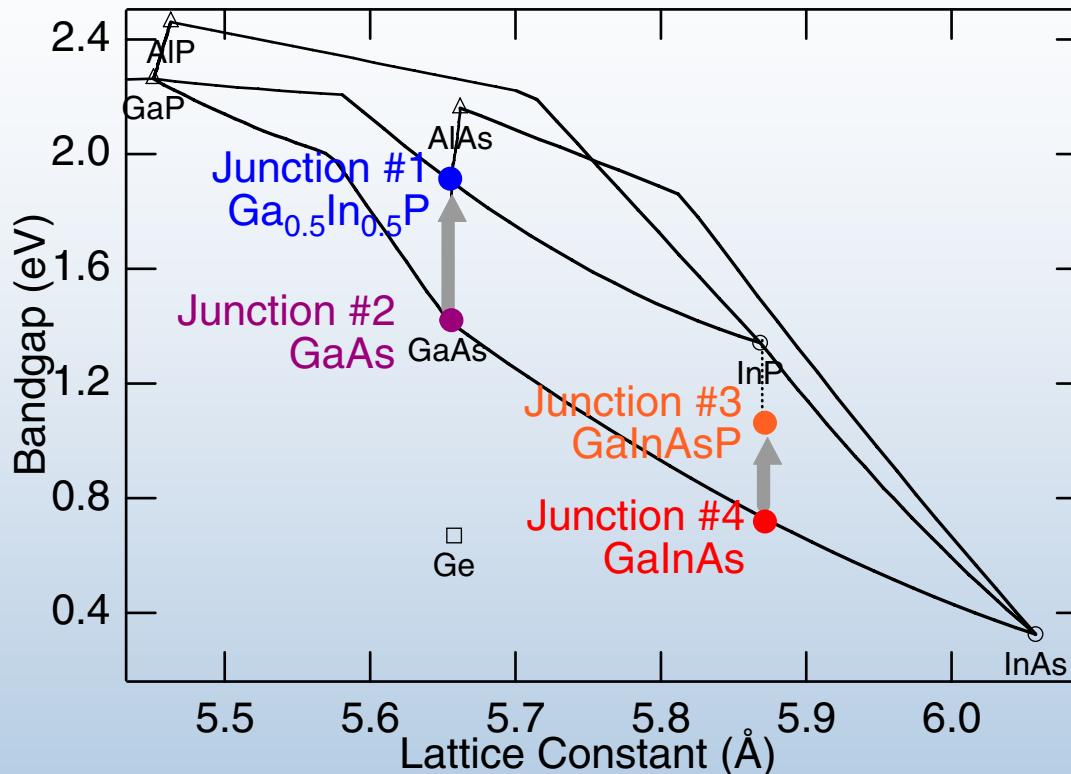
- Extremely wide range of materials/bandgaps accessible: high efficiencies; e.g. 32.6% for GaAs/GaSb back in 1990¹
- Not a single chip; multiple growths required

¹ Fraas et al, 21st PVSC 1990, p. 190

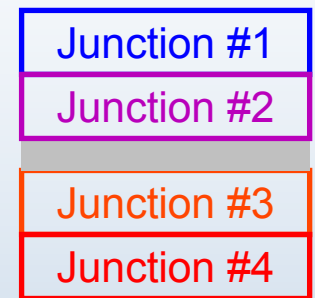
² Fraas et al, 31st PVSC 2005, p. 751

³ Bett et al, 17th Eur.Solar Energy Conf. 2001 p.84

Wafer-bonded Stacked Junctions



Device structure:

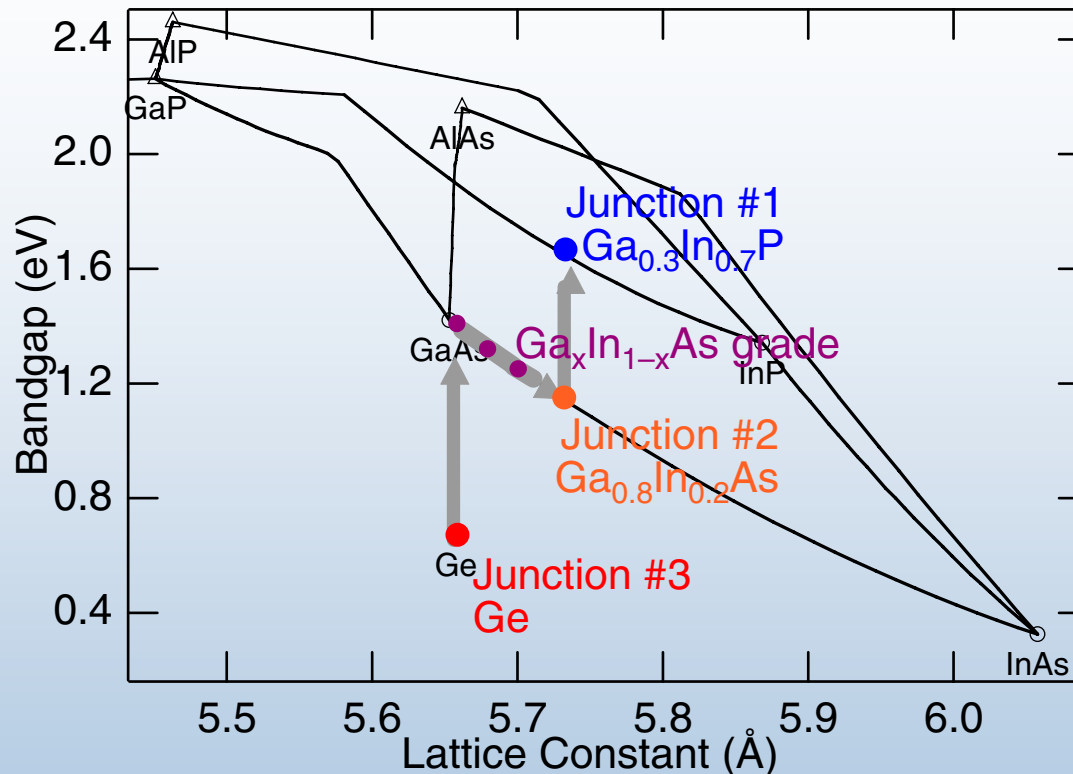


Atwater et al¹

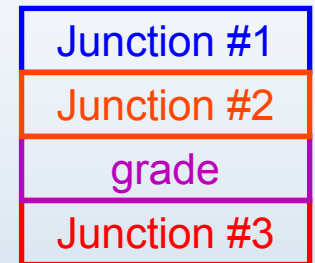
¹ Zahler et al, 29th PVSC 2002, p. 1039

- 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:



Spectrolab¹,
Fraunhofer ISE²
EMCore³

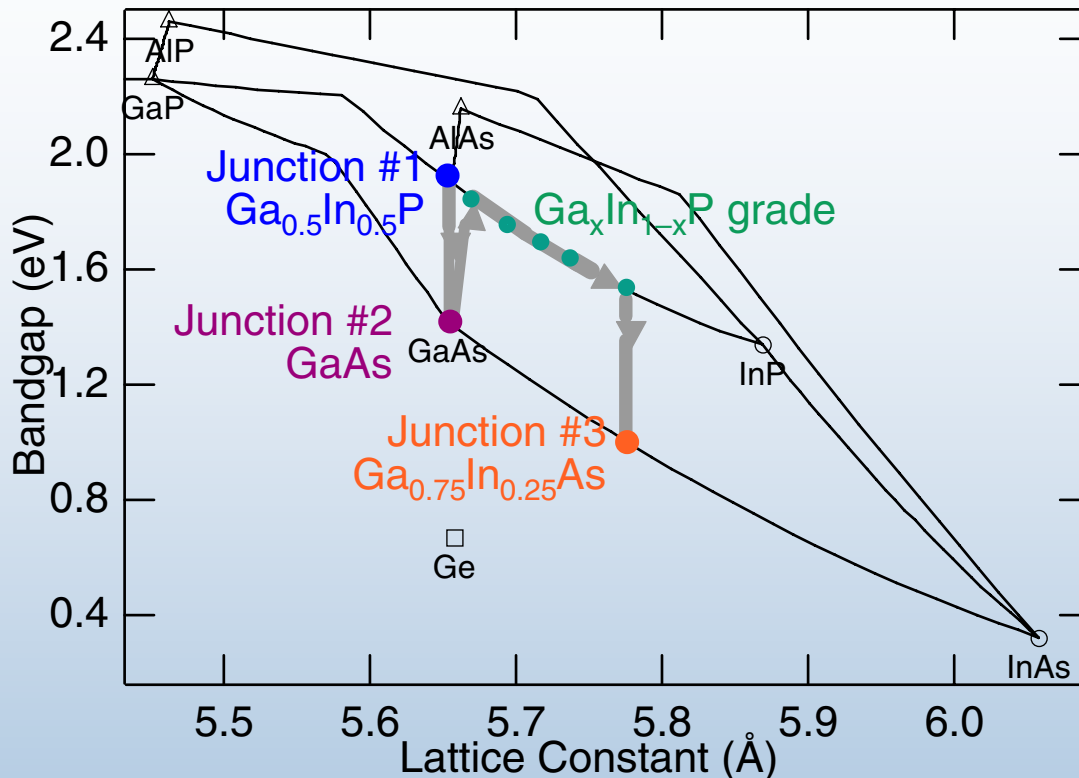
¹ Law et al, 31st PVSC, 2005, p.575

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

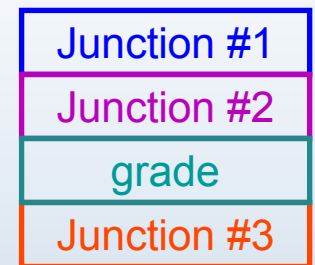
³ Stan et al, 31st PVSC, 2005, p. 770

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

Inverted Lattice-Mismatched Structure



Device structure:



Wanlass et al^{1,2}

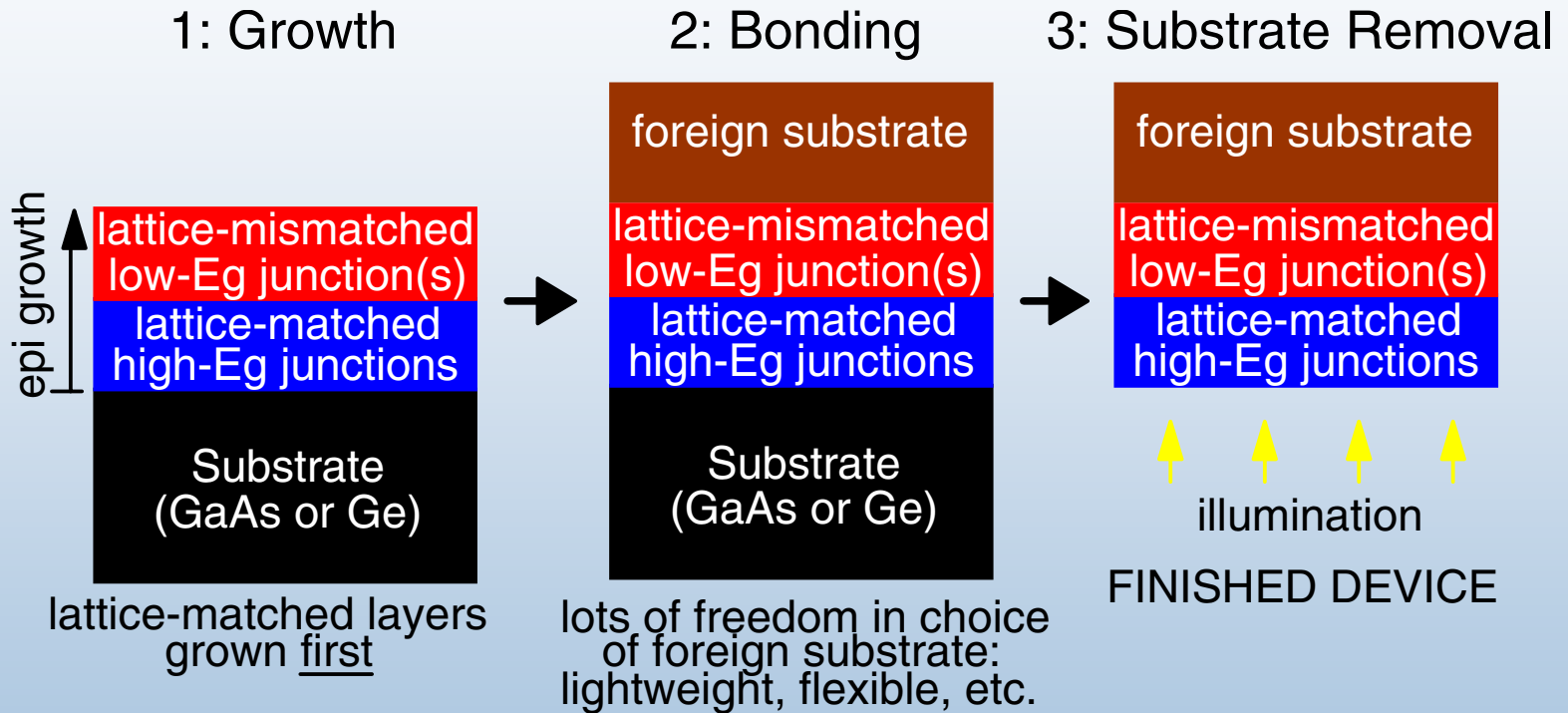
¹ Wanlass et al, 31st PVSC 2005, p. 530

² Wanlass et al, this meeting

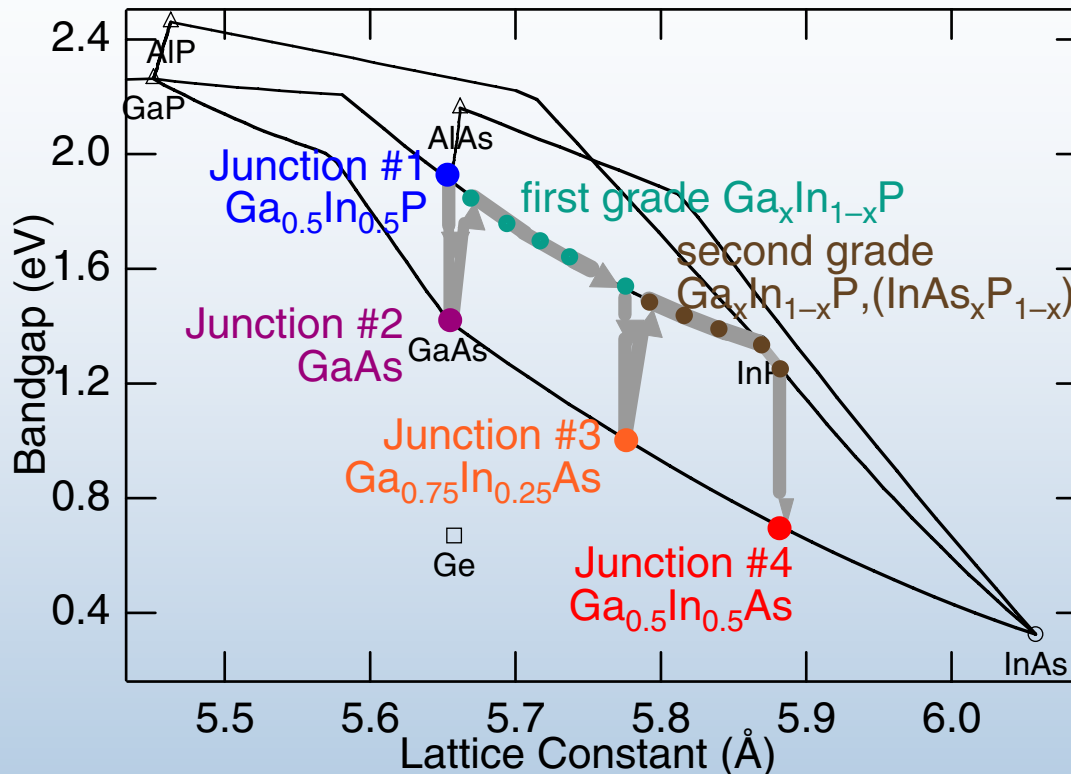
³ Schultz et al, 21st PVSC 1990, p. 148

- Only the bottom junction is grown mismatched
 - Similar philosophy to Varian GaInP/GaAs/substrate/GaInAs design³
- 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



Device structure:

Junction #1
Junction #2
first grade
Junction #3
second grade
Junction #4

- 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:

GaInAs Junction (0.7 eV)
GaInP Grade
GaInAs Junction (1 eV)
GaInP Grade
GaAs Junction (1.4 eV)
GaInP Junction (1.8 eV)
GaAs or Ge Substrate (removed after growth)

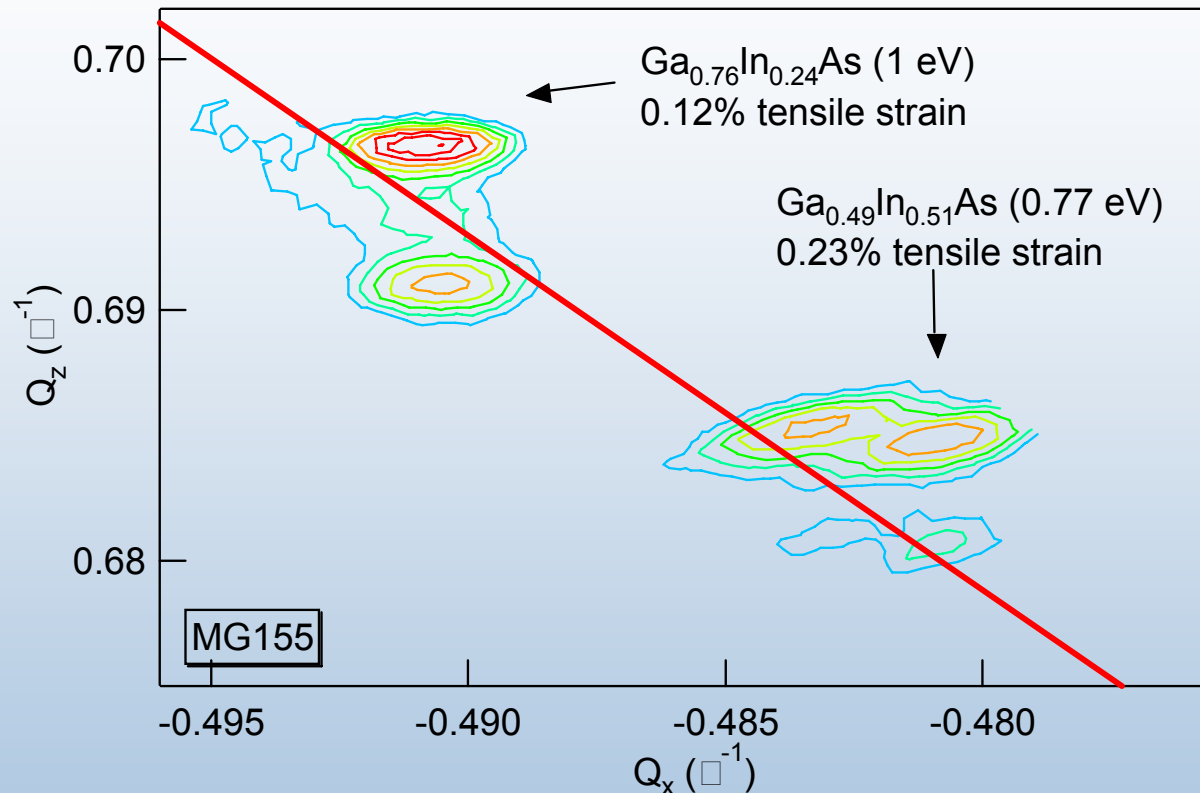
not
to
scale

4th Junction
Test Structure:

GaInAs Junction (0.74-0.88 eV)
GaInP Grade
GaInAs Isotype Layer Simulated Junction (1 eV)
GaInP Grade
GaAs Substrate

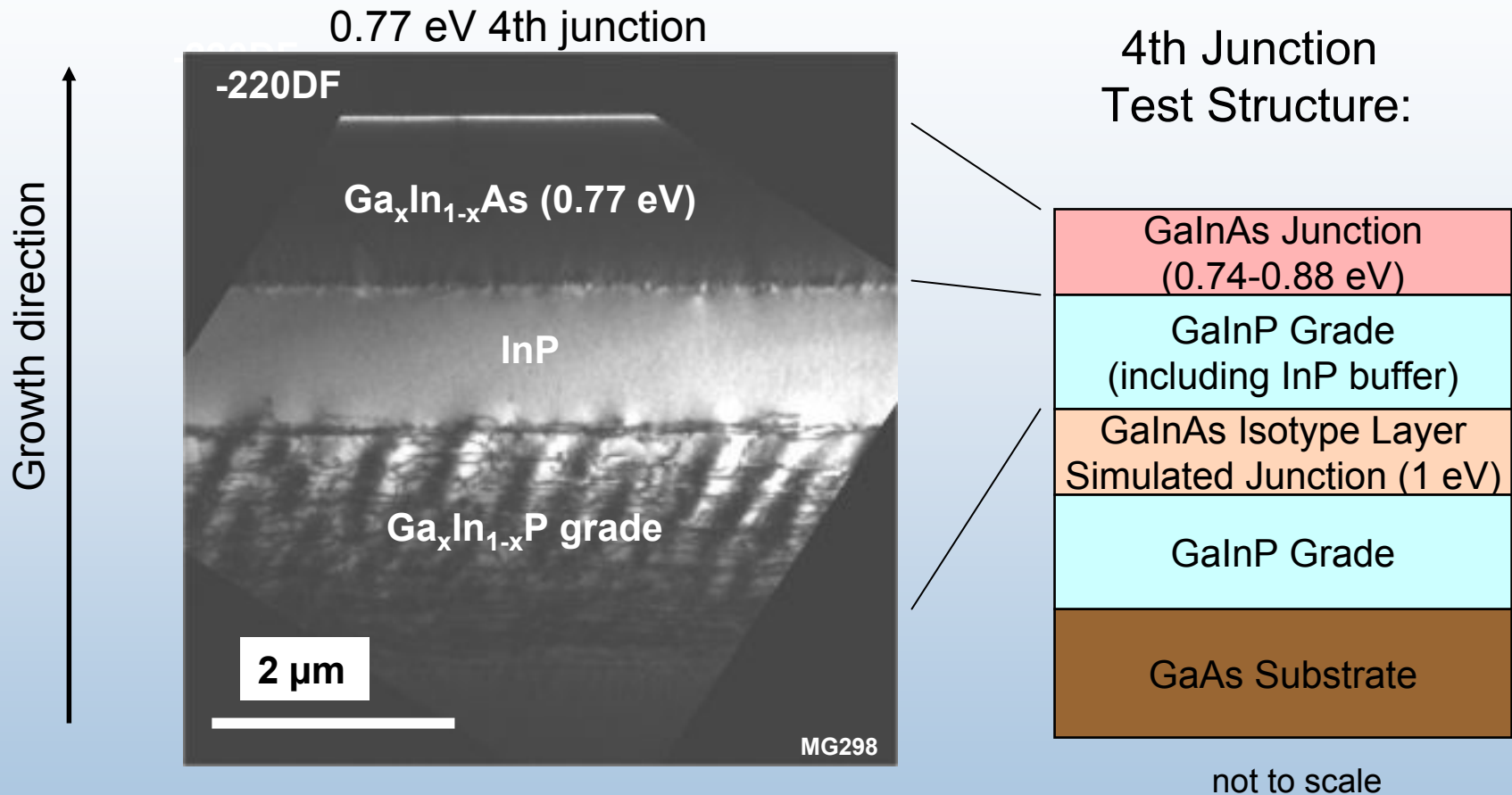
- Accounts for effect of lattice-mismatched growth
- Bypasses complexities of growth and especially of measurement of the other three junctions
- Tried bandgaps from 0.88–0.74 eV

X-ray Characterization of Strained Layers



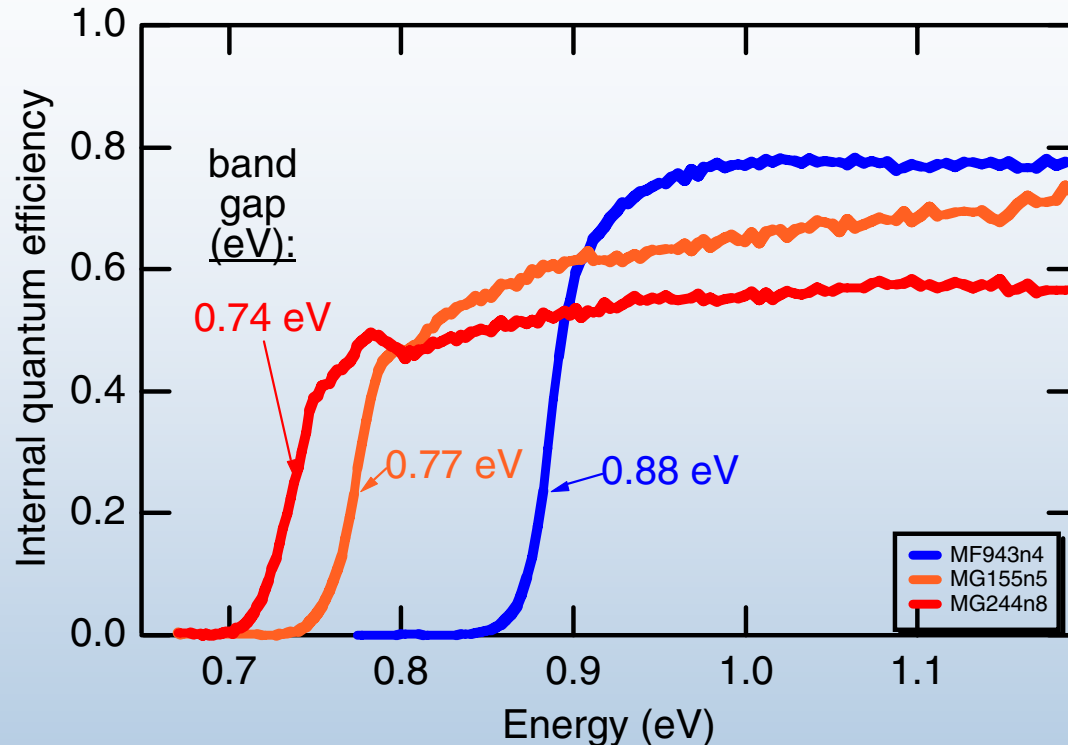
- XRD analysis critical to getting the compositions correct

TEM Characterization: 4th Junction



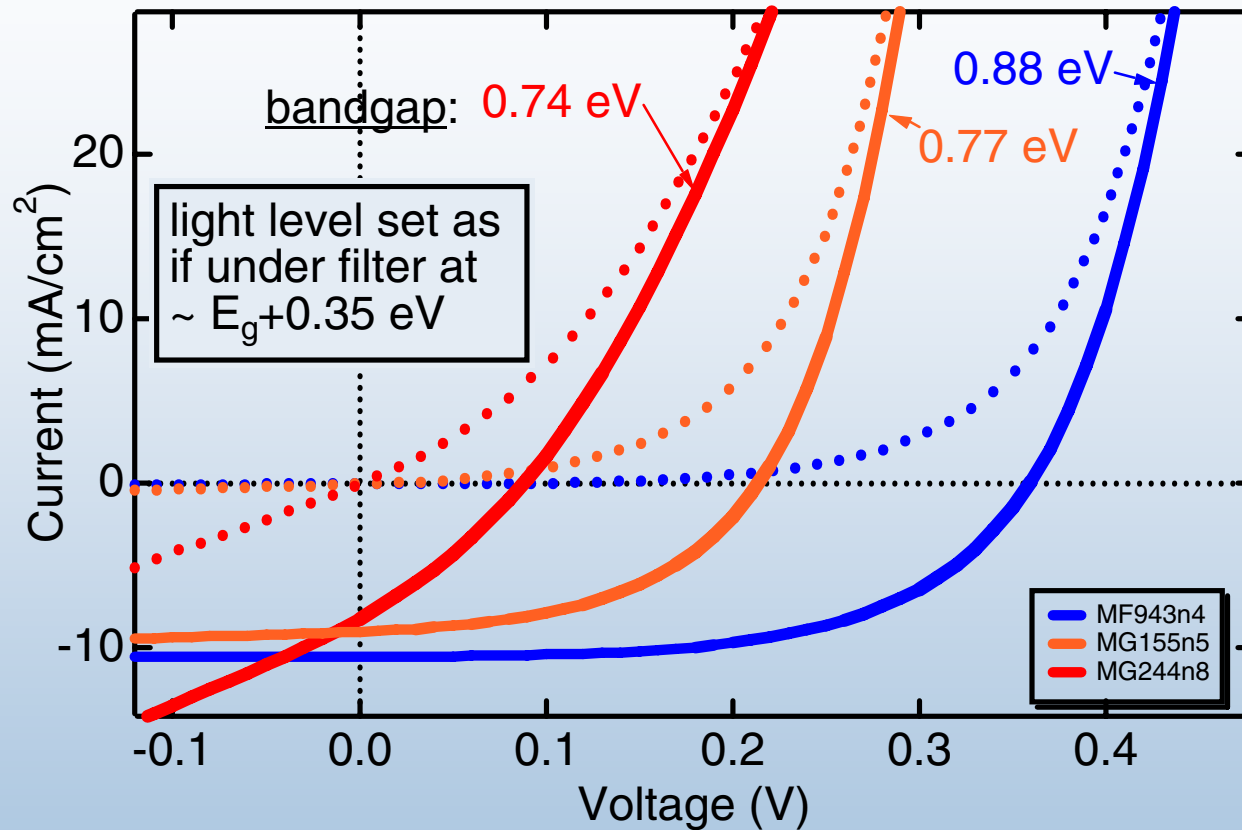
- Dislocations largely confined to grade

Quantum Efficiency



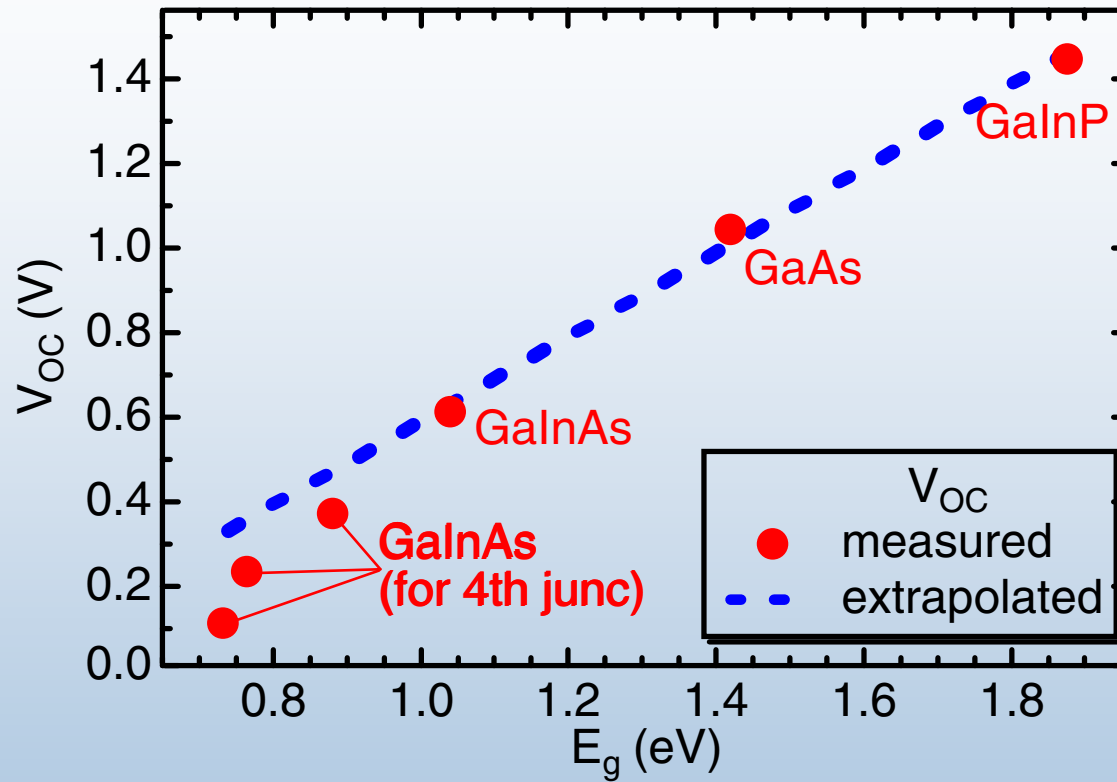
- QE degrades with increasing mismatch (decreasing E_g) (note -- still room for improvement in these devices)
- QE of 0.88 eV device approaches performance required (note -- QE achieved without significant depletion region)

Current-Voltage Characteristics



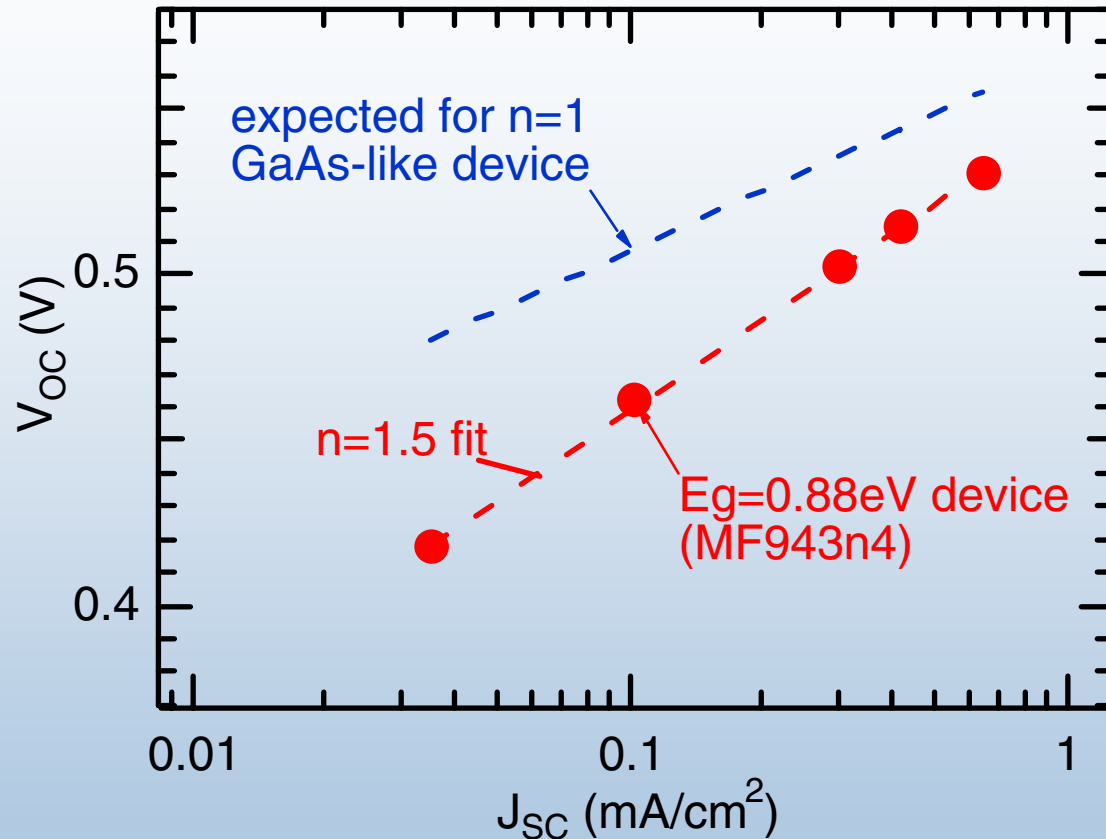
- $E_g = 0.74$ eV junction leaky, others good

Dependence of V_{OC} on Band Gap



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

Improvement of Voc with Concentration

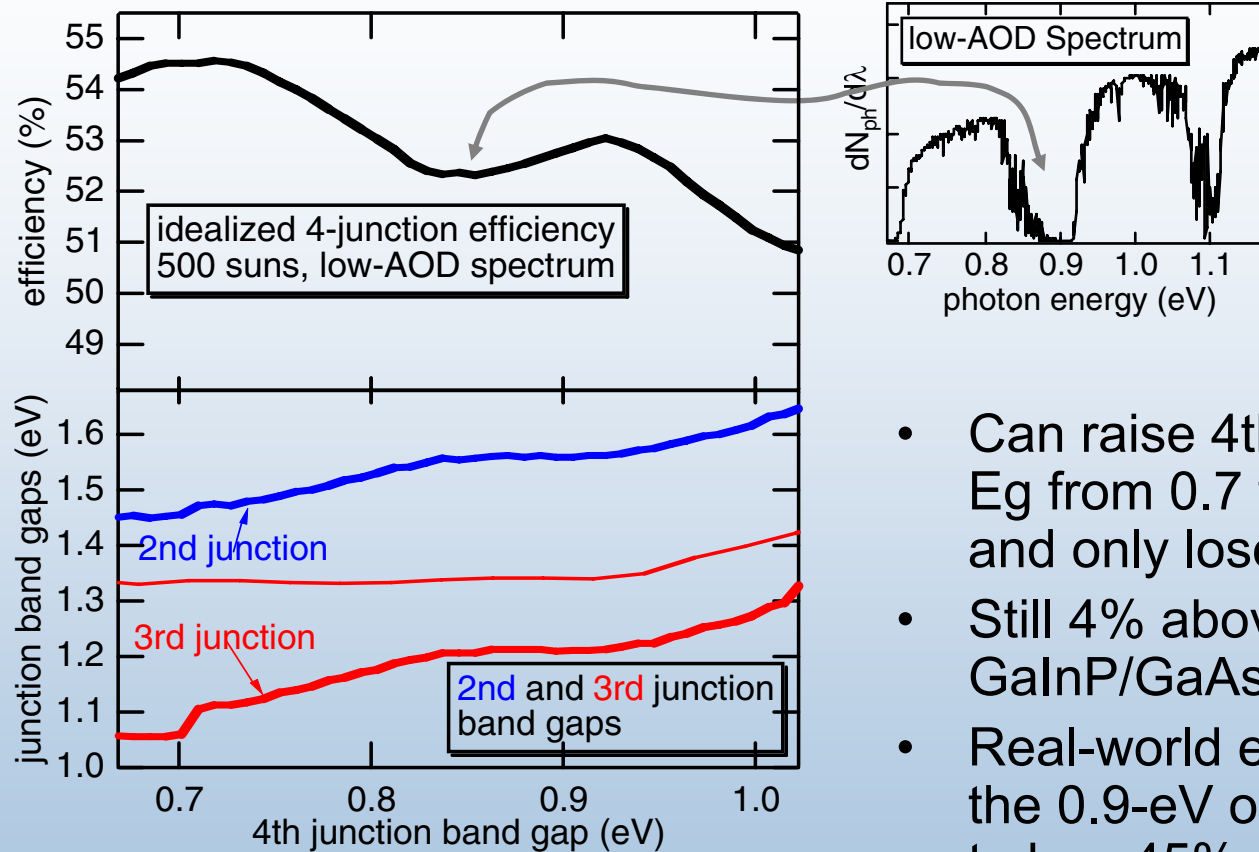


- V_{oc} does get closer to GaAs-like with concentration, as expected

4th-Junction E_g - 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 E_g 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 $E_g=0.9$ 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!

