Ryan France
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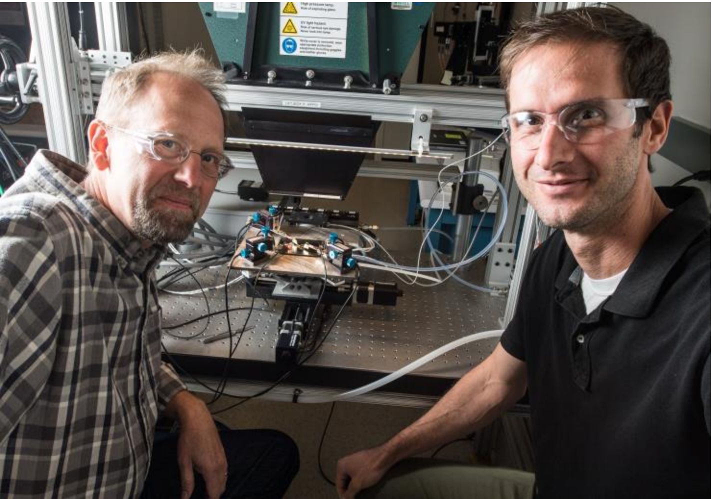
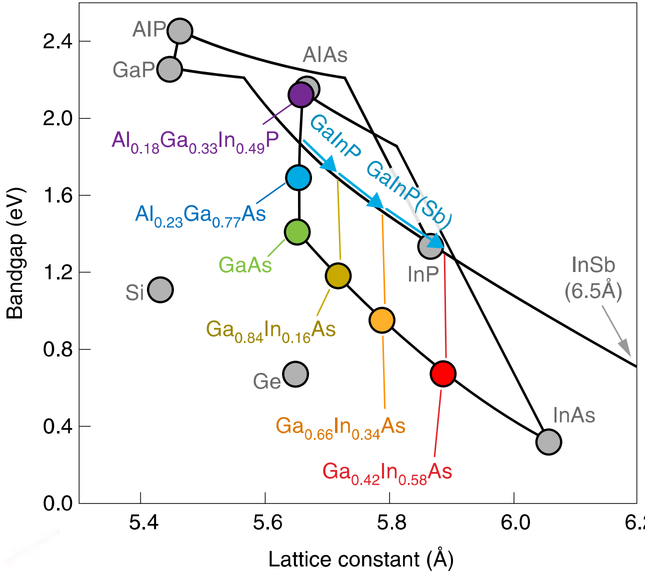
Space Power Workshop
April 21st, 2021

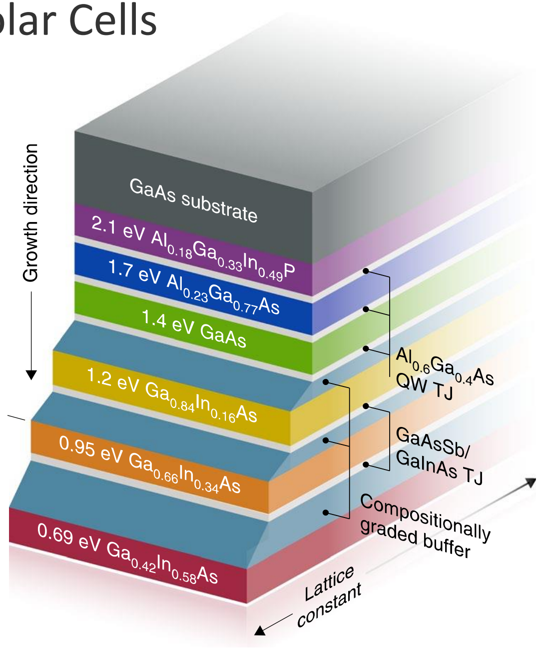


Radiation Hard Multijunction Component Development at NREL

Multijunctions at NREL

Inverted Metamorphic Multijunction Solar Cells

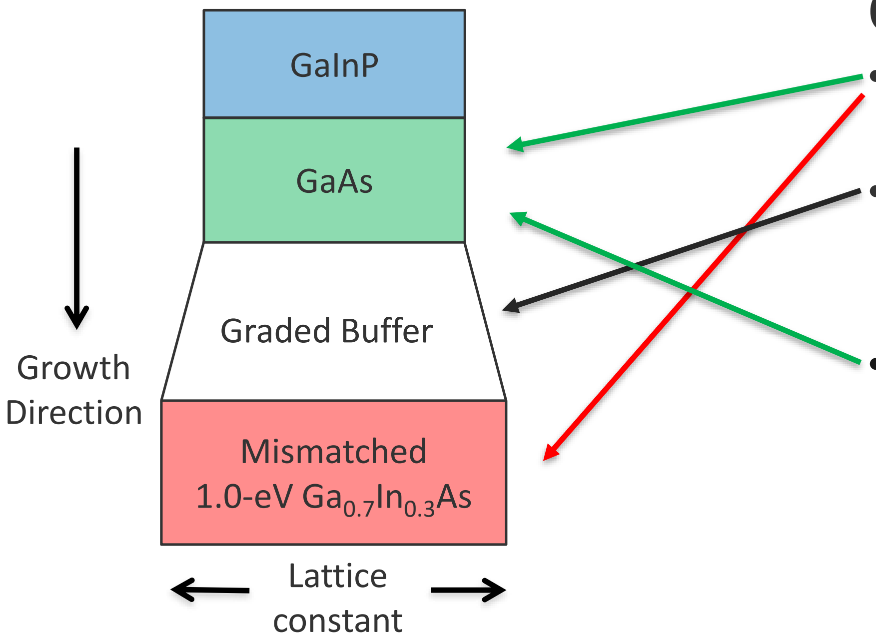




IMM efficiencies	2J	3J	4J	6J
Concentrated PV	35.5	41.2	45.7	47.1
1-sun terrestrial	32.6	37.4	38.3	39.2
1-sun AM0	-	-	35.3	-

Outline

3-Junction IMM



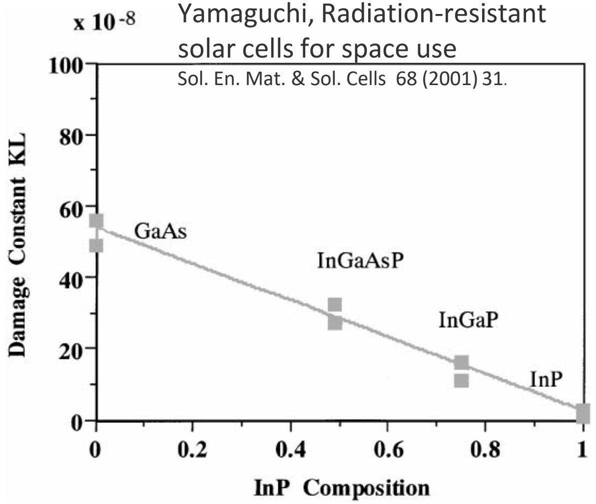
Component Development

- Metamorphic GaInAsP
  - replace radiation-soft GaAs or GaInAs
- Graded Buffer Bragg Reflector
  - enable thin GaAs subcell without dedicated DBR
- GaAs subcell improvements
  - strain-balanced solar cells

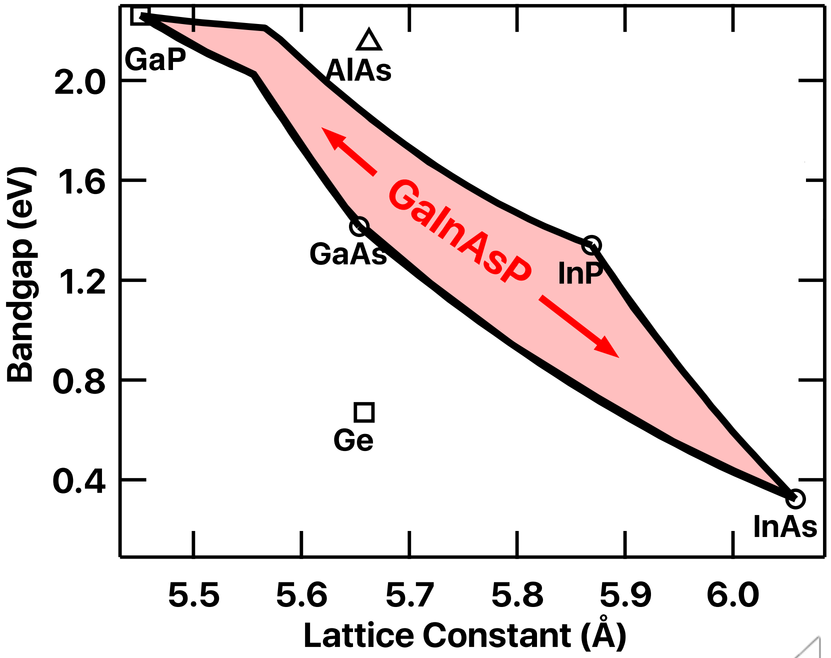
Metamorphic GaInAsP

Metamorphic GaInAsP

- Wide range of accessible bandgaps
- Lattice-matched GaInAsP previously studied, shown to be radiation hard
- Limited work on lattice-mismatched GaInAsP



Yamaguchi, Radiation-resistant solar cells for space use
Sol. En. Mat. & Sol. Cells 68 (2001) 31.

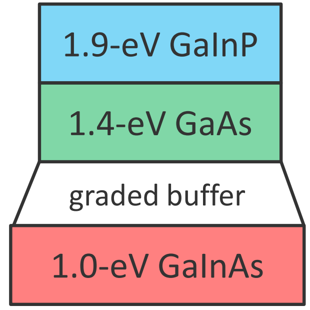


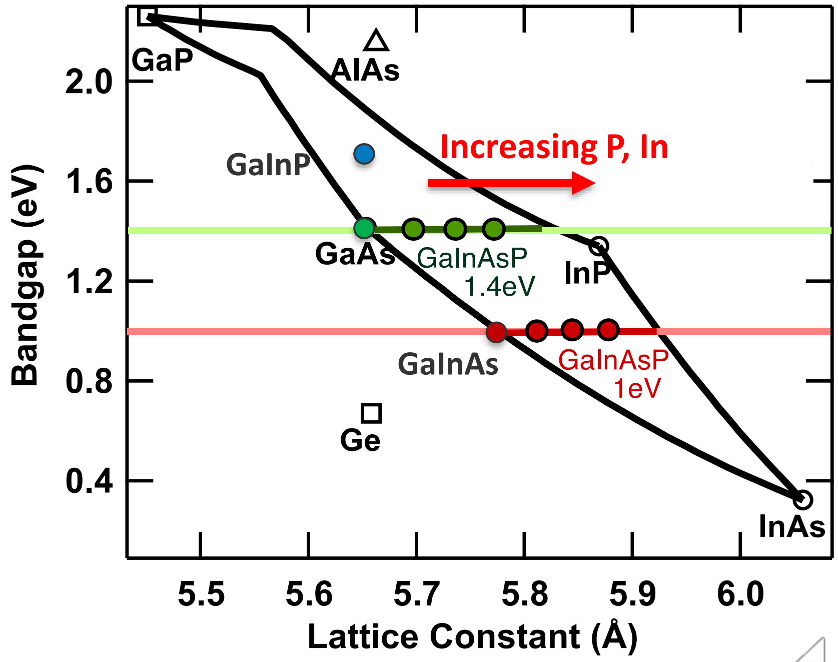
GaInAsP solar cells:
Sharps, IEEE PVSC, 1991

Lattice-mismatched GaInAsP

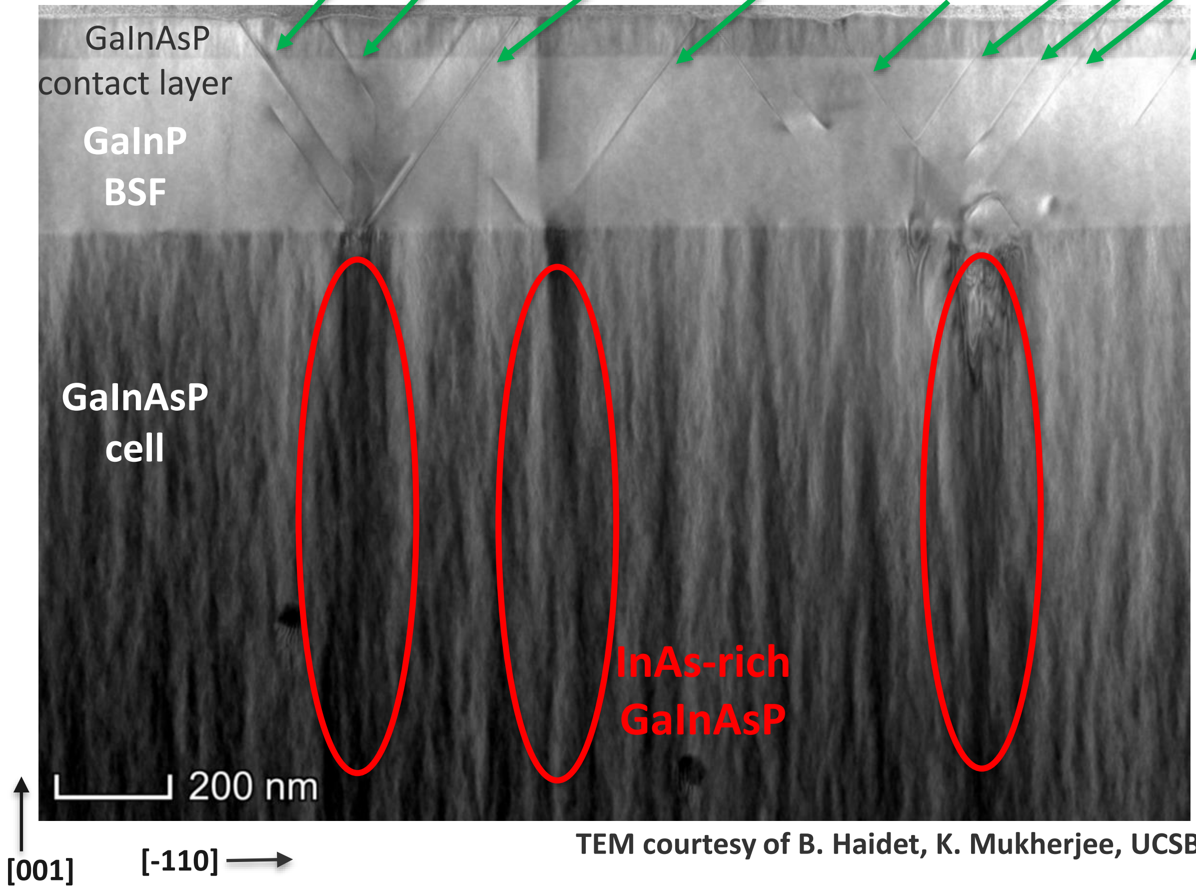
- Drop-in replacements for IMM or UMM subcells
  - 1.4 eV GaAs, 1.0 eV GaInAs, for example
- Study radiation hardness vs alloy content

3J IMM structure





TEM of lattice-mismatched GaInAsP



TEM courtesy of B. Haidet, K. Mukherjee, UCSB

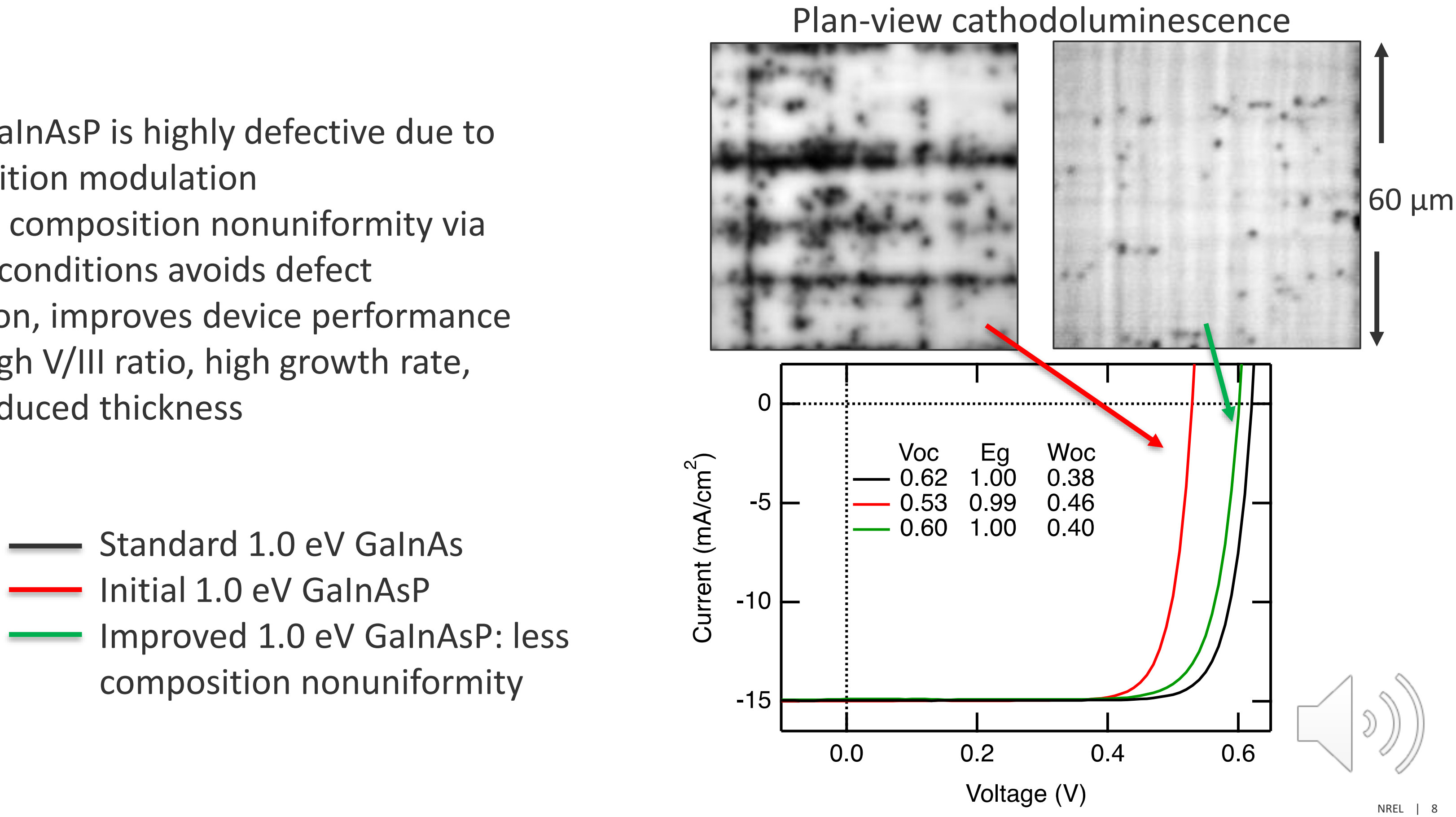
Defects:
stacking faults and dislocations

Cross-sectional TEM
BF STEM

- GaInAsP separates into InAs-rich and GaP-rich regions
- Composition nonuniformity leads to defects at GaInAsP – GaInP BSF interface
- High defect density > 5 x10^7/ cm^2

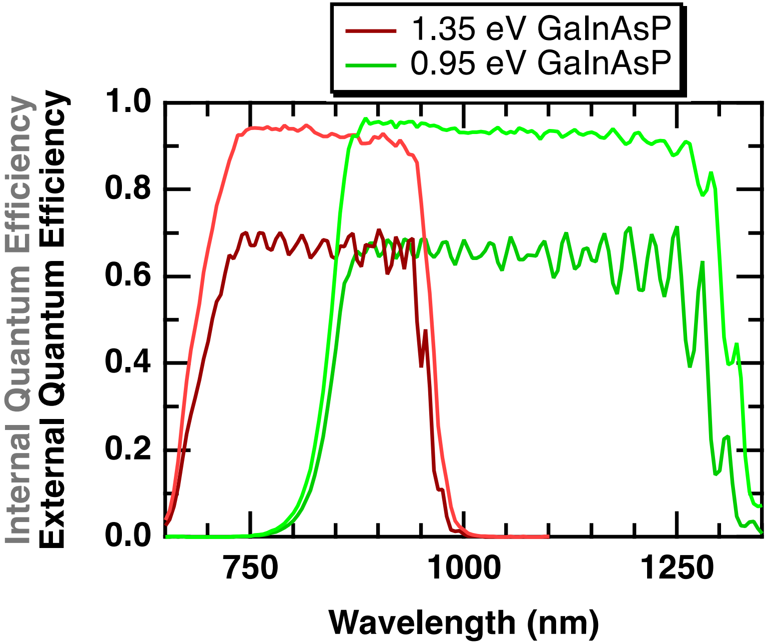
CL and IV of improved 1.0-eV GaInAsP

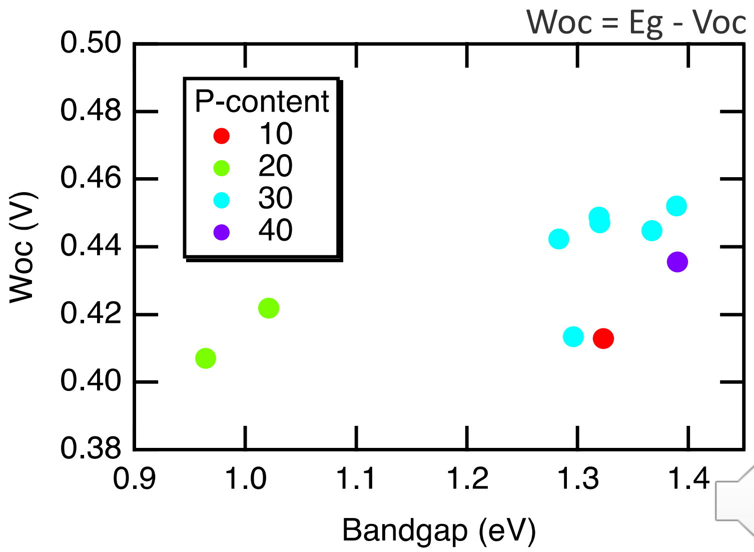
- Initial GaInAsP is highly defective due to composition modulation
- Limiting composition nonuniformity via growth conditions avoids defect formation, improves device performance
  - High V/III ratio, high growth rate, reduced thickness



Metamorphic GaInAsP cell results

- GaInAsP has a tunable bandgap → enables higher current than GaAs
- Excellent EQE and IQE for GaInAsP with both 0.95 and 1.35-eV
- Phosphorous contents up to 40% demonstrated → potentially higher rad tolerance

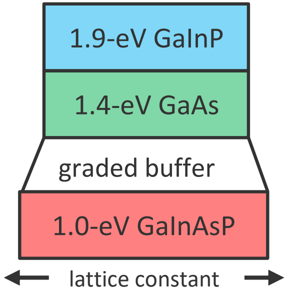


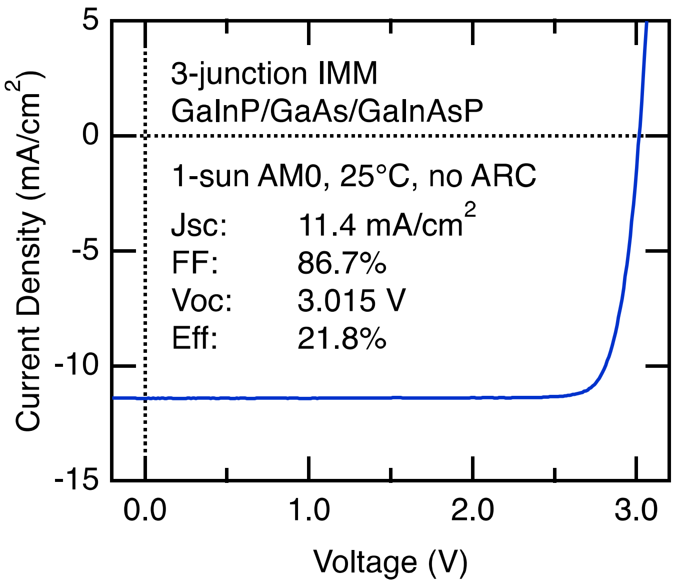


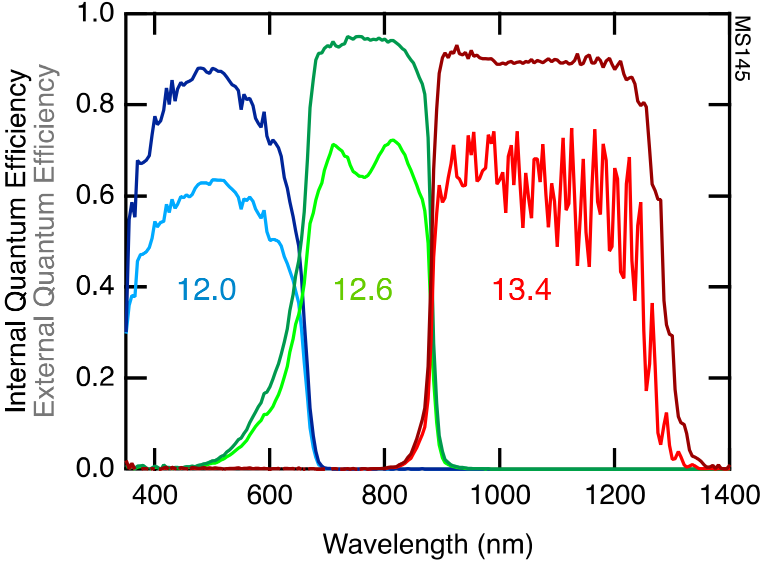
GaInAsP subcell in 3J IMM

- Total Voc is high, GaInAsP Woc = 0.40 (from EL),
- Excellent carrier collection (no ARC)
- No loss in GaInAsP subcell performance in a multijunction

3J IMM structure



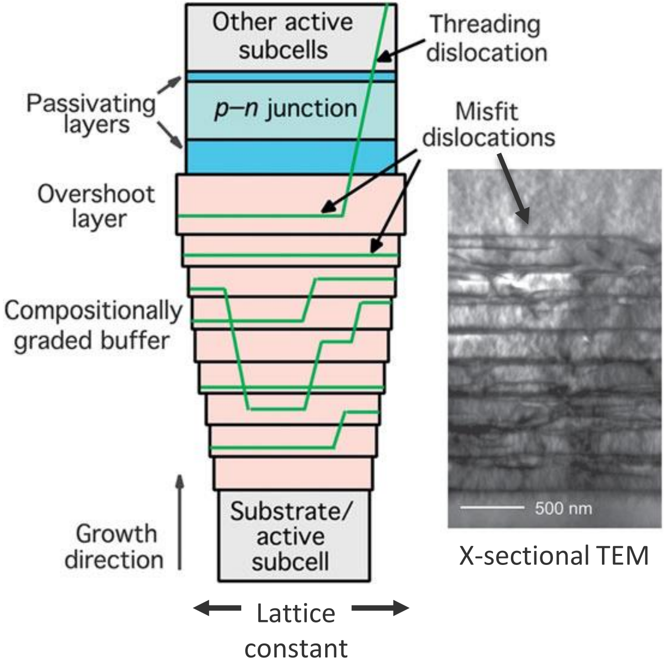




Graded Buffer Bragg Reflectors

Graded Buffer + Bragg Reflector = GBBR

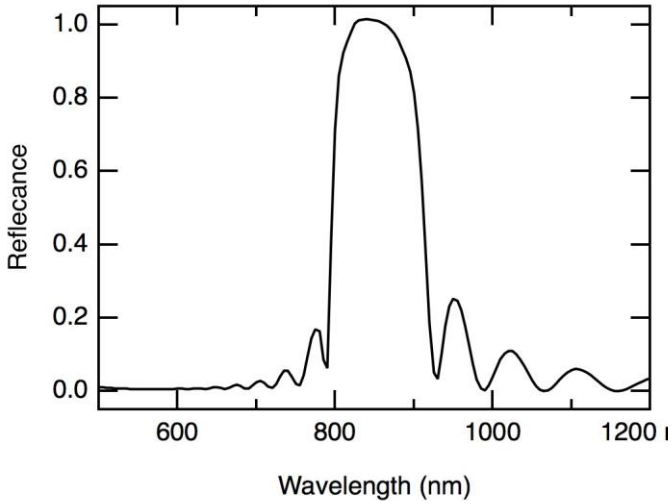
Compositionally Graded Buffer (CGB)



X-sectional TEM

- Grades the lattice constant to metamorphic material with desired bandgap
- Strain relieved via dislocation glide

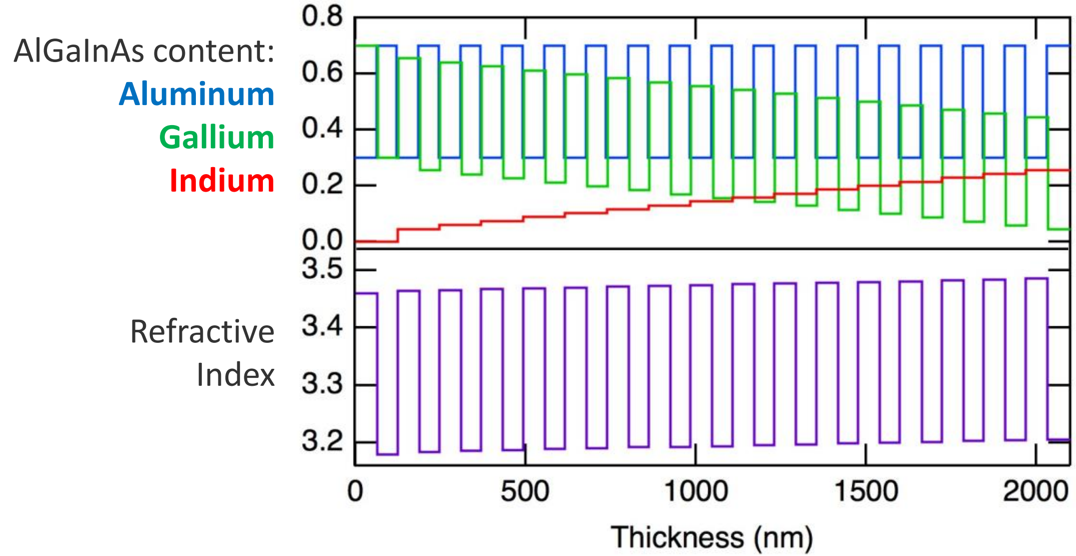
Distributed Bragg Reflector (DBR)



- DBR aids collection in an optically thin subcells
  - Low diffusion length
  - High bulk recombination
  - Radiation hardness
  - Quantum wells
- Alternating layers with refractive index contrast

R.M. France et al., Metamorphic Epitaxy for Multijunction Solar Cells, MRS Bulletin, **41**, 202 (2016).

Design and TEM of AlGaInAs GBBR

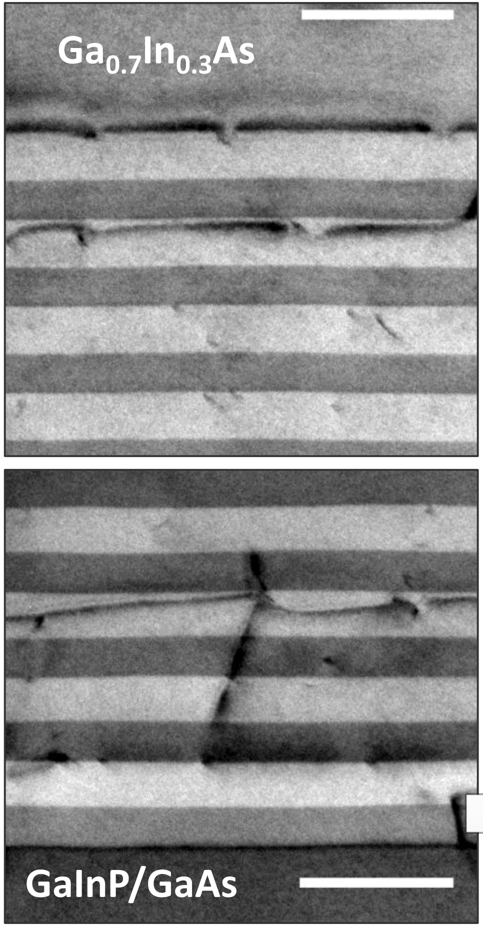


Design:

- Slowly increase Indium-content to increase lattice constant
- Alternate Aluminum-content for refractive index contrast

Cross-sectional TEM:

- No noticeable affect of alternating Al on dislocations
- Low threading dislocation density

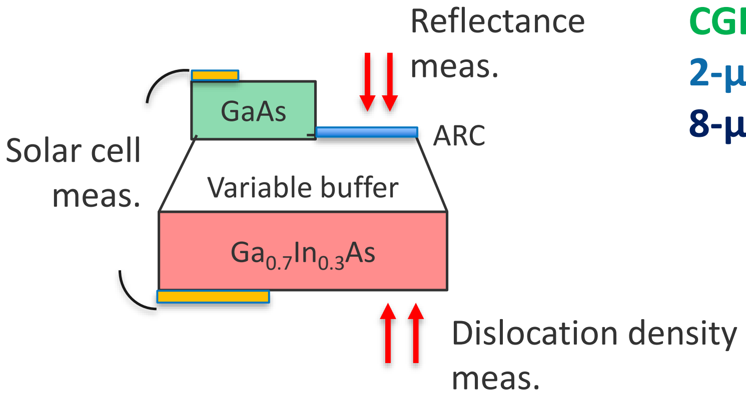


004 2-beam TEM

Low Al
High Al
Low Al
High Al
Low Al
High Al

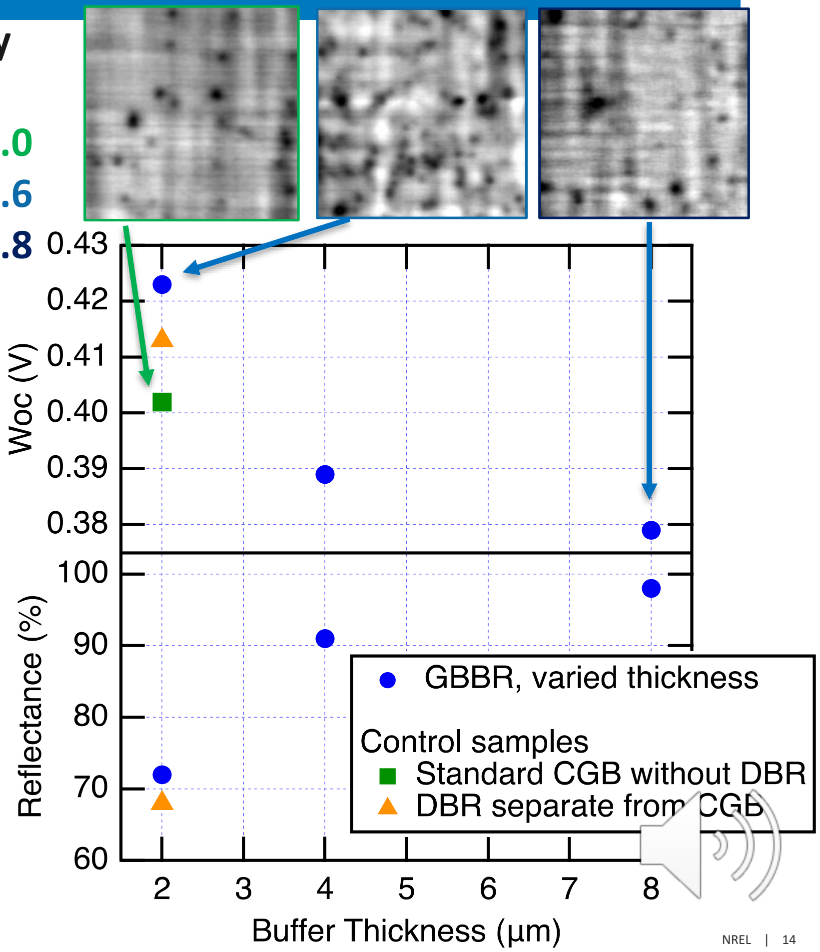
scalebar
200 nm

Reflectance and Dislocation Density of GBBR



Dislocation Density ($\times 10^6$ /cm^2)

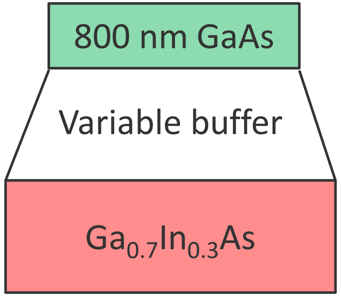
CGB control	**1.0**
2-µm GBBR	**1.6**
8-µm GBBR	**0.8**

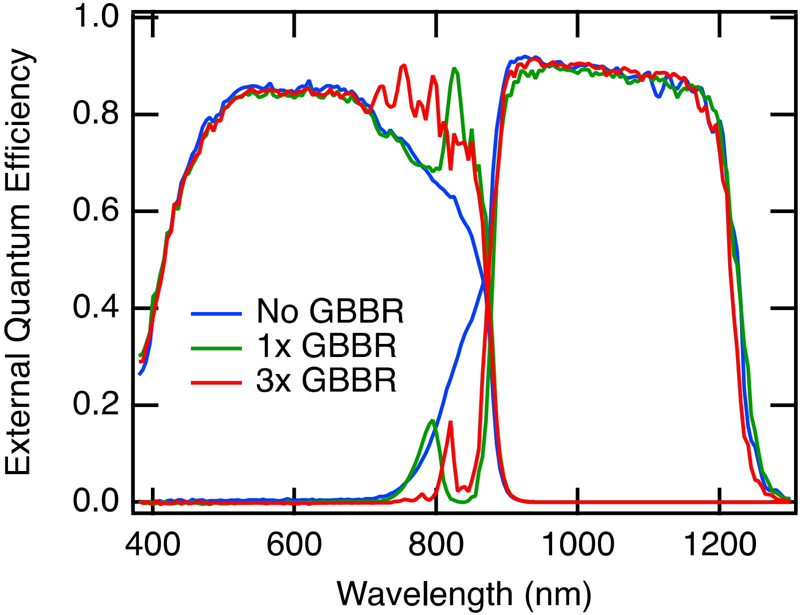


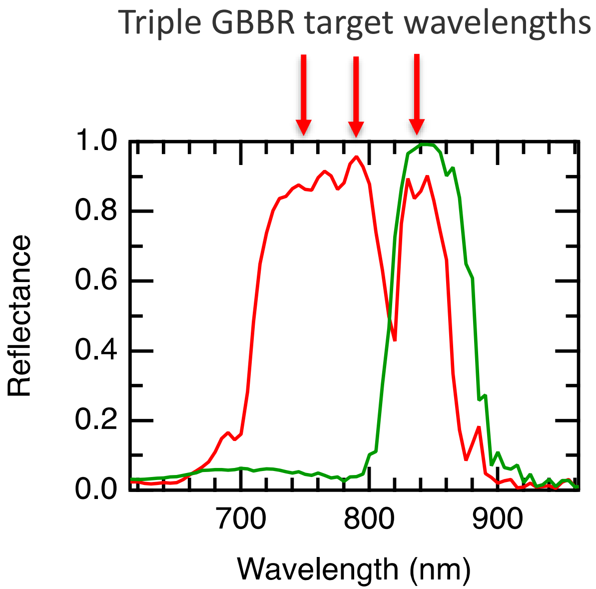
Vary thickness of GBBR, compare to controls

- Minor increase in Woc, TDD wrt control
- Reflectance increases and Woc, TDD decreases with increasing buffer thickness, as expected
- Over 99% reflectance possible in GBBR

Triple GBBR for radiation-hard, thin GaAs





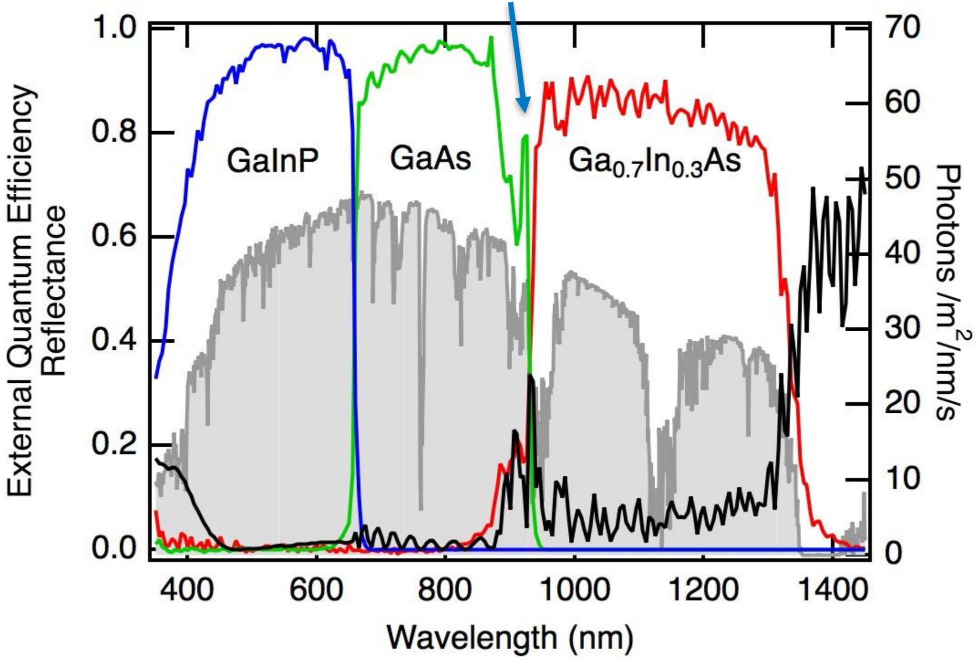


- GBBR enables thin GaAs for improved radiation hardness
- Jsc increased by 1.5 mA/cm^2 under AM0 compared to baseline 800 nm thick GaAs cell without GBBR

GBBR design	Bandwidth (nm)	Jsc increase (mA/cm^2)
1xGBBR	**65**	**1.0**
3xGBBR	**140**	**1.5**

3J-IMM + MQW demonstration

MQW excitonic peak,
80% EQE @ 925 nm



- GBBR allows second pass through MQWs, which increase sub-bandgap absorption

Photocurrents from EQE (mA/cm²)

	Global	Direct	AM0
J1	15.6	15	19.4
J2	16.2	16.6	18.1
J3	14.4	15.2	18.4
J2 QW + GBBR gain	***2.0***	***2.1***	***2.5***

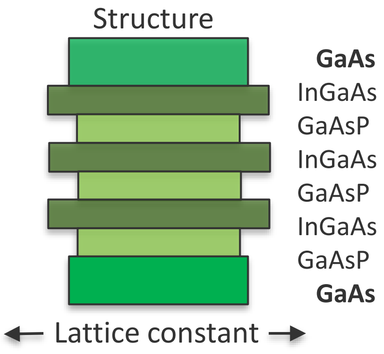
I-V results

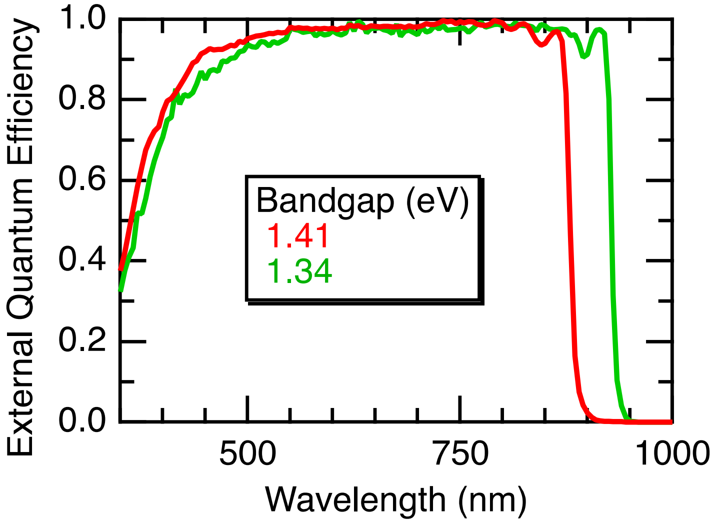
	Global	Direct	AM0
Efficiency	**36.5**	**36.6**	**32.4**
Voc	2.93	2.93	2.95

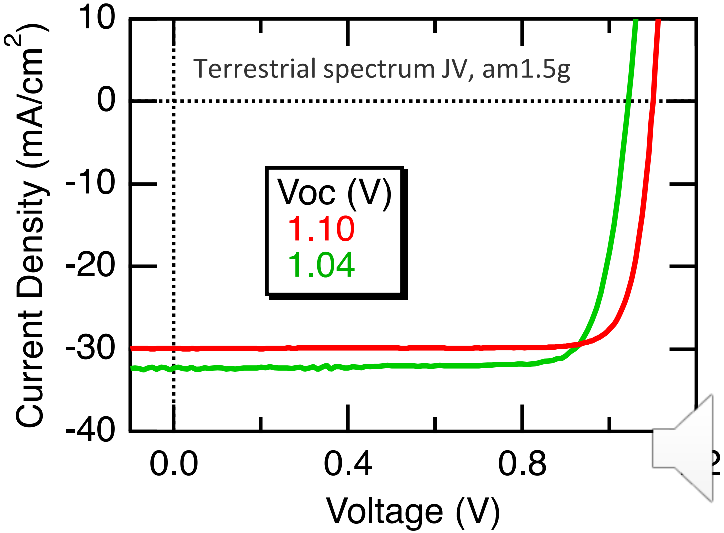
GaAs strain-balanced solar cells

Strain-balanced solar cells

- Excellent EQE and Voc achieved in strain-balanced solar cell
- Sub-bandgap Jsc increase of 3 mA/cm^2 under space spectrum, am0



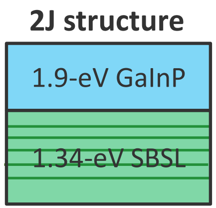


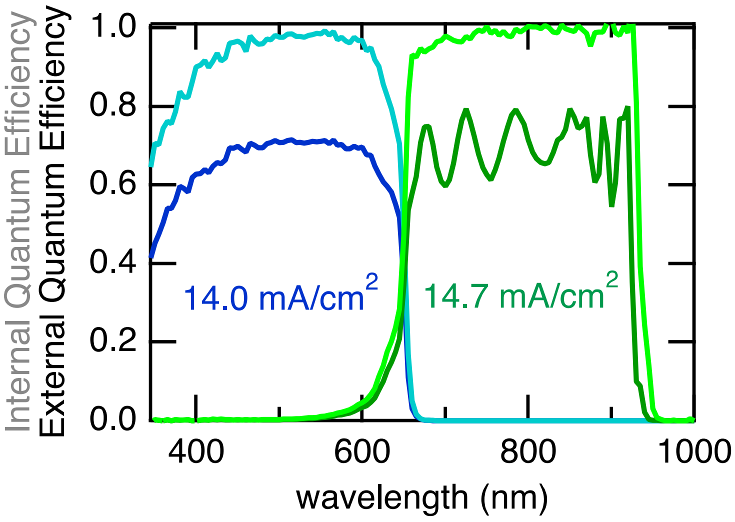


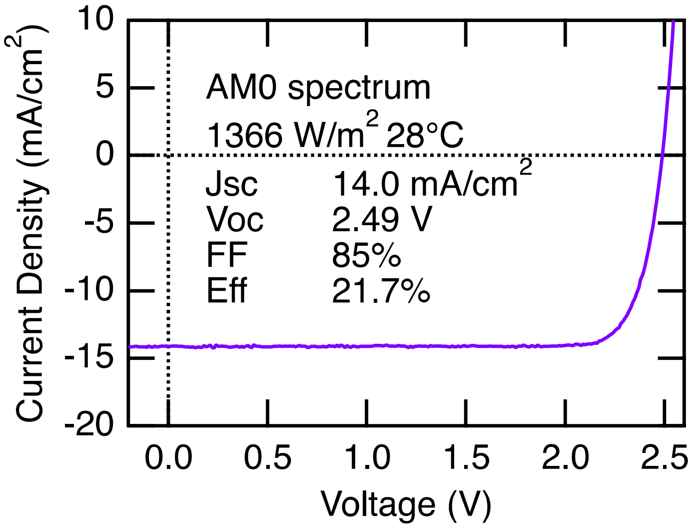
2-junction strain-balanced am0 device

SBSL increases BOL efficiency

- Measured without ARC: Jsc = 14.0 mA/cm², Eff. = 21.7%
- Predicted with ARC: Jsc > 19 mA/cm², Eff. >29%



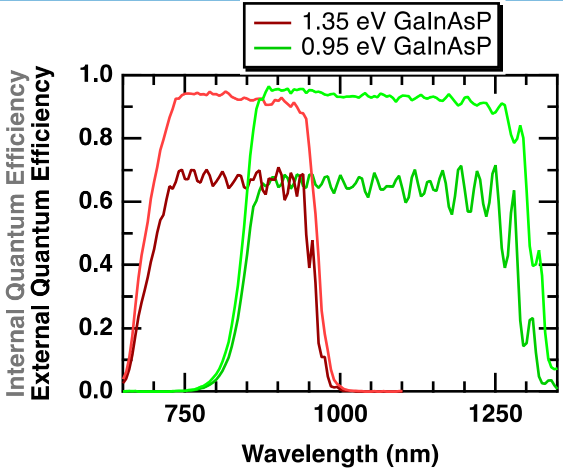


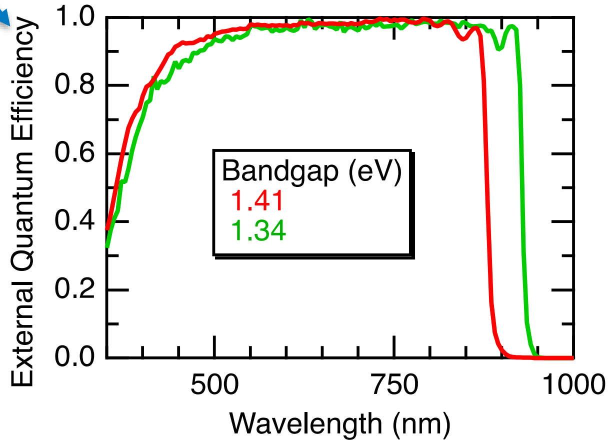


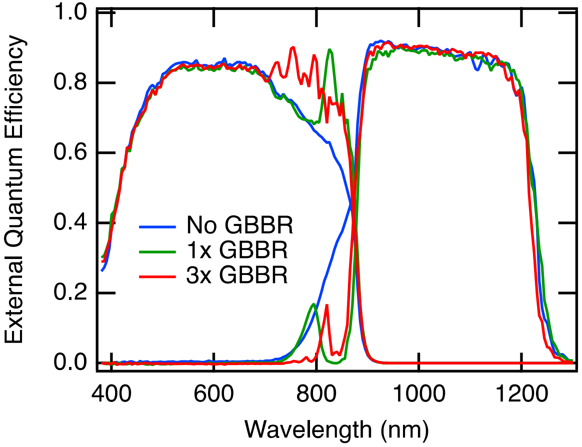
Summary

Component Development

- Metamorphic GaInAsP
  - replace radiation-soft GaAs or GaInAs
- Graded Buffer Bragg Reflector
  - enable thin GaAs subcell without dedicated DBR
- Strain-balanced solar cells
  - Excellent BOL efficiency







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