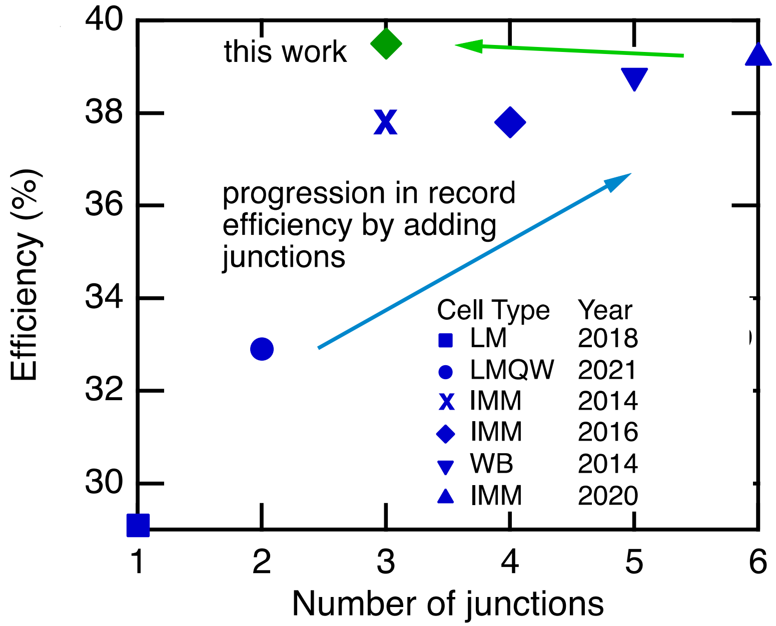
Triple-Junction III-V Solar Cells with 39.5% AM1.5G and 34.2% AM0 Efficiencies

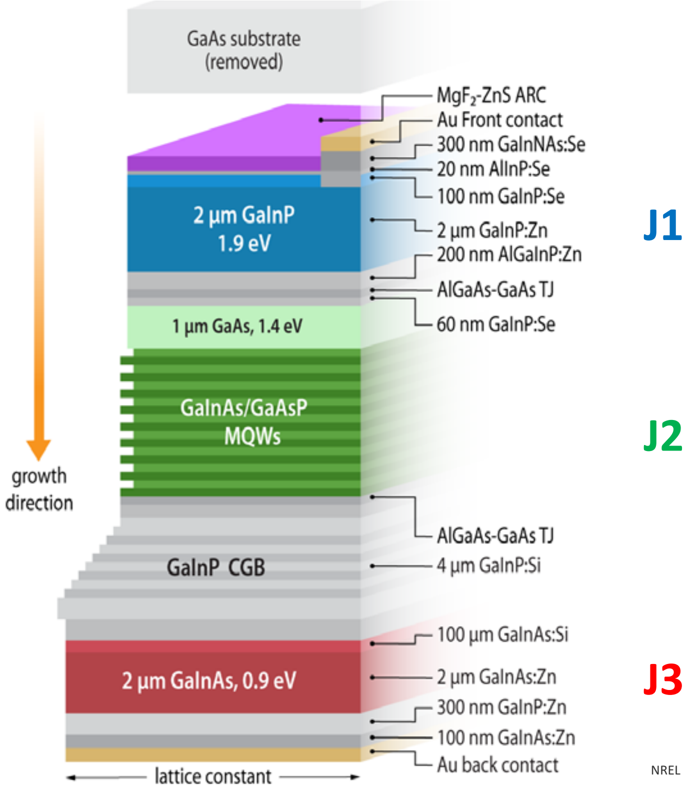
Ryan France



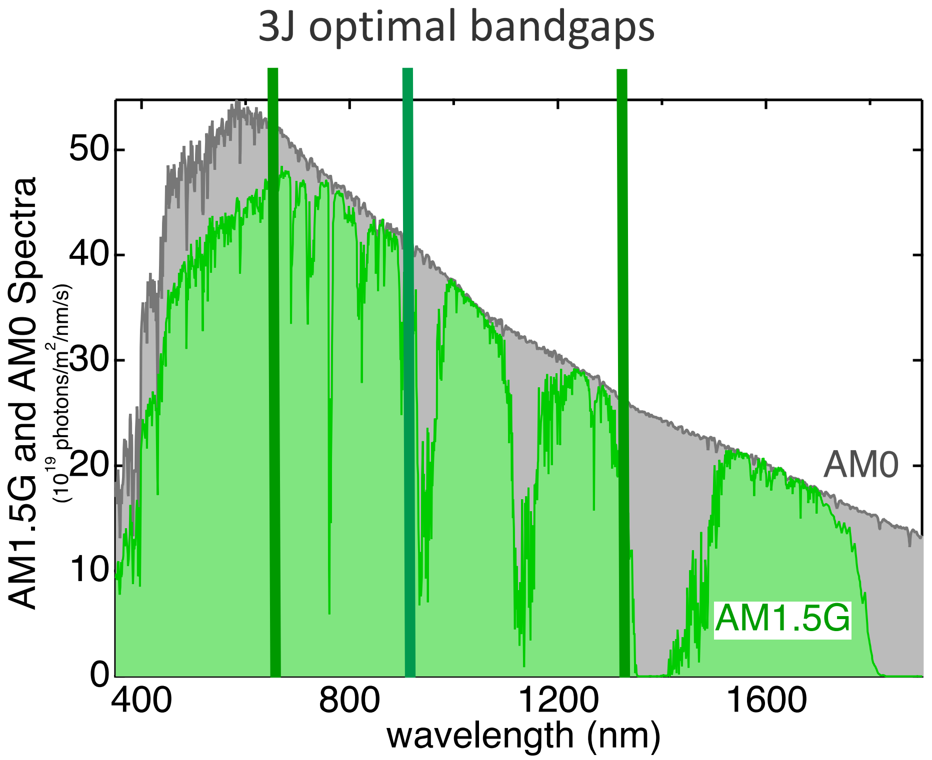
Outline

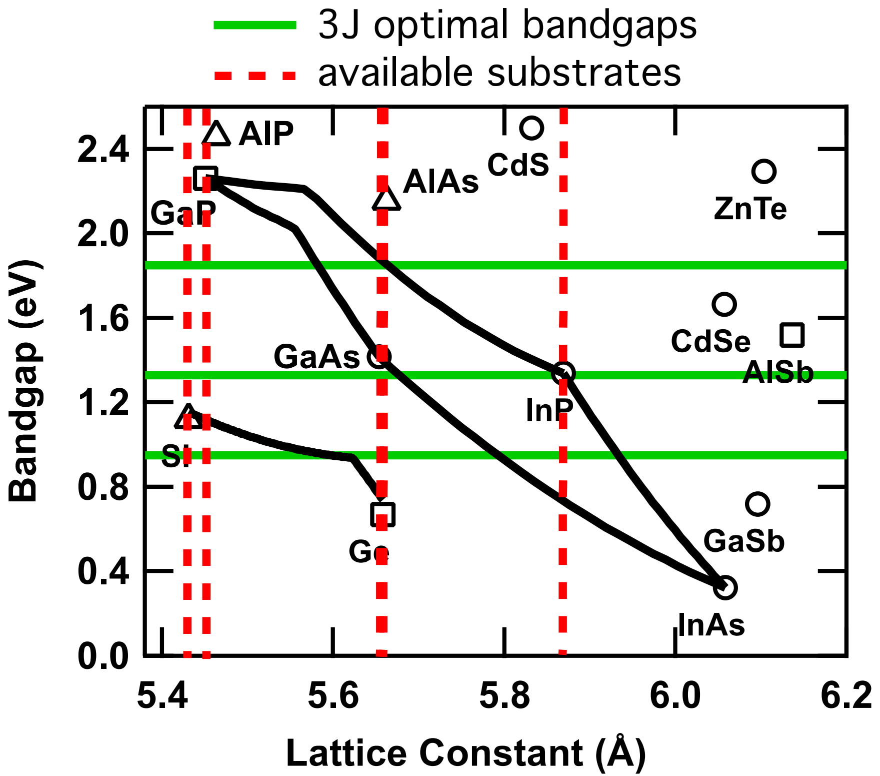
- Materials Science
  - Quantum well cell : optical thickness
  - GaInP top cell : point defect annihilation
  - Metamorphic GaInAs : dislocation glide
- Device integration & results
  - 2-junction cell
  - 3-junction cell
- Applications
  - Radiation data
  - Other uses

3-junction inverted metamorphic multijunction (IMM)

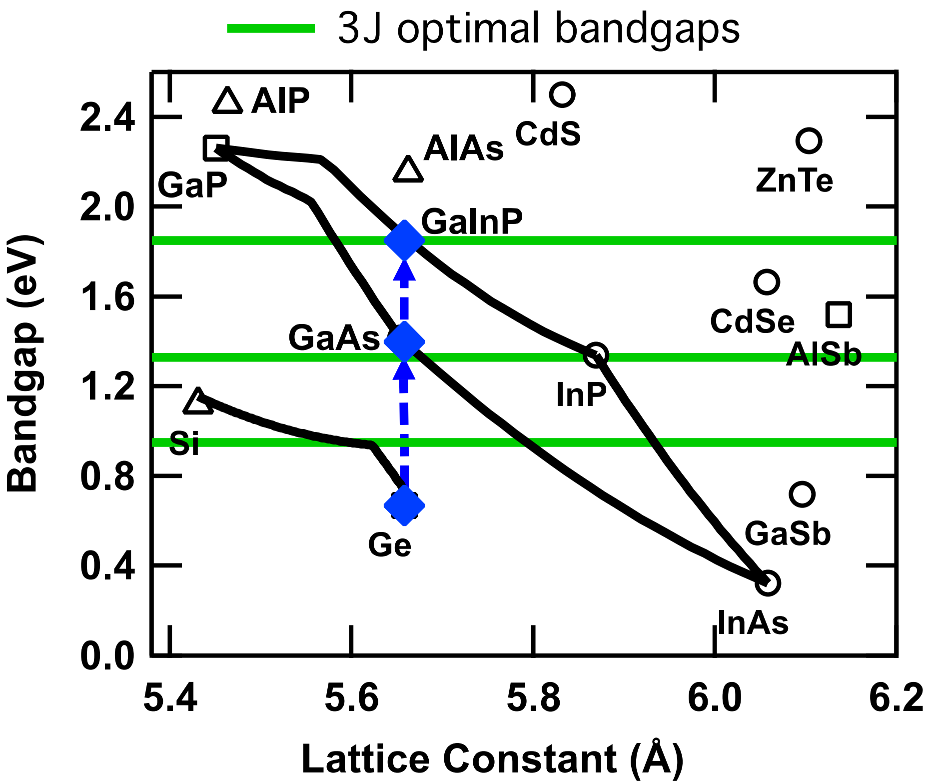


Optimal III-V materials for incident spectrum





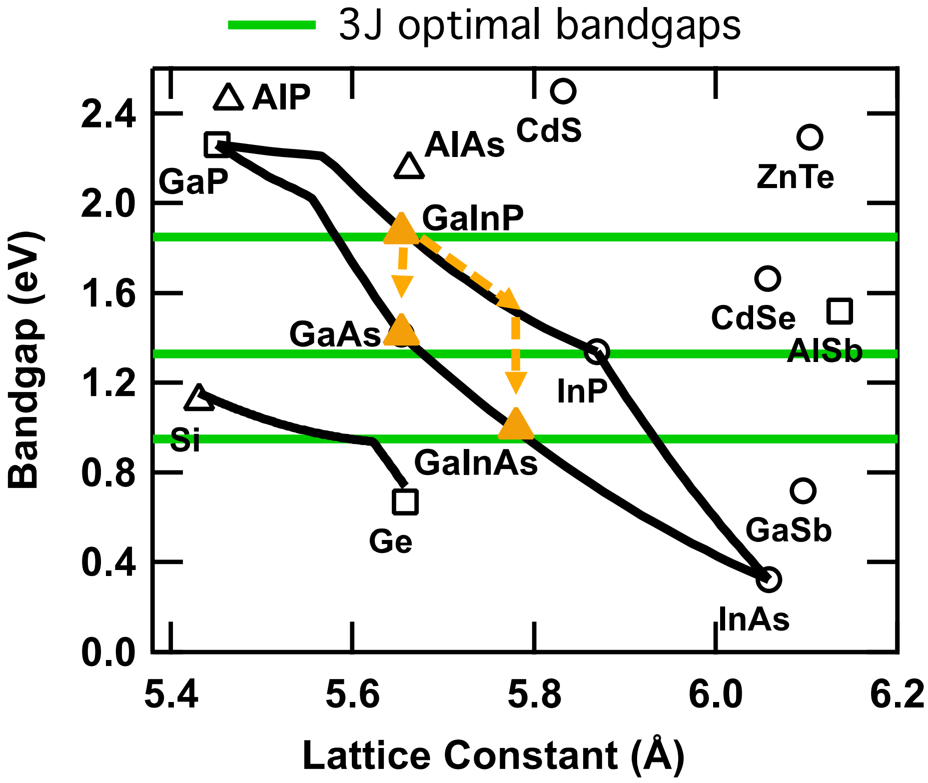
3-junction solar cell approaches



- Standard Ge-based
- Inverted Metamorphic
- QW + metamorphic

- Lattice-matched, high-performance
- High efficiency despite not having optimal bandgaps
- Ge is indirect, has low bandgap

3-junction solar cell approaches

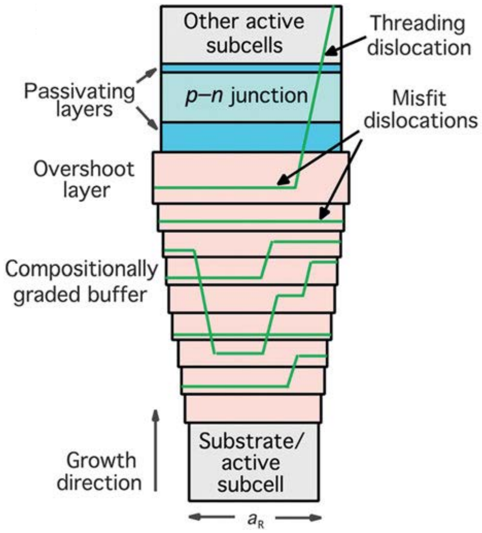


Standard Ge-based

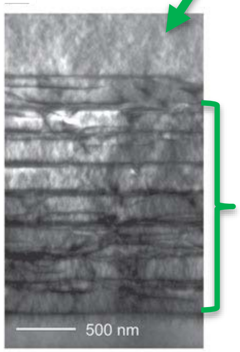
Inverted Metamorphic

QW + metamorphic

- More optimal bandgap combination
- Record efficiency 3J, 37.9% AM1.5G



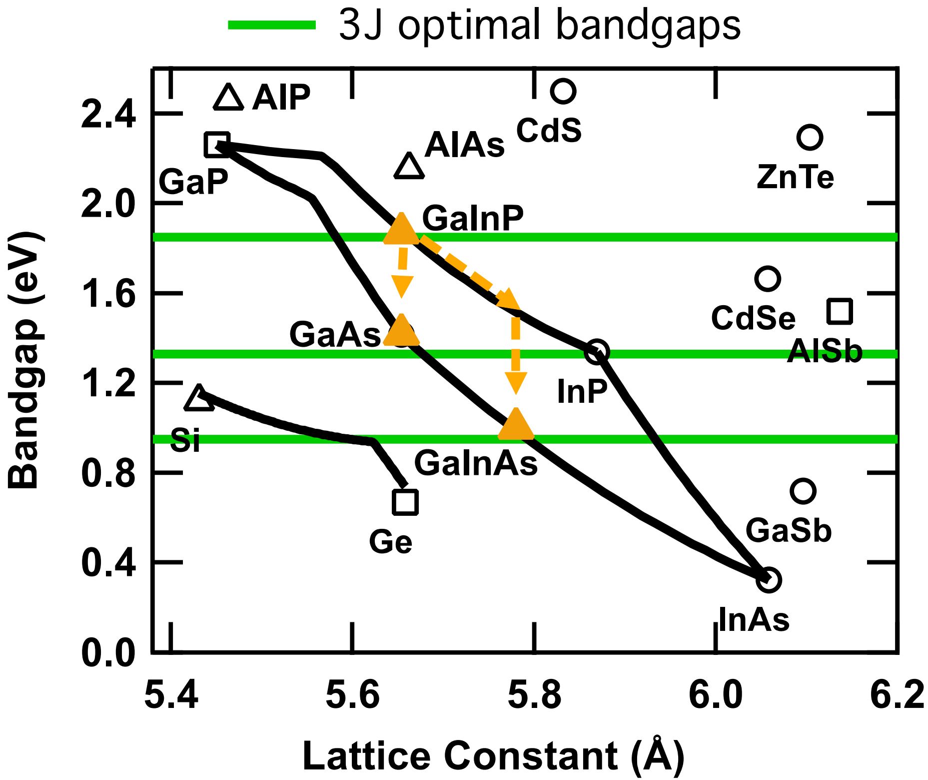
Low- dislocation density active material



Dislocations within graded buffer

TEM

3-junction solar cell approaches

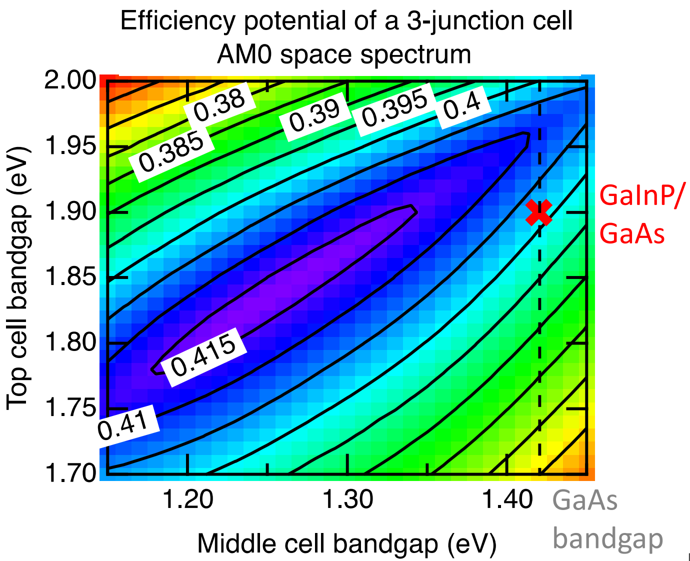


Standard Ge-based

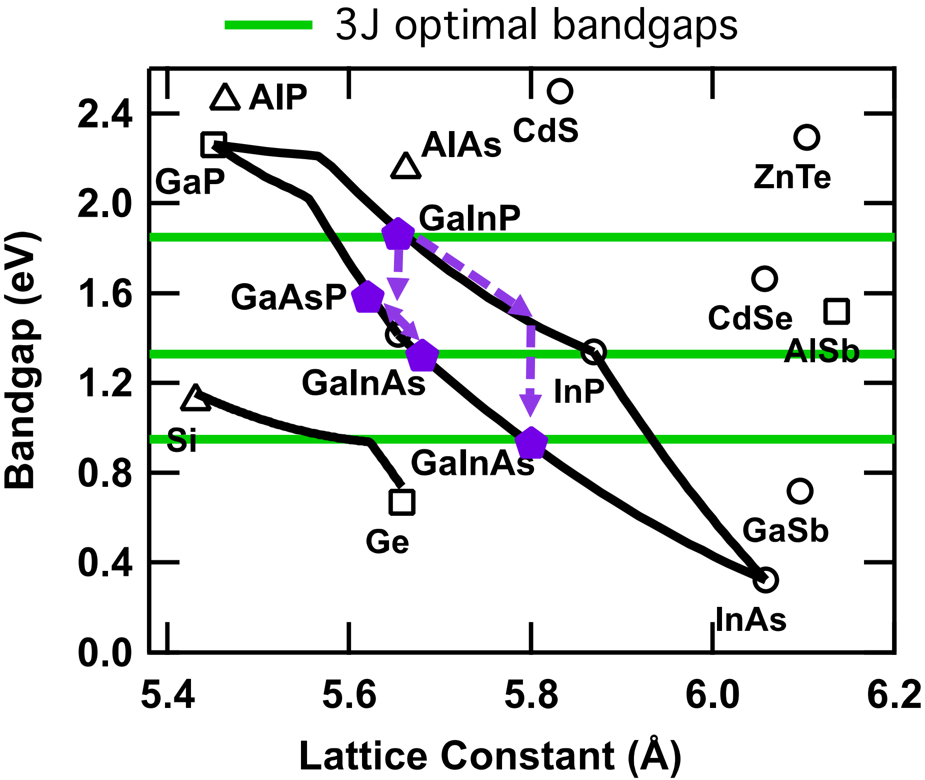
Inverted Metamorphic

QW + metamorphic

- Lower bandgap middle cell is better, but competes with high-quality GaAs



3-junction solar cell approaches

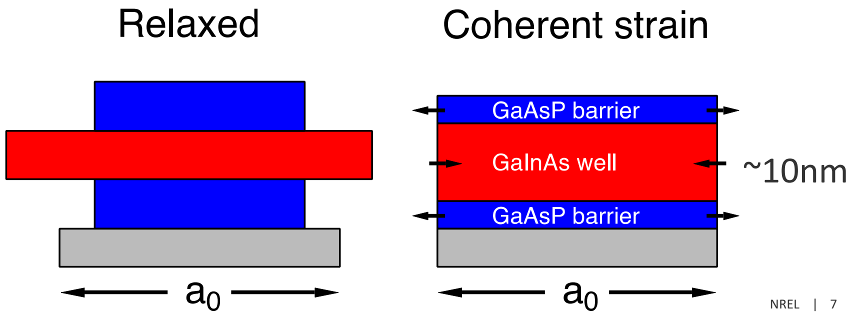


Standard Ge-based

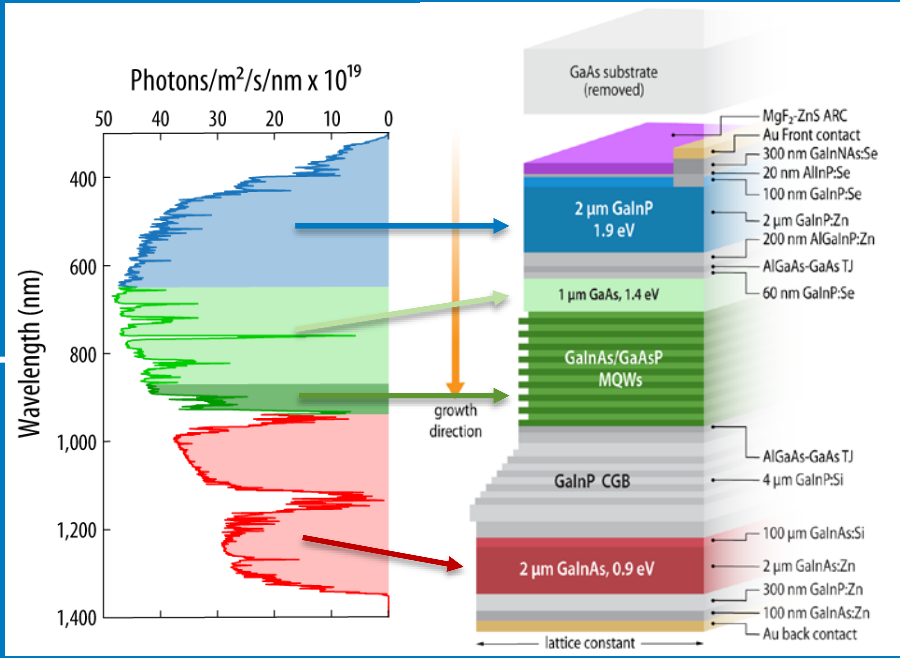
Inverted Metamorphic

QW + metamorphic

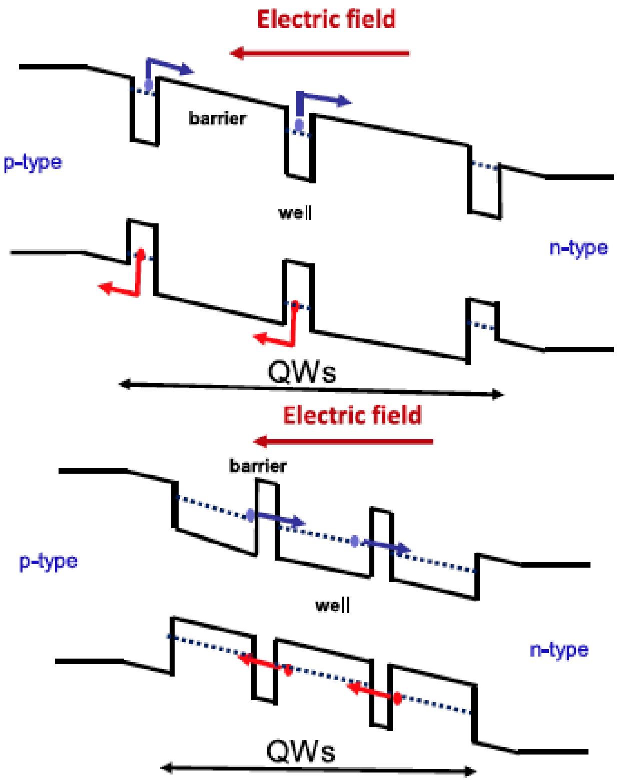
- Pseudomorphic compressive $Ga_{0.9}In_{0.1}As$, thinner than the critical thickness
- Stress-balance with tensile $GaAs_{0.9}P_{0.1}$
- Optimal 3J bandgap combination



Quantum-well Solar Cells



Quantum-well solar cell background



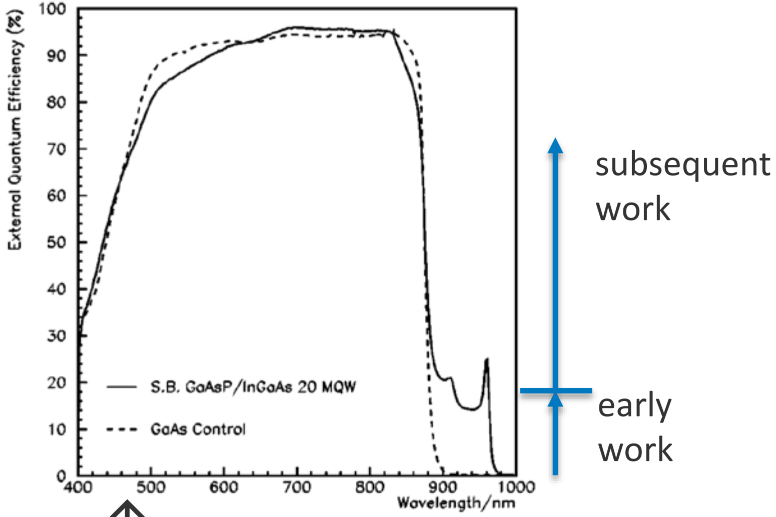
Thermionic emission out of wells

Tunneling through the barriers

Transport is dominated by drift in the electric field, rather than diffusion.

Sayed and Bedair, JPV **9**, 402 (2019)

Quantum efficiency



Ekins-Daukes *et al.*, APL **75**, 4195 (1999)

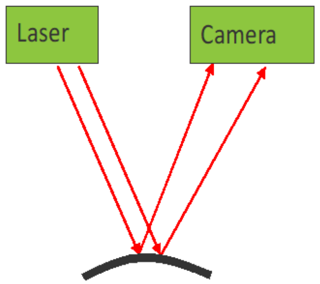
Initial quantum well solar cell work:
-Wanlass and Blakeslee, 1982
-Chaffin, Osbourn, Dawson, Biefeld, 1989
-Barnham, 1990, many works from Imperial College
QW solar cell commercialization:
-Tibbits et al, 2008, Brown et al, 2013

Challenges with QW solar cells

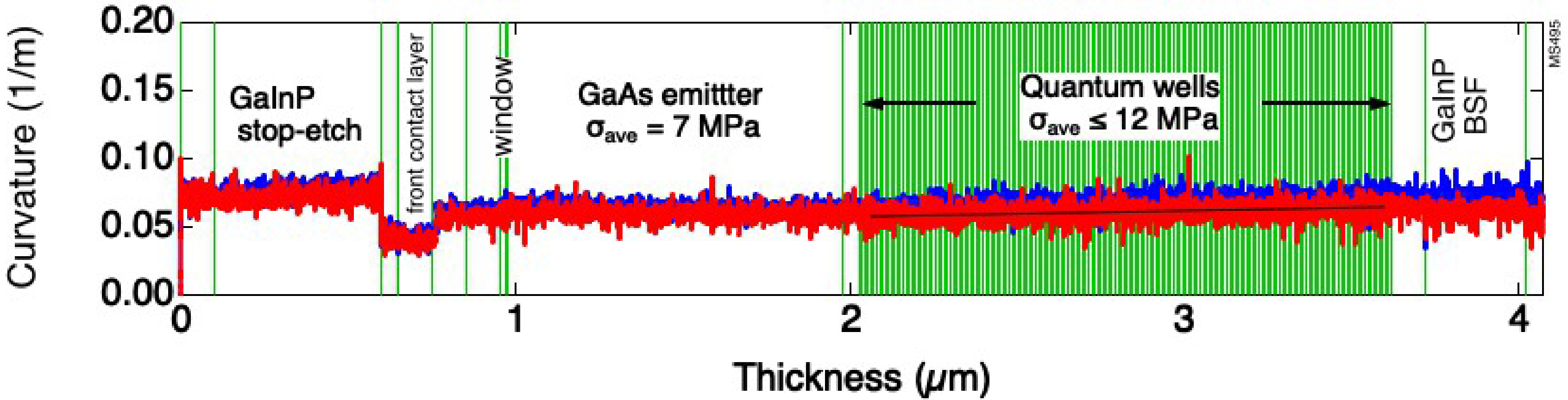
Materials challenges

- **Strain-balancing**
- Interfacial layers
- Strained-surface control

Wafer curvature



MQW solar cell



Challenges with QW solar cells

Materials challenges

- Strain-balancing
- **Interfacial layers**
- Strained-surface control

TEM of QW solar cell

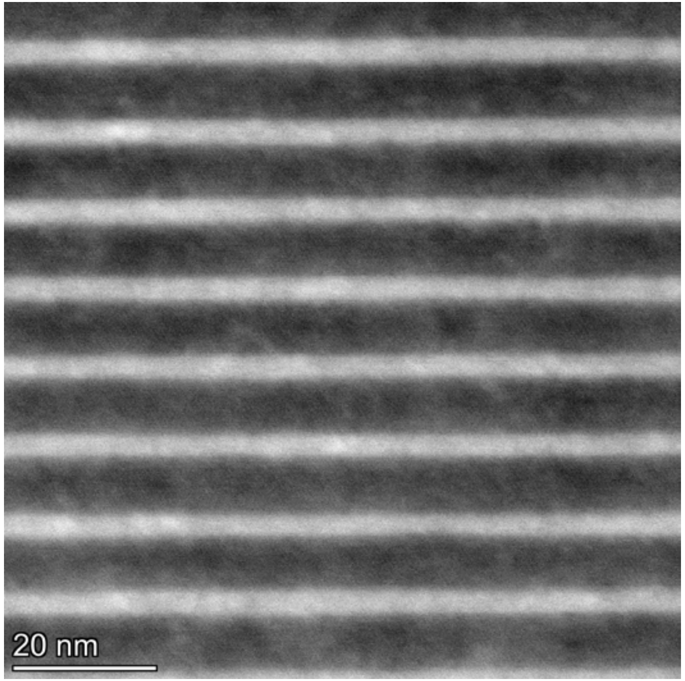
- High mag. imaging shows good interfaces

Transmission Electron Microscopy

high magnification

GaAsP
GaInAs

GaAsP
GaInAs

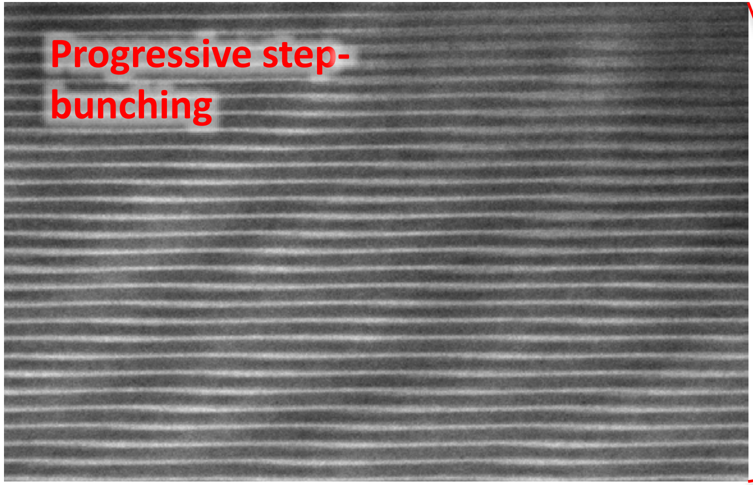


BF STEM performed by J. Selvidge, UCSB

Challenges with QW solar cells

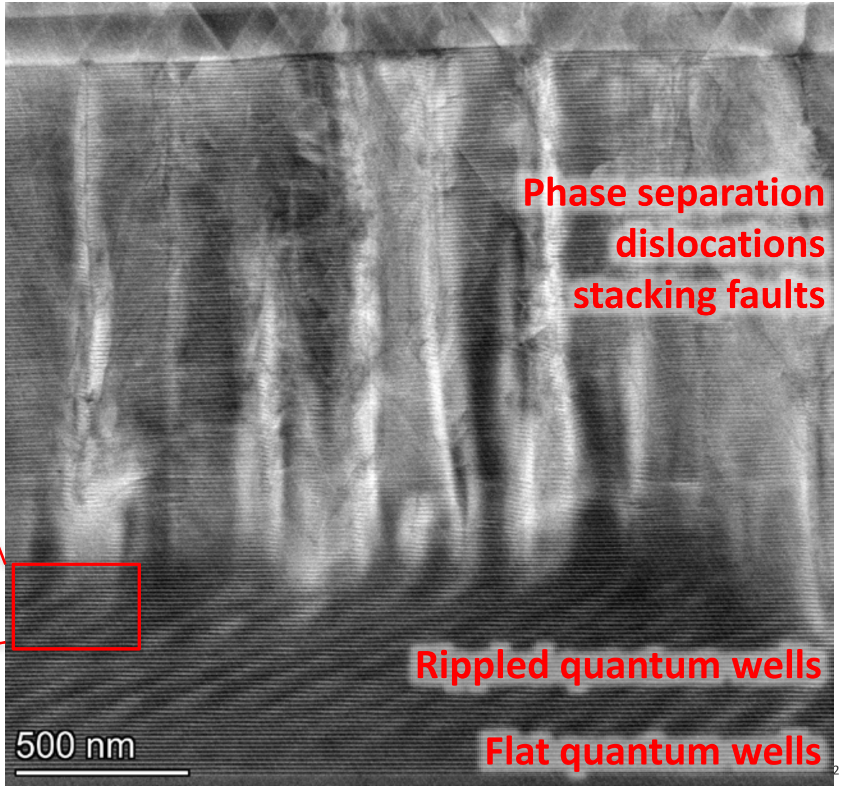
Materials challenges

- Strain-balancing
- Interfacial layers
- **Strained-surface control**



“Self-organized growth of alloy superlattices”
P. Venezuela et al, Nature, **397**, 678 (1999).

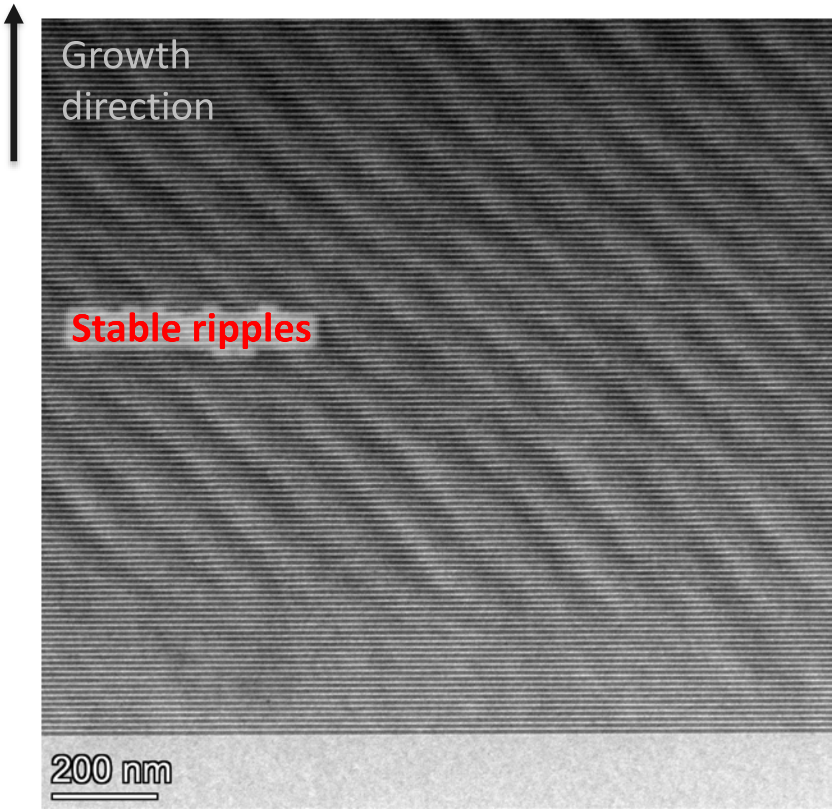
Transmission Electron Microscopy
low magnification

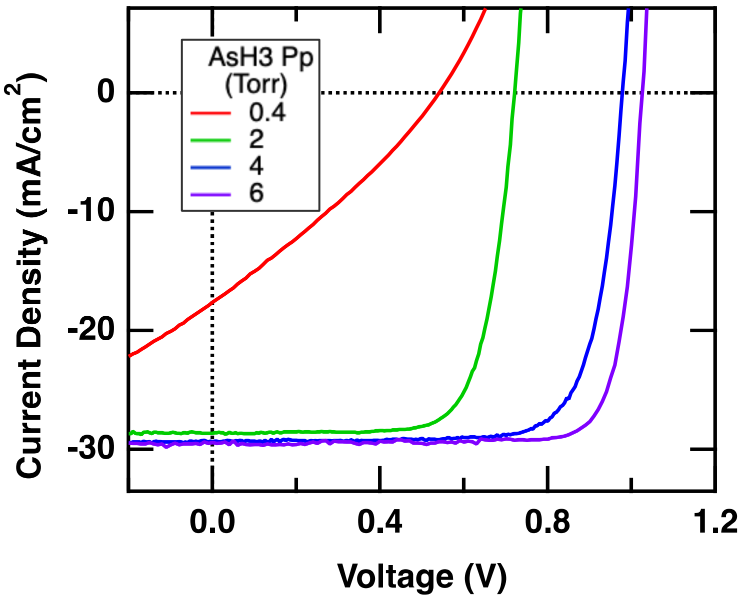


Material quality in QWs

MQW solar cell with **high** GaInAs AsH_3 partial pressure

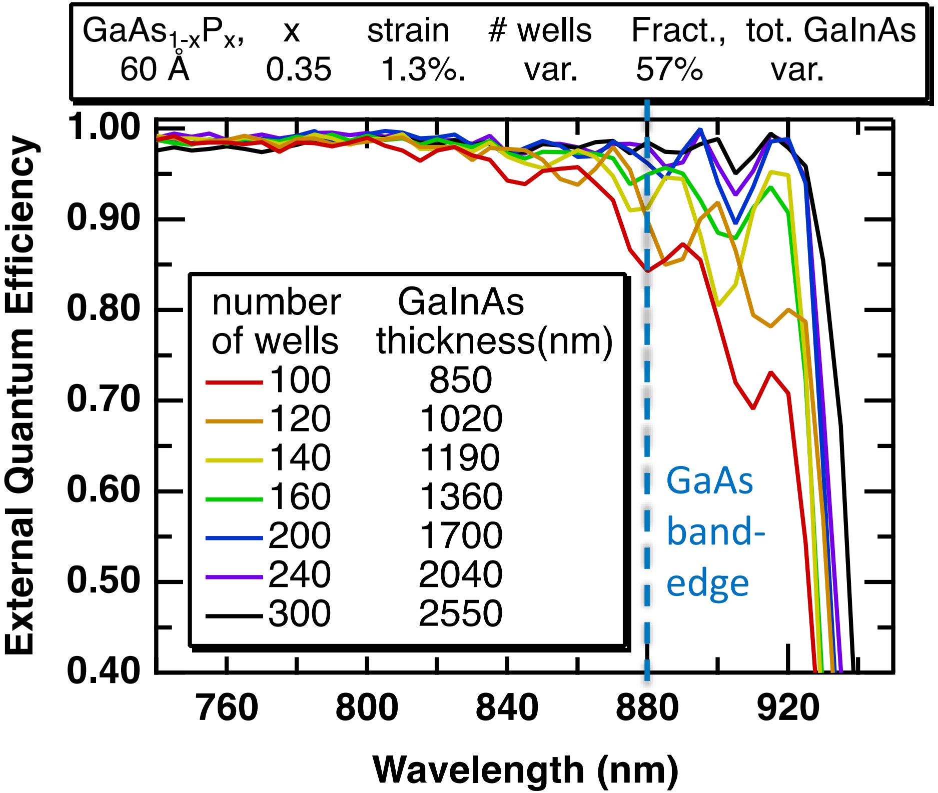
- Eg = 1.34 eV
- Voc > 1.02 V

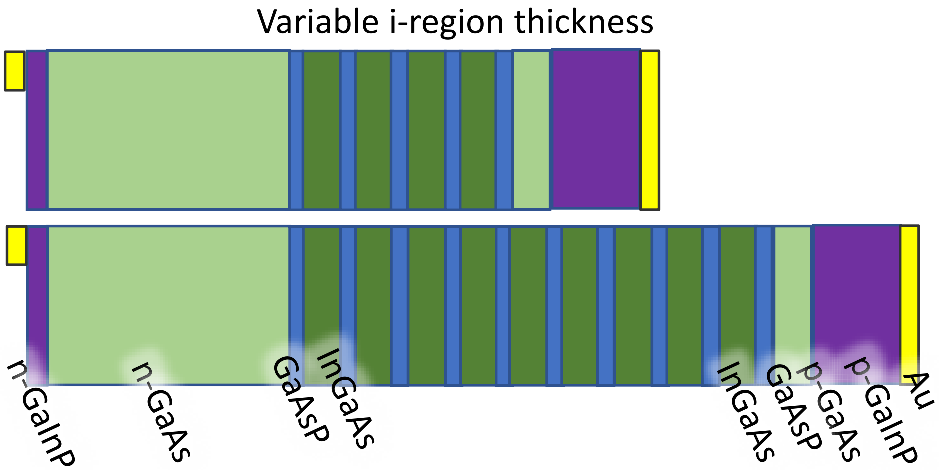




Growth conditions limit surface segregation, improves solar cell performance

Optically-thick QW devices





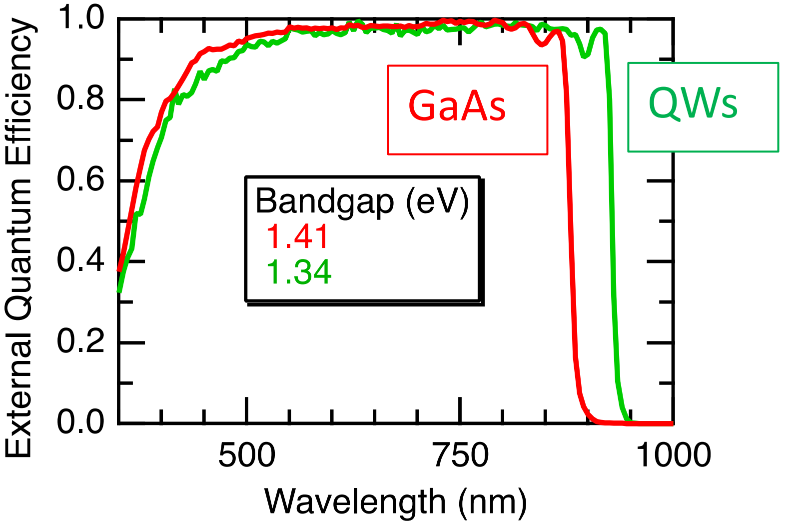
Sub-bandgap Jsc increase up to:

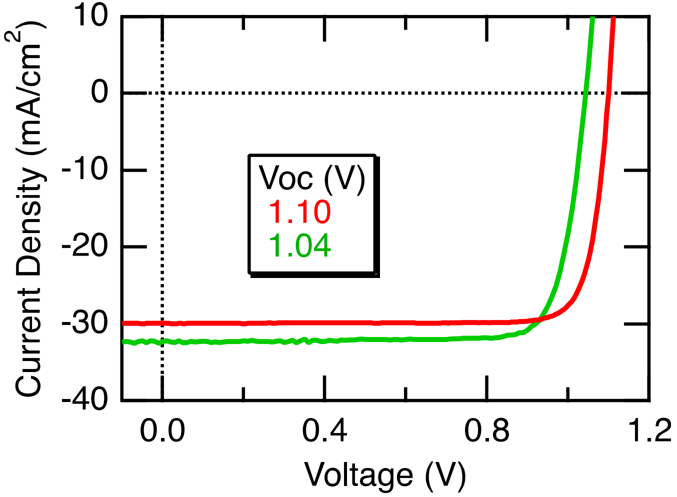
2.8 mA/cm² AM1.5G

3.6 mA/cm² AM0

High performance QW devices

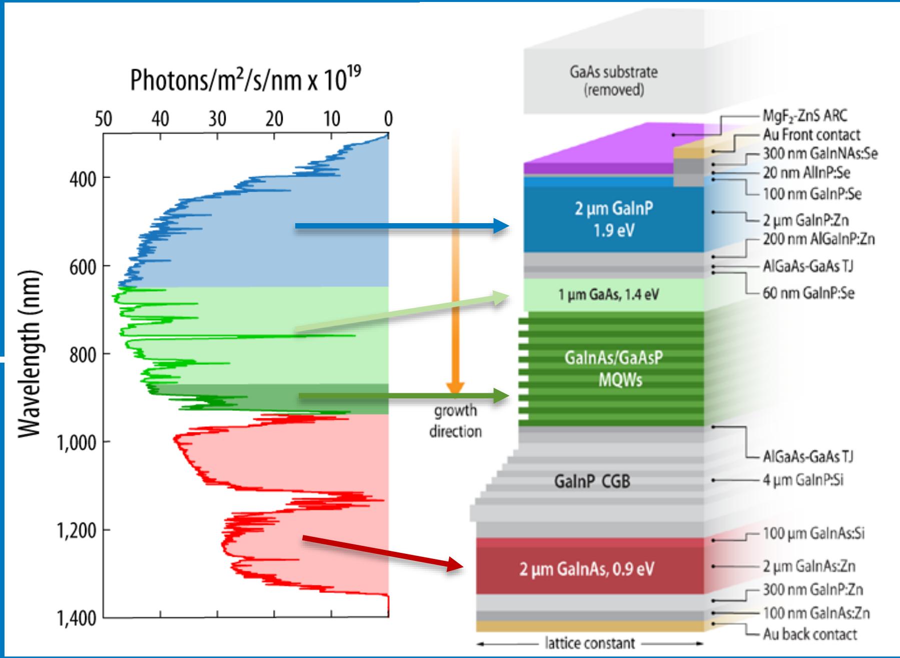
- Jsc increase wrt GaAs of 2.5 mA/cm^2 AM1.5G and 3.1 mA/cm^2 AM0
- Max 1J QW efficiency of 27.5% AM1.5G and 23.9% AM0
- Other work: thin GaAsP barriers, doped QWs, DBRs





Demonstrated optically-thick QW device with excellent performance

GaInP top cell



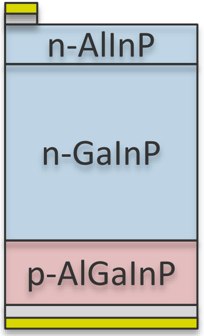
GaInP top cell structure: rear vs front junction

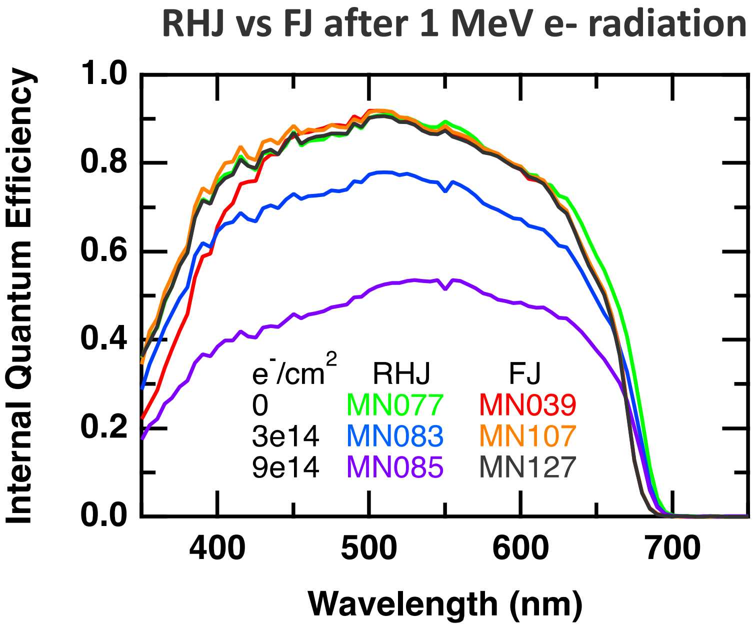
Rear Heterojunction (RHJ)

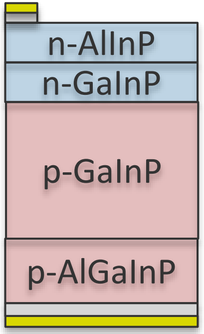
- voltage is excellent
- diffusion length is limited
- poor post-radiation performance

Front homojunction (FJ)

- voltage is low
- diffusion length is good
- good post-radiation performance

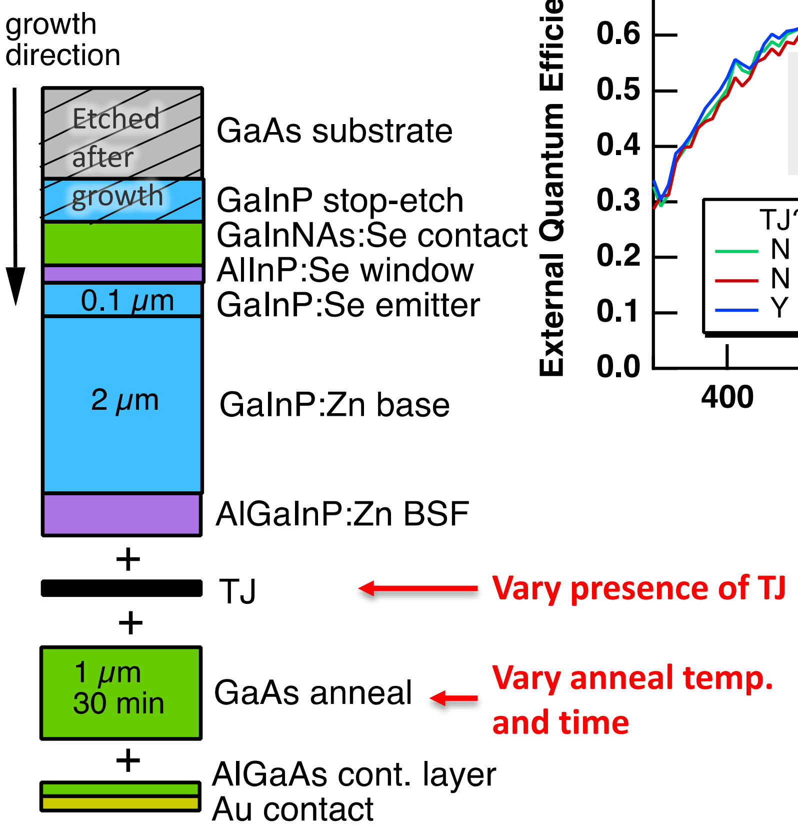


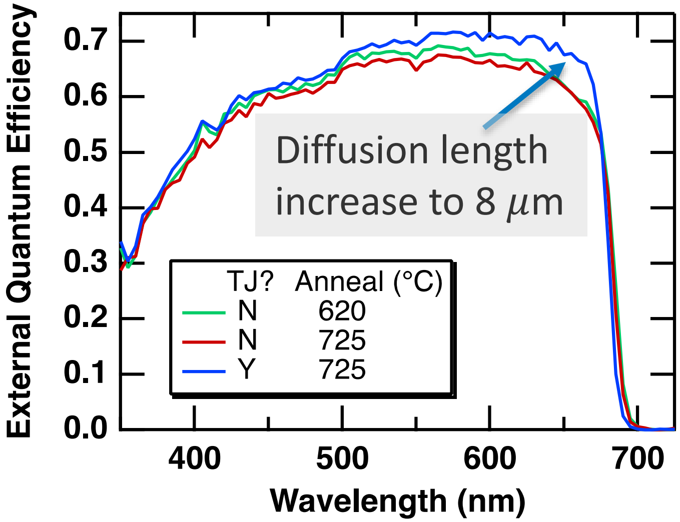


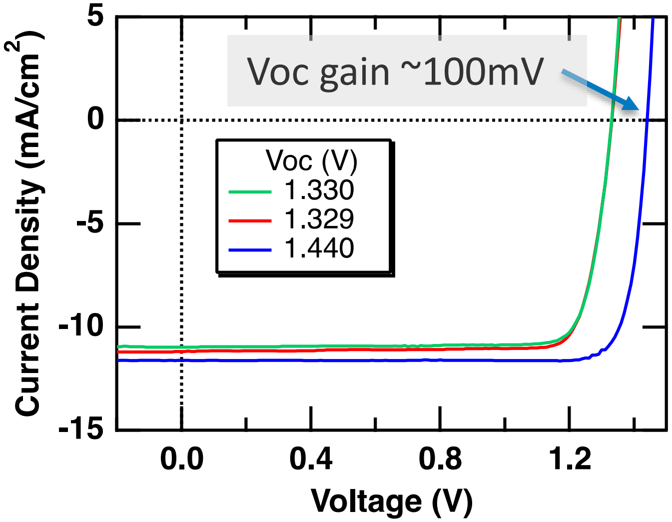


High performance GaInP:Zn by annealing

Inverted GaInP solar cells

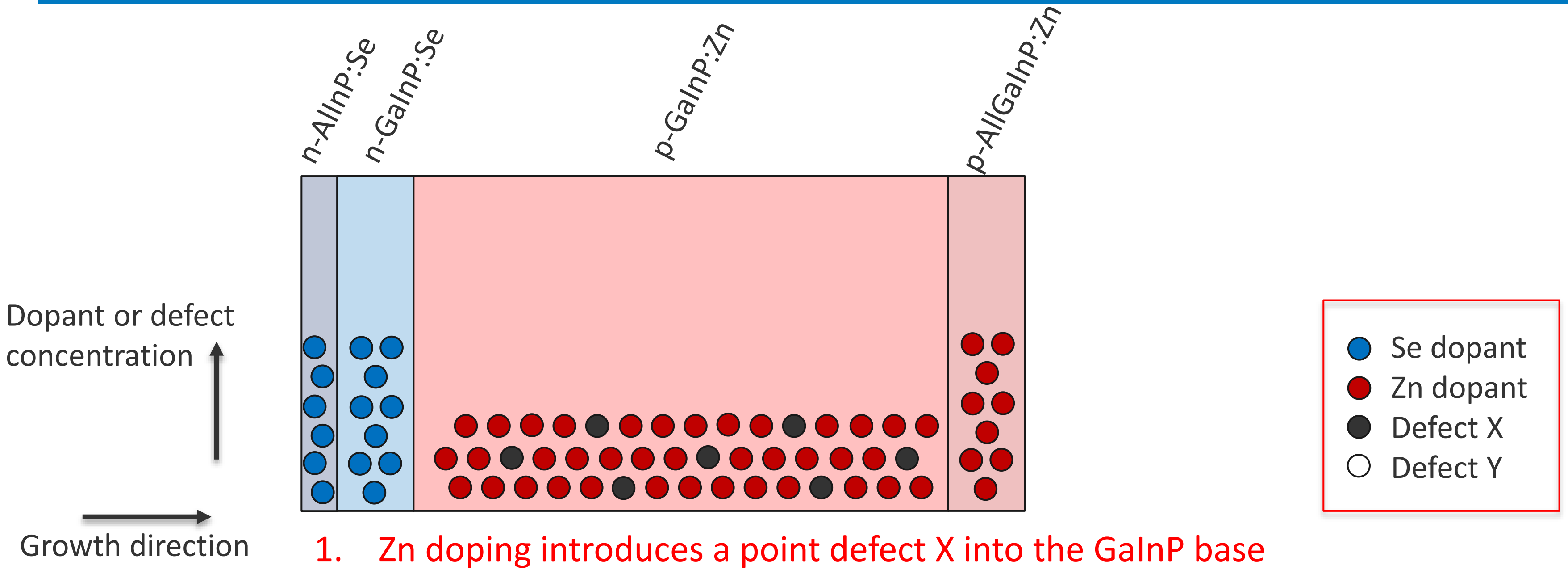






- 19.8% AM1.5G efficiency front-junction GaInP (w/out rear reflector)
- Theory: TJ introduces complementary point defects that annihilate native defects

Hypothesis: point defect passivation

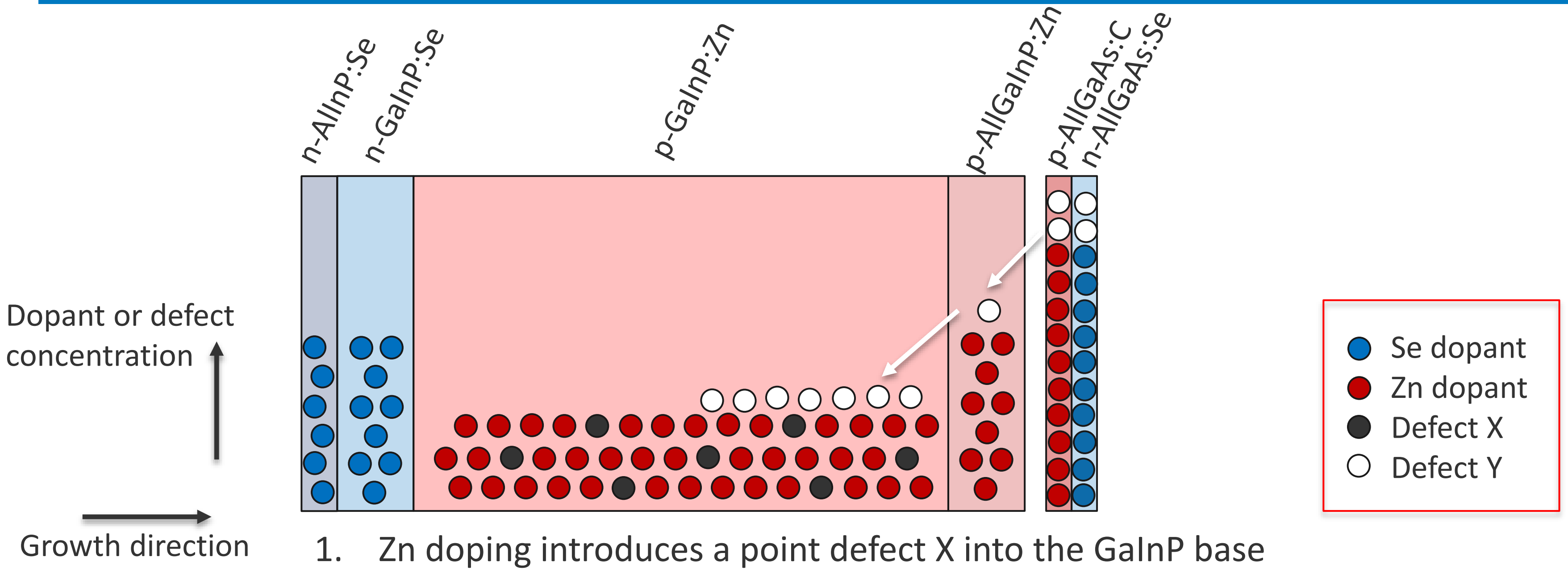


1. Zn doping introduces a point defect X into the GaInP base
2. The TJ injects a complementary point defect Y
3. After anneal, defect Y passivates defect X

Examples: X = V_Ga, Y = i_Ga

X = i_Zn,   Y = V_Ga

Hypothesis: point defect passivation



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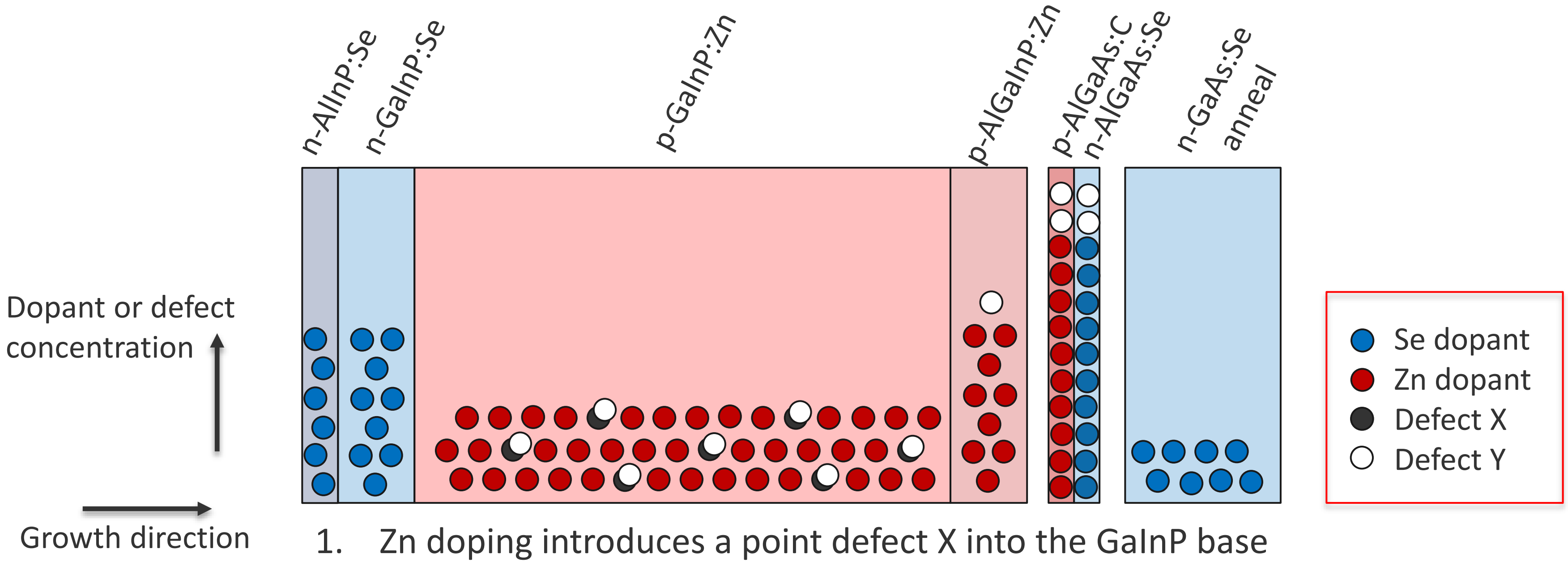

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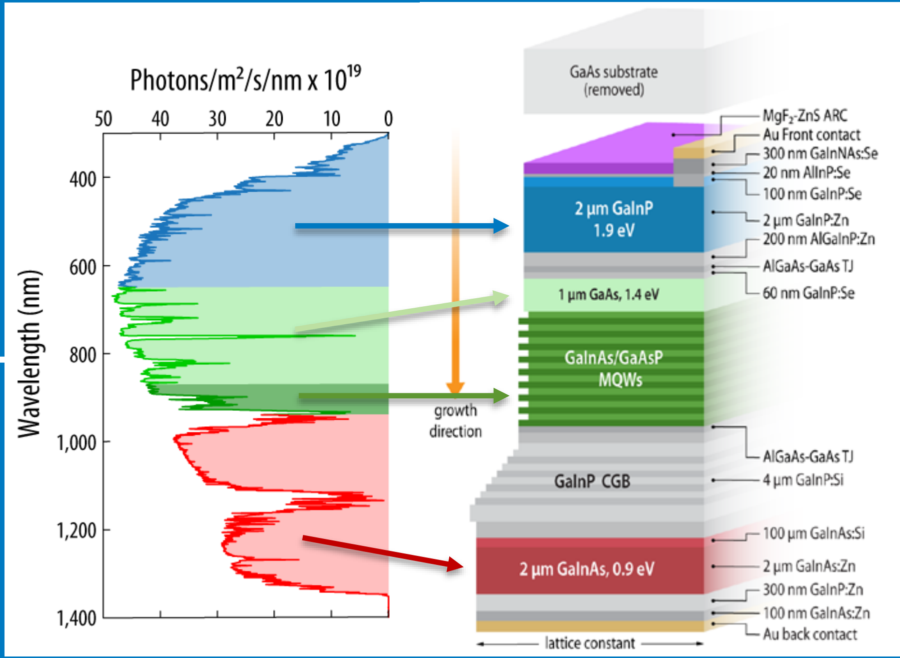
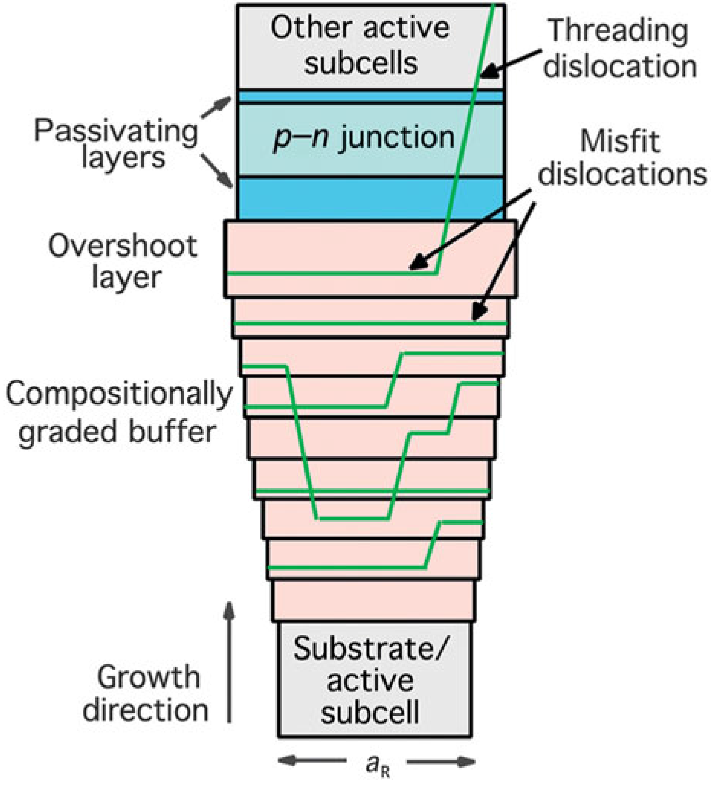
Examples: X = V_Ga, Y = i_Ga
X = i_Zn, Y = V_Ga

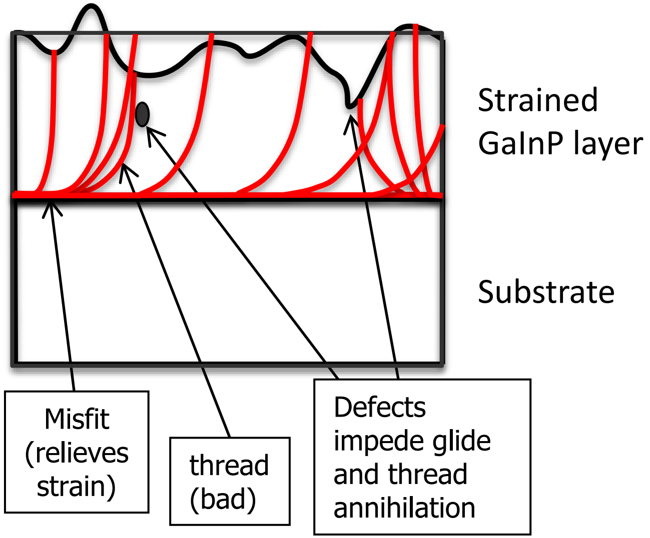
Metamorphic bottom cell



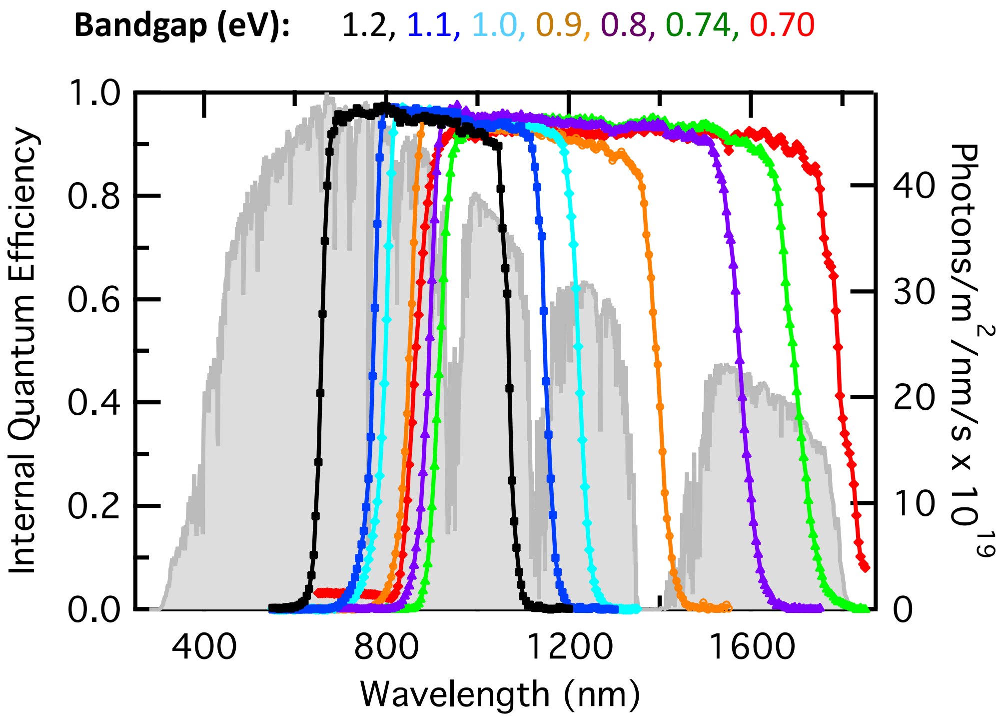
Metamorphic Material

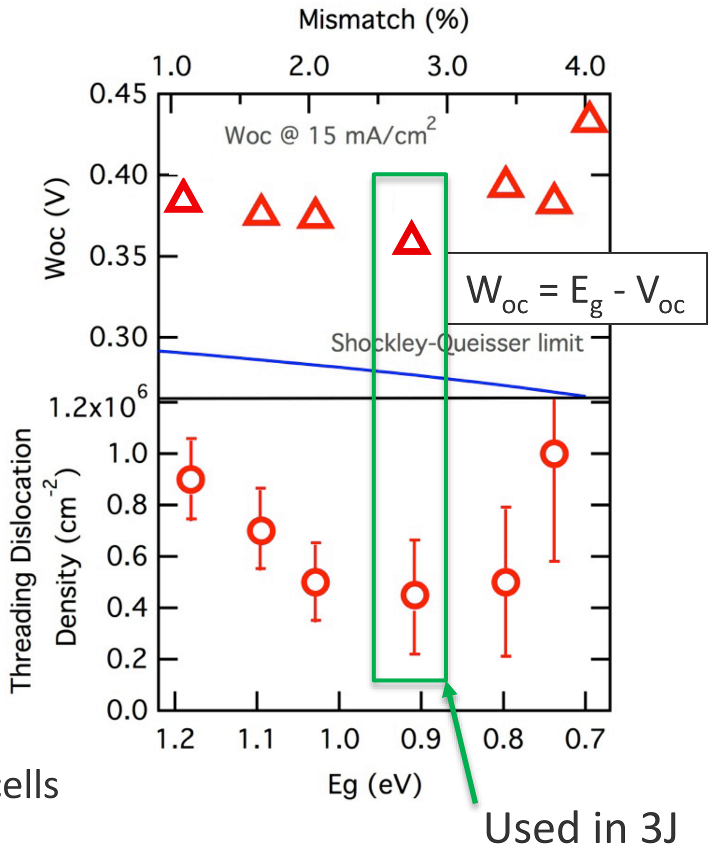


- Intentionally introduce dislocations to alter in-plane lattice constant
- Need to minimize threading dislocation density for performance
- *Maximize dislocation glide*



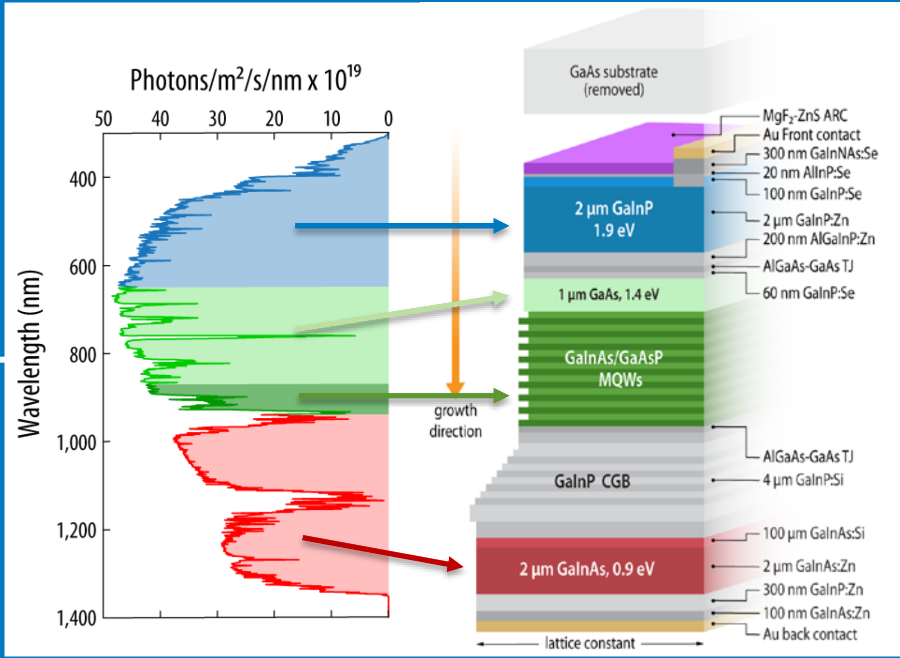
Metamorphic GaInAs cell performance





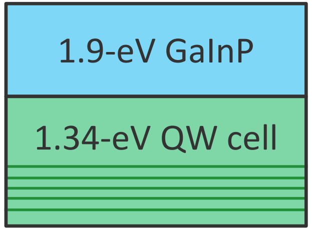
Graded buffers can be used for lattice-mismatched GaInAs subcells with collection spanning large portion of solar spectrum

Multijunction cell results



Two-Junction GaInP/GaAs+MQW cells

2J structure



- 184 GaInAs wells

RECORD RESULTS

AM1.5G IV data

Voc = 2.51 V

FF = 87.3 %

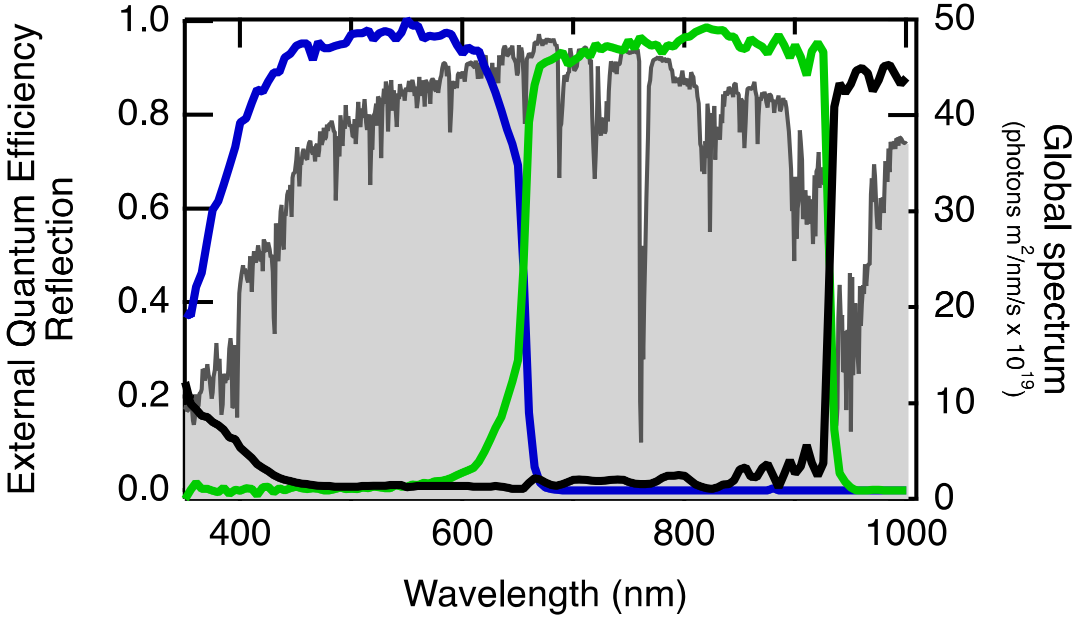
Jsc = 15.0 mA/cm^2

AM1.5G Efficiency = 32.9%

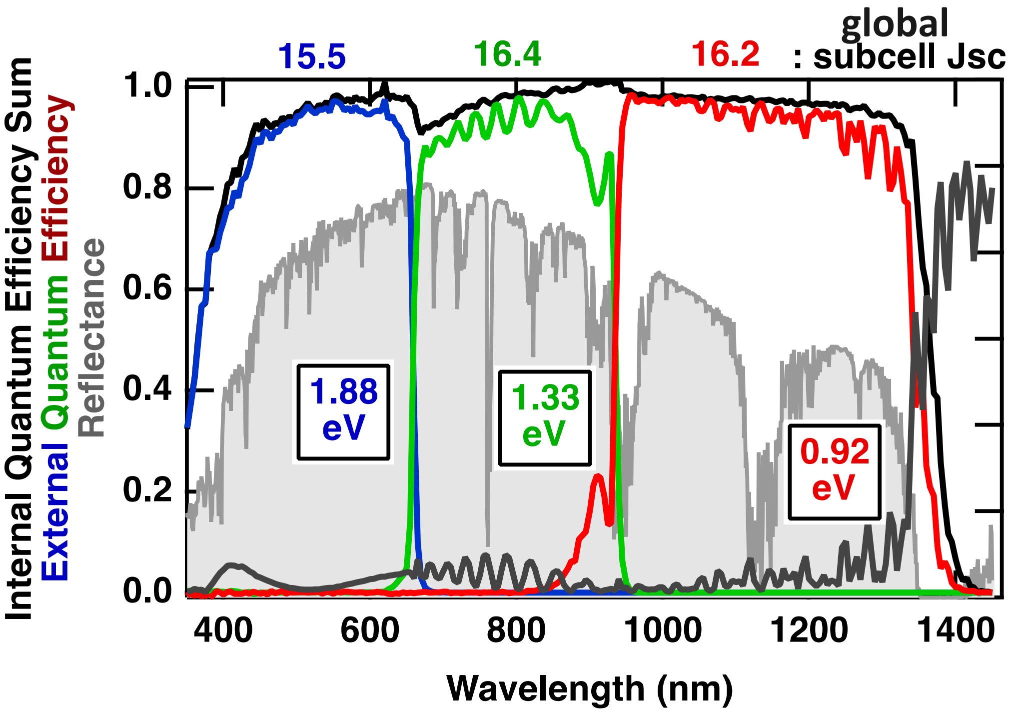
AM0 Efficiency = 29.2%

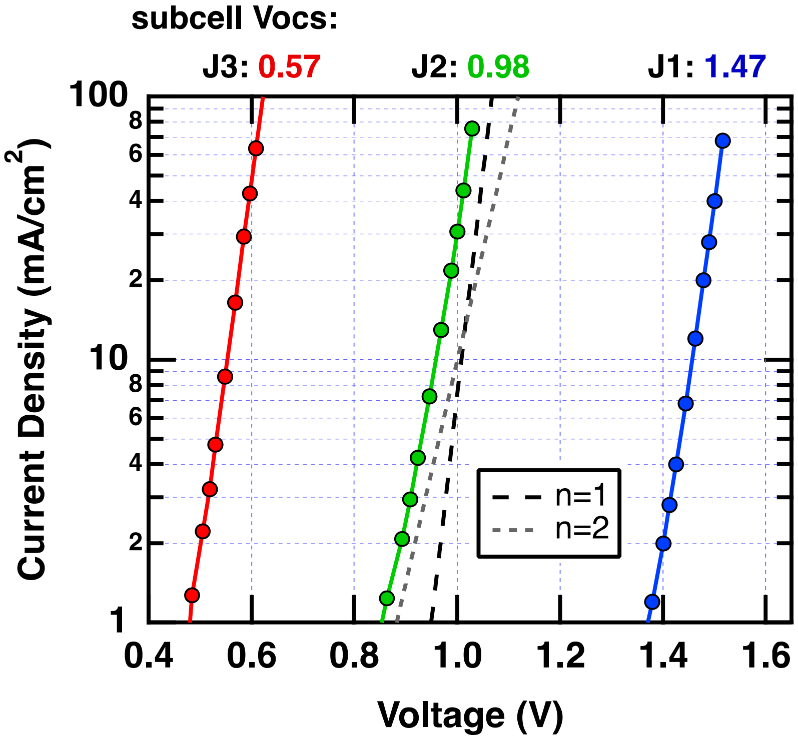
Integrated subcell Jscs

	J1	J2
AM1.5G (1000 W/m^2)	15.3	17.6
AM0 (1366 W/m^2)	19.1	19.8



3-junction cell results: subcell analysis

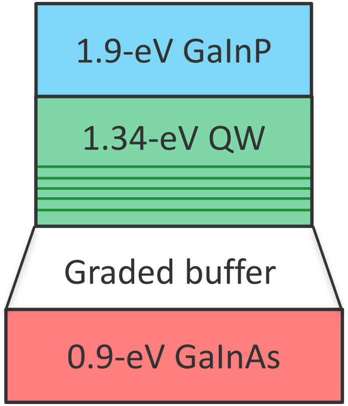




Woc = E_g/q - Voc : GaInP = 0.41 V / GaAs-QW = 0.35 V / LMM GaInAs = 0.35 V

Record 3-Junction GaInP / GaAs+MQW / GaInAs cells

3J structure



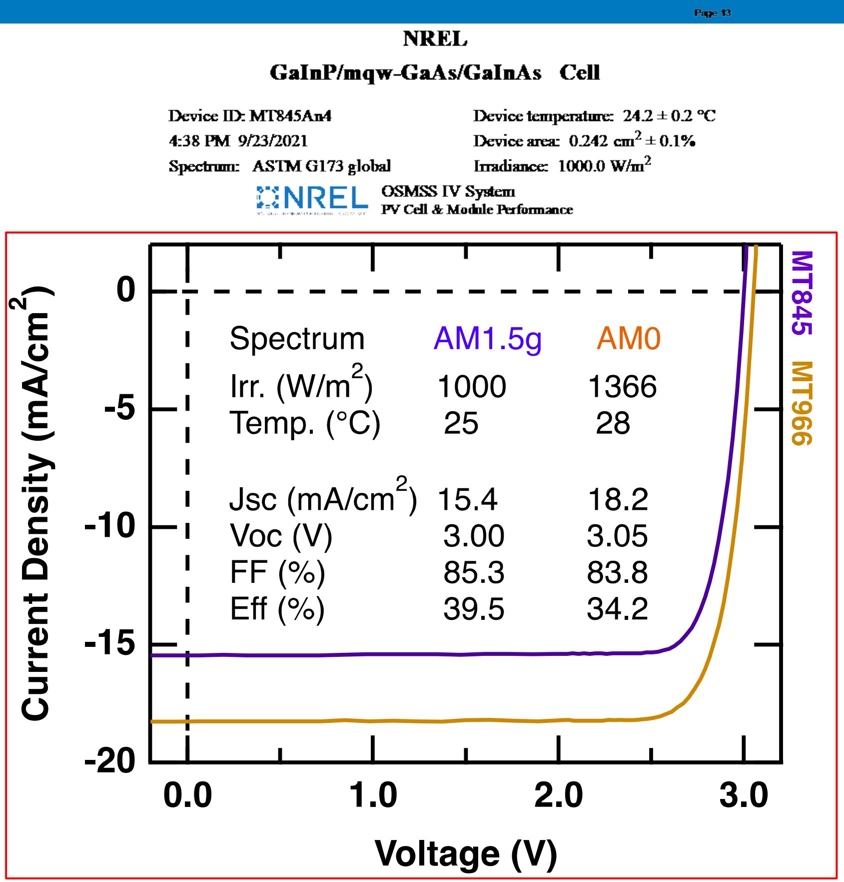
- 184 GaInAs wells
- 1560 nm GaInAs
- No DBR behind QWs

AM1.5G efficiency = 39.5%

AM0 efficiency = 34.2%

France *et al.*, Joule, 6, 1121, (2022)

Green *et al.*, Prog. Photovolt., 30, 3, (2022)

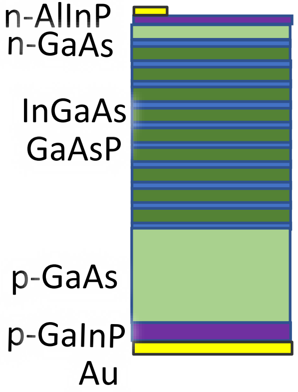


New world record!

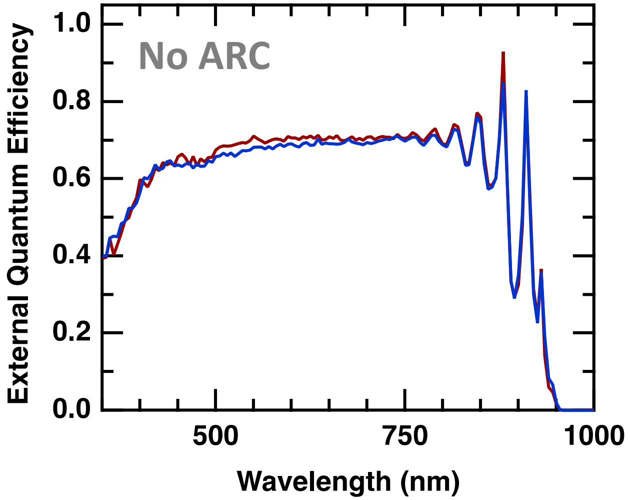
Radiation data: single junction QW cell

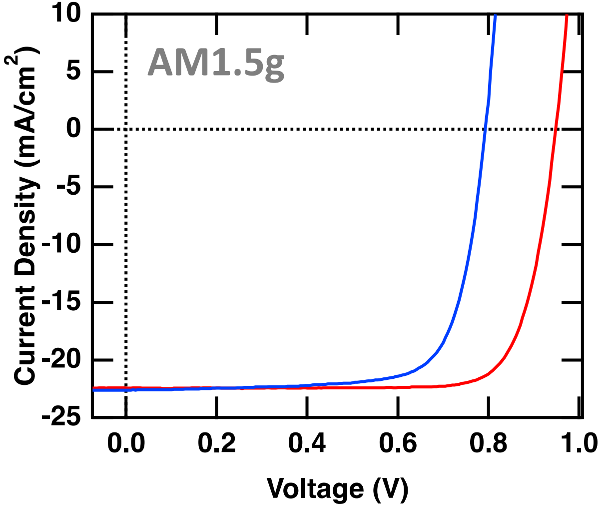
Structure

- Front junction QW cell
- p-i-n



BOL — EOL — 1MeV 5e14 e- radiation



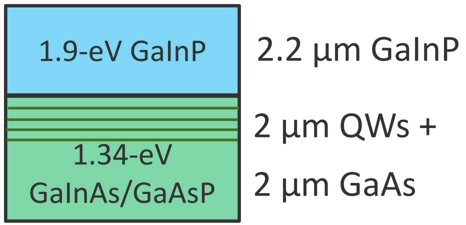


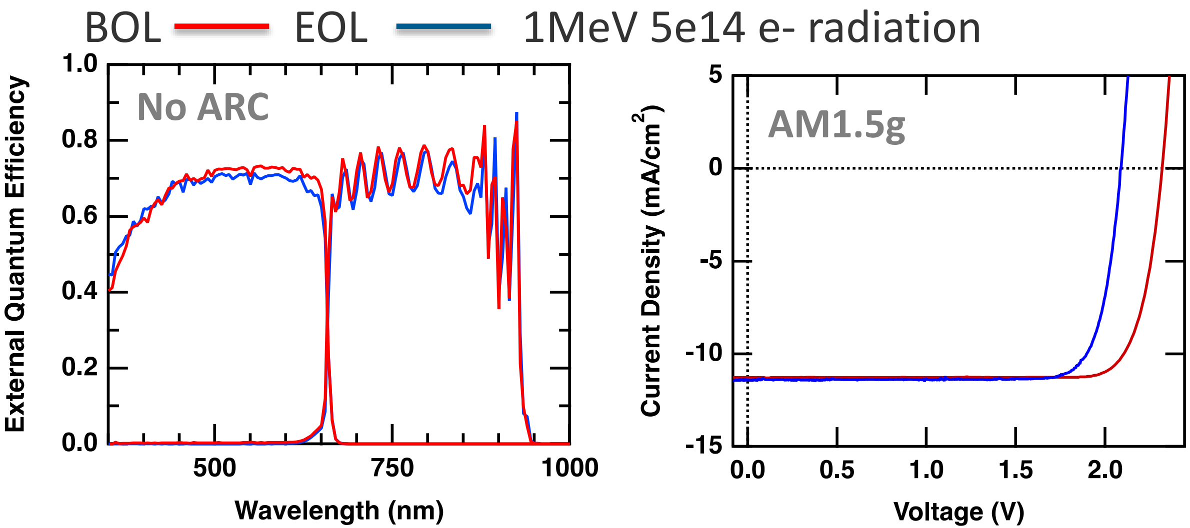
AM1.5g	BOL	EOL	Retention
Jsc (mA/cm²)	22.5	22.5	1.0
Voc (V)	0.948	0.793	0.84
FF (%)	79.7	75.0	0.94

- Voltage loss due to large depletion region
- EOL Woc of p-i-n QW cell is the same as a comparable p-i-n GaAs cell

Radiation data: dual junction cells

2J Structure





EOL subcell Jscs:

J1: 11.5 mA/cm^2

J2: 12.0 mA/cm^2

- Overdriven QW cell prevents FF loss
- Over 90% power retention after 5e14 1MeV e-

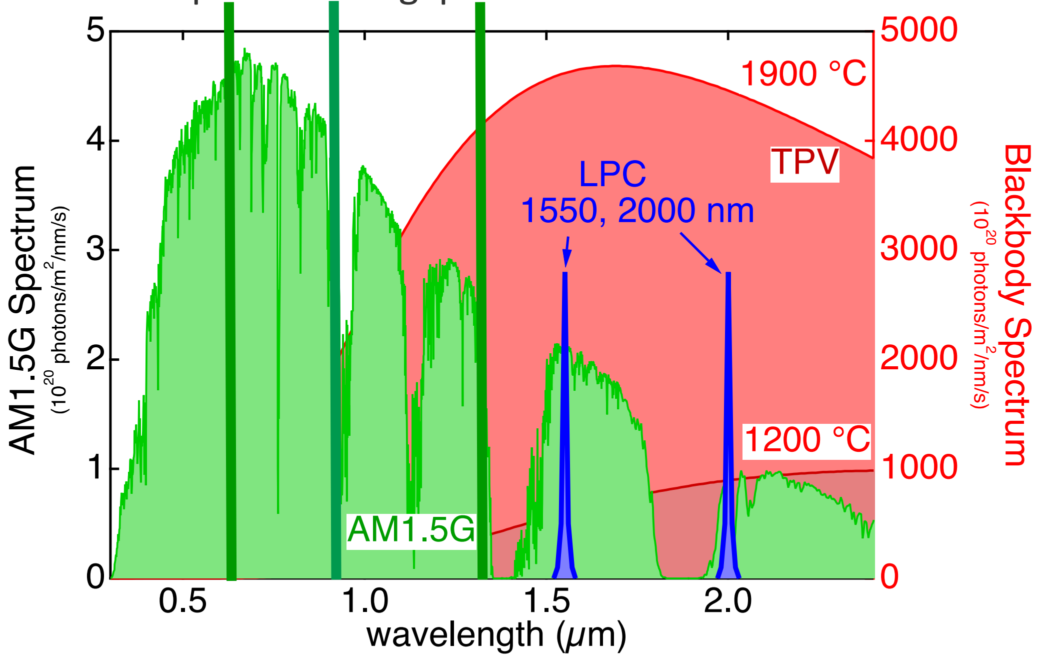
- Predicted AM0 EOL efficiency : >24%
  - Adapted to AM0 spectrum with ARC

AM1.5g	Pre-rad	Post-rad	Retention
Jsc (mA/cm^2)	11.28	11.45	1.01
Voc (V)	2.319	2.088	0.90
FF (%)	83.8	83.1	0.99
Eff (%)	21.9	19.9	0.91

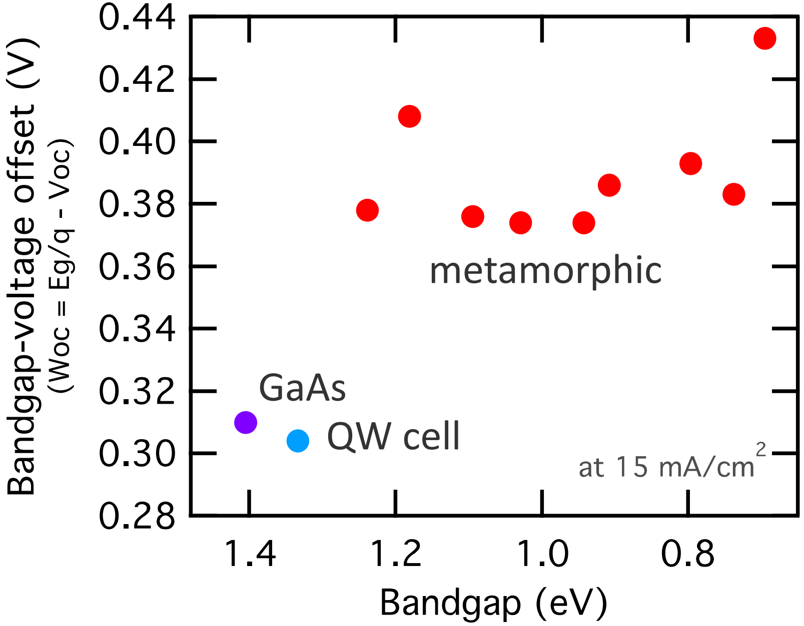
III-V applications

- Area-constrained applications, concentrators
- Space PV: Low-radiation, and potentially higher radiation
- Other uses of bandgap modification

3J optimal bandgaps



III-V cells grown on GaAs



III-V applications

nature

Article

Thermophotovoltaic efficiency of 40%

Alina LaPotin[1], Kevin L. Schulte[2], Myles A. Steiner[2], Kyle Buznitsky[1], Colin C. Kelsall[1], Daniel J. Friedman[2], Eric J. Tervo[2], Ryan M. France[2], Michelle R. Young[2], Andrew Rohskopf[1], Shomik Verma[1], Evelyn N. Wang[1] & Asegun Henry[1]✉

Sustainable Energy & Fuels

Photoelectrochemical water splitting using strain-balanced multiple quantum well photovoltaic cells†

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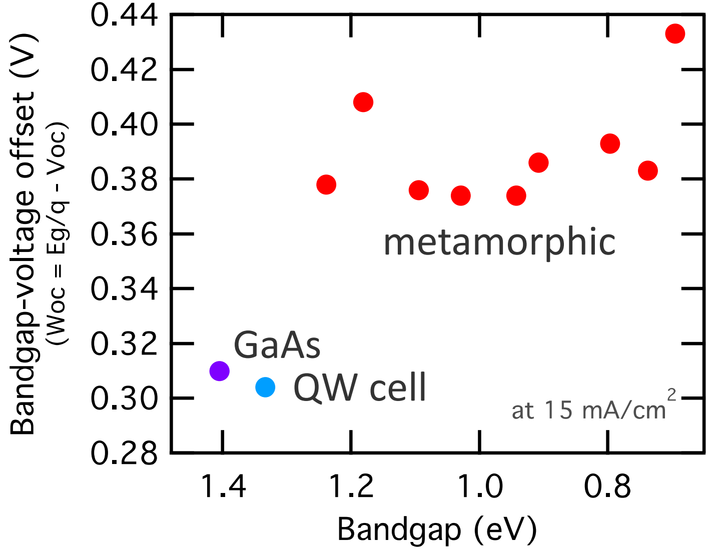
III-V cells grown on GaAs



Conclusions

QW solar cell

- excellent voltage
- optically thick

Record 2J and 3J solar cells

- optimal bandgap combination

2-junction cell efficiency

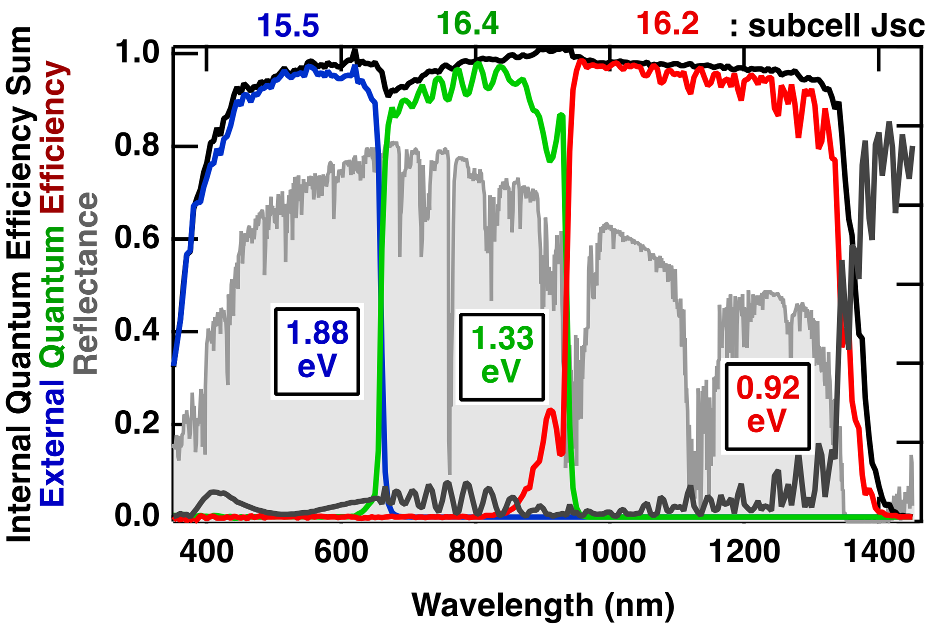
AM1.5G = **32.9%**

AM0 = **29.2%**

3-junction cell efficiency

AM1.5G = **39.5%**

AM0 = **34.2%**



Bandgap Voltage offset

($W_{oc} = E_g/q - V_{oc}$)

GaInP = 0.41 V

GaAs-QW = 0.35 V

LMM GaInAs = 0.35 V

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Thank you!

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