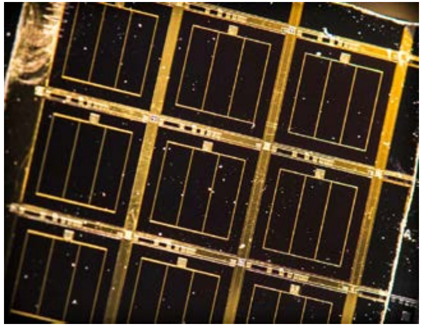
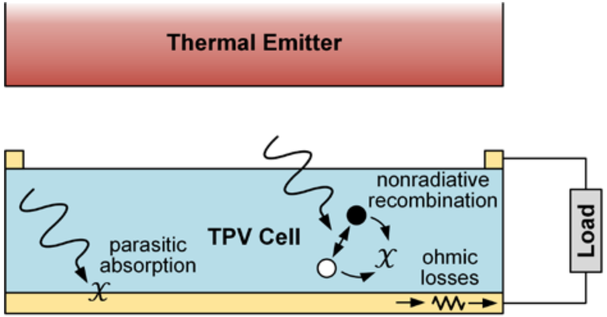
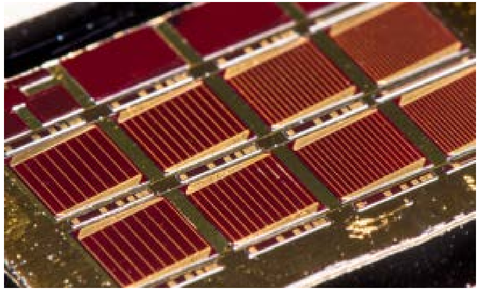
High efficiency multijunction devices:

Solar cells, Thermophotovoltaics, LEDs

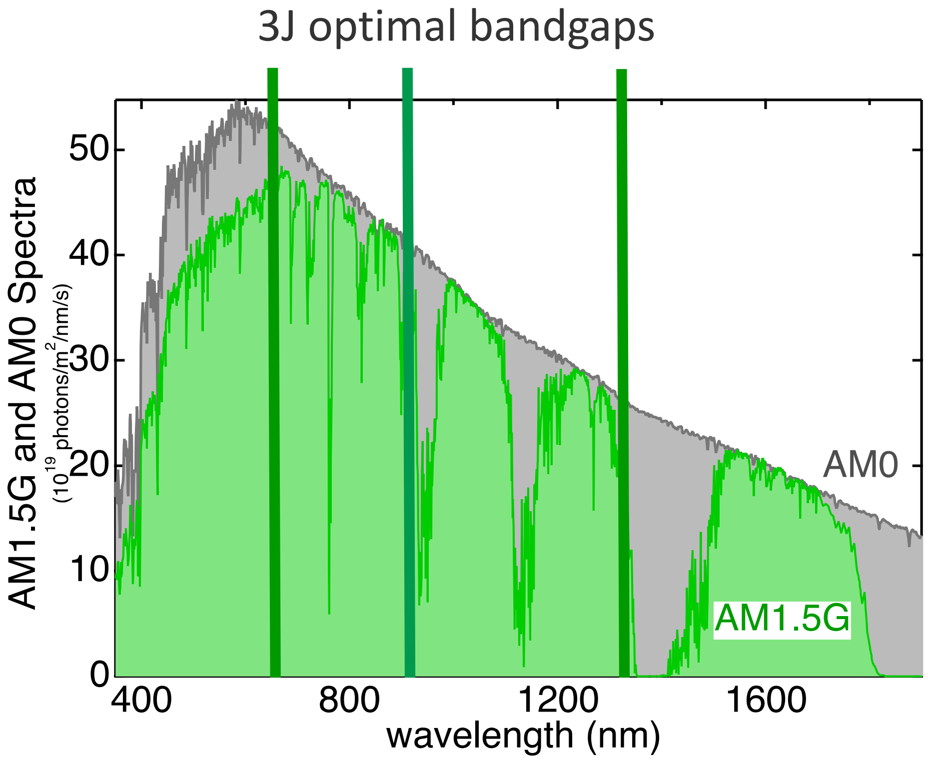
Ryan France 1/30/23

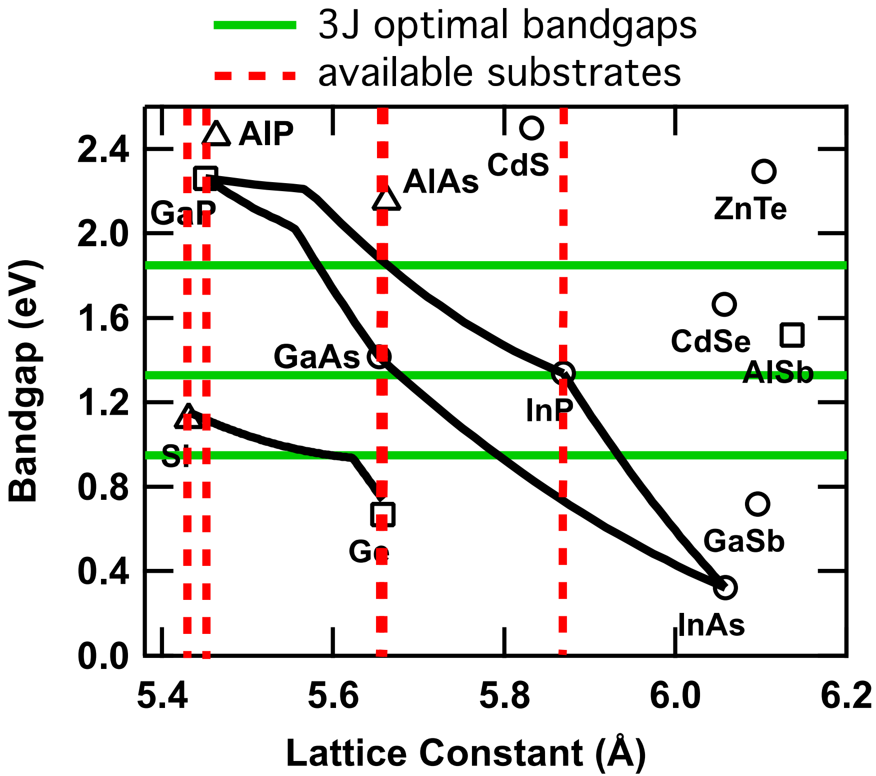






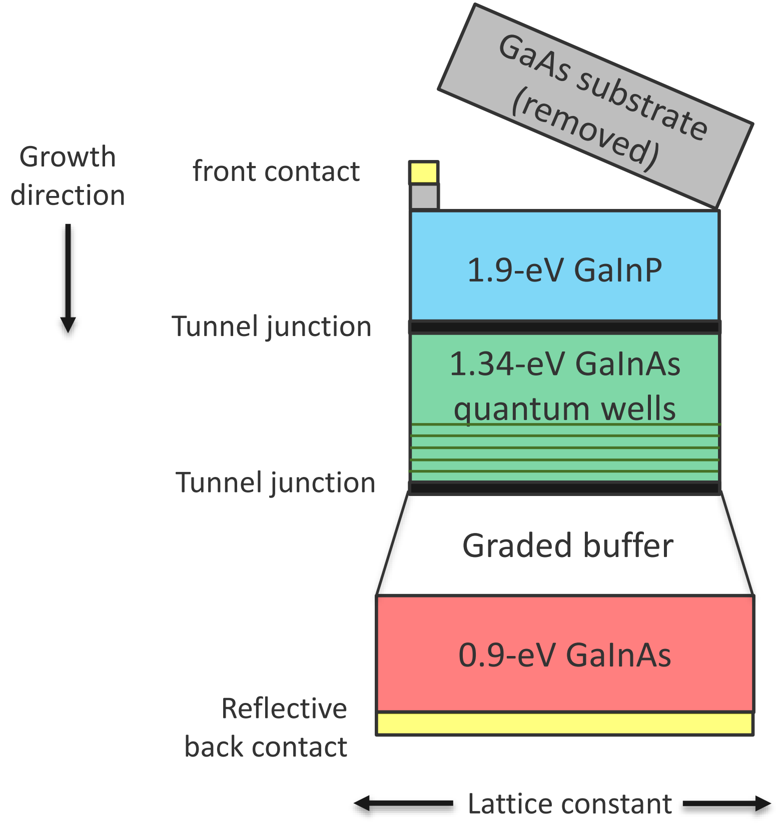
Optimal III-V materials for incident spectrum

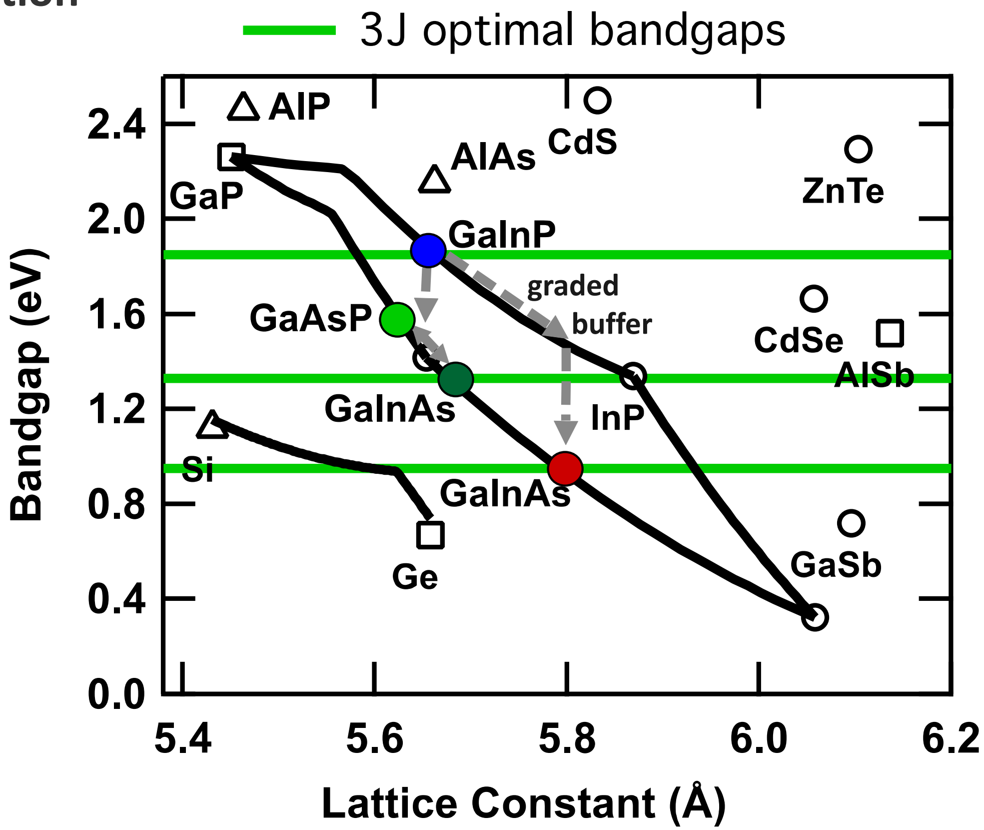




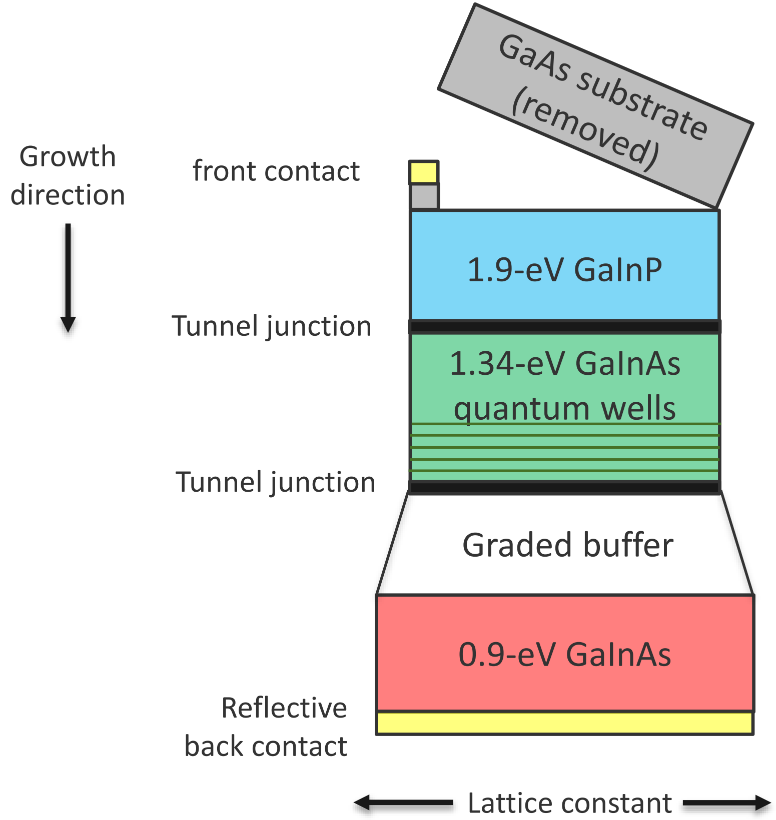
Record 3J components: optimizing bandgaps

Inverted metamorphic multijunction



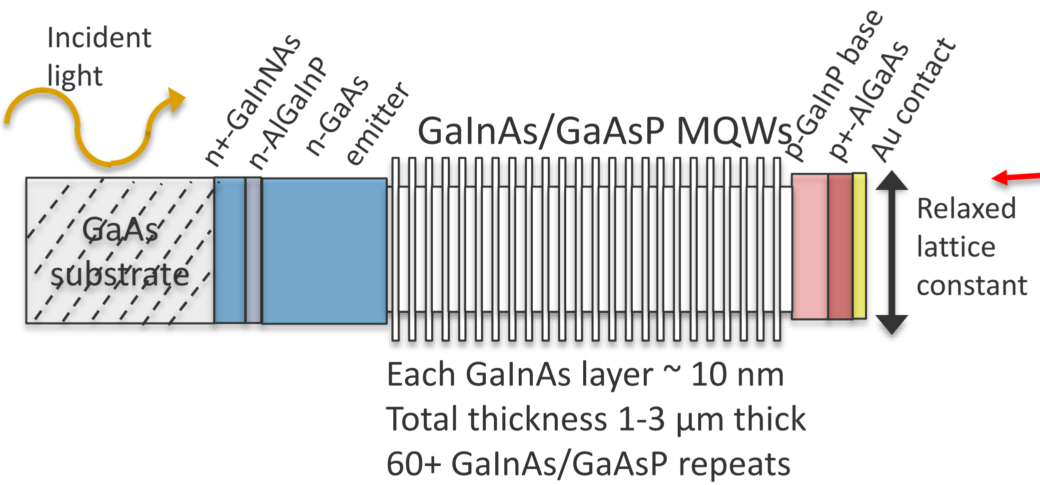


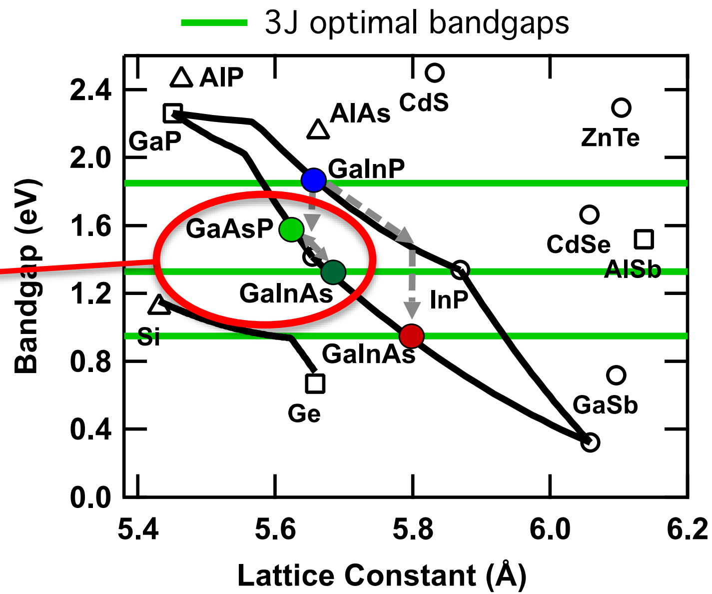
Outline



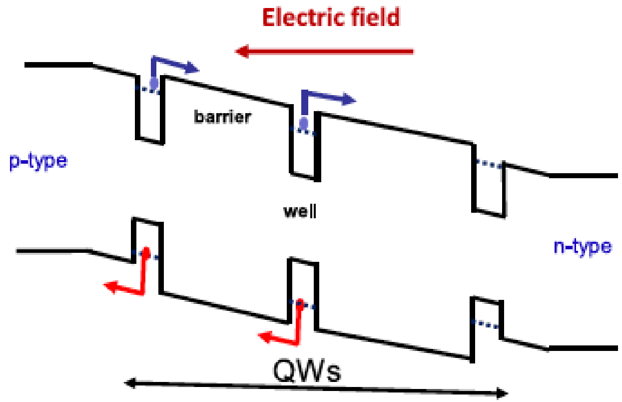
- 3-Junction cell device components
  - High performance GaInP
  - Quantum well solar cells
  - Graded buffers and mismatched solar cells
  - High bandgap tunnel junction
  - Thin film device with reflective contact
- 3J cell results
- Other uses of device components
  - Thermophotovoltaics
  - LEDs

Quantum-well Solar Cells

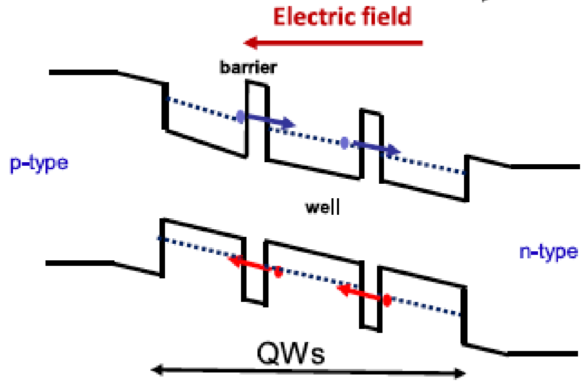




Quantum-well solar cell background



Thermionic emission out of wells

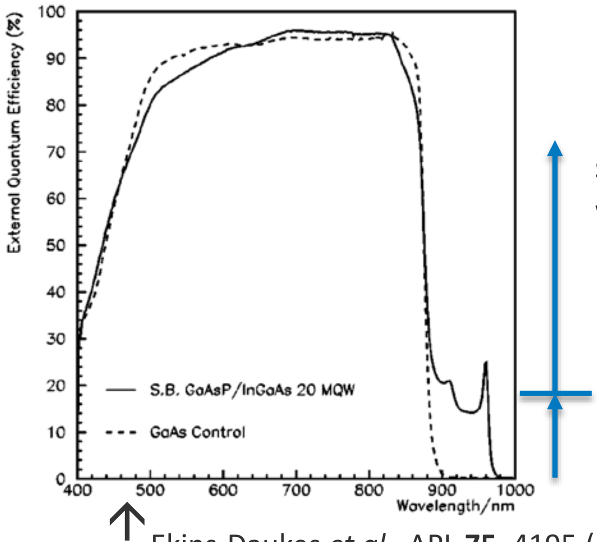


Tunneling through the barriers

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

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

Quantum efficiency



subsequent work

early work

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

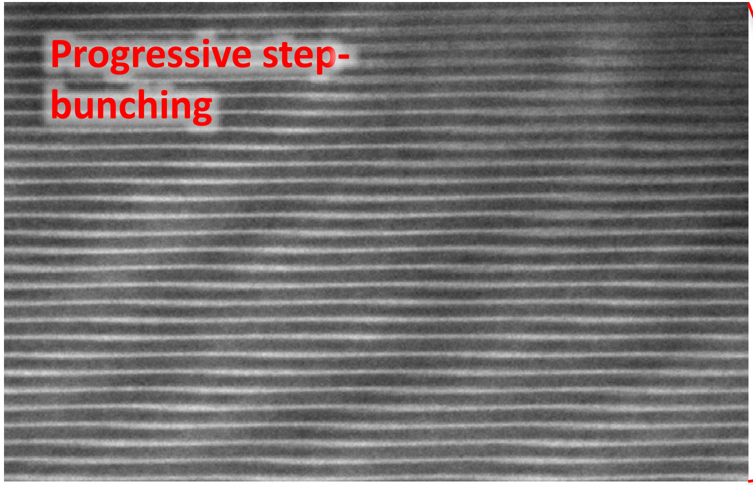
GaInAs/GaAsP materials challenges

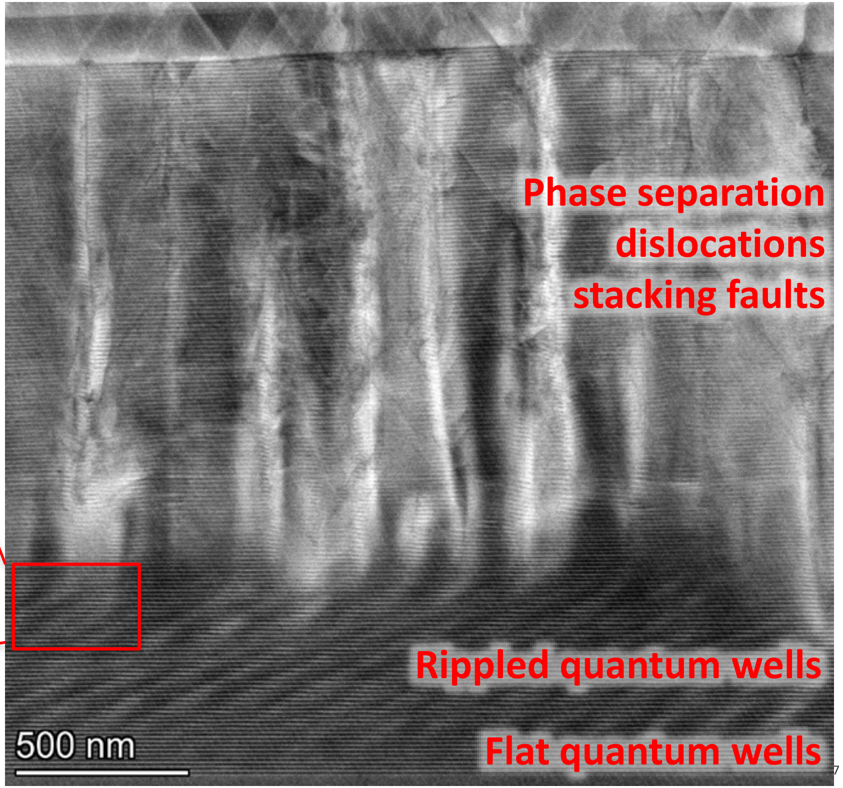
- Strain-balancing
- Interfacial layers
- **Strained-surface control**

Transmission Electron Microscopy

low magnification

Alternating
GaInAs
GaAsP





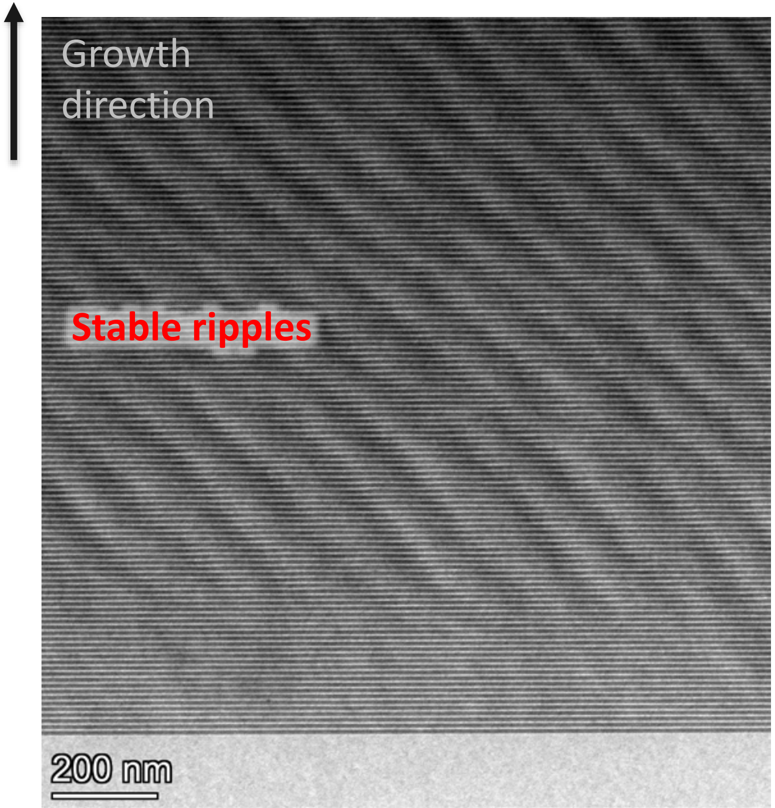
Growth
direction

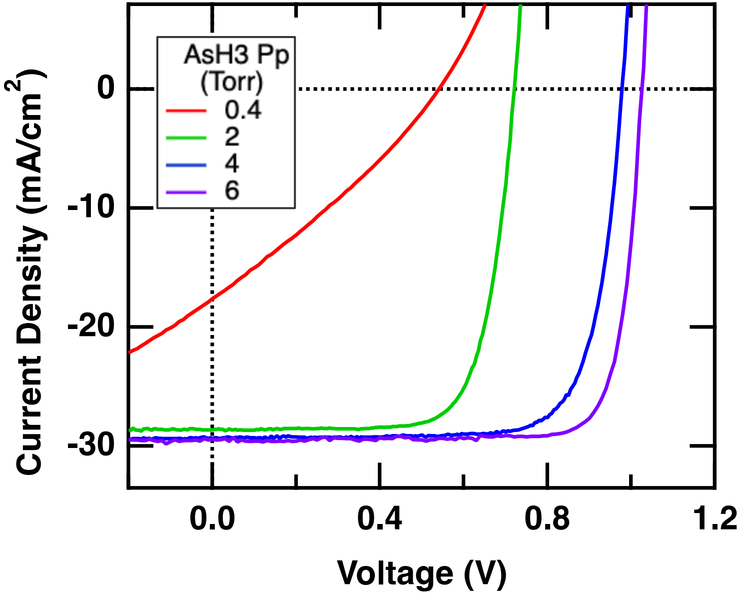
TEM performed by J. Selvidge, UCSB
R.M. France et al, JAP, 132, 184502 (2022).

Material quality in QWs

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

- Eg = 1.34 eV
- Voc > 1.02 V

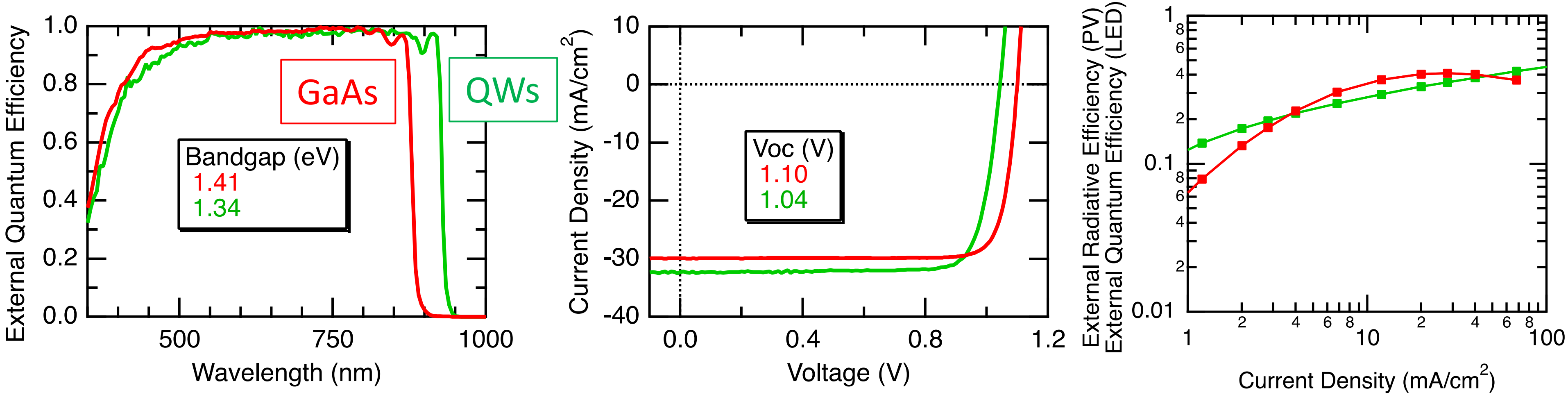




- Growth conditions limit surface segregation, improves solar cell performance
- 300 QWs possible, enabling optically thick QW solar cells

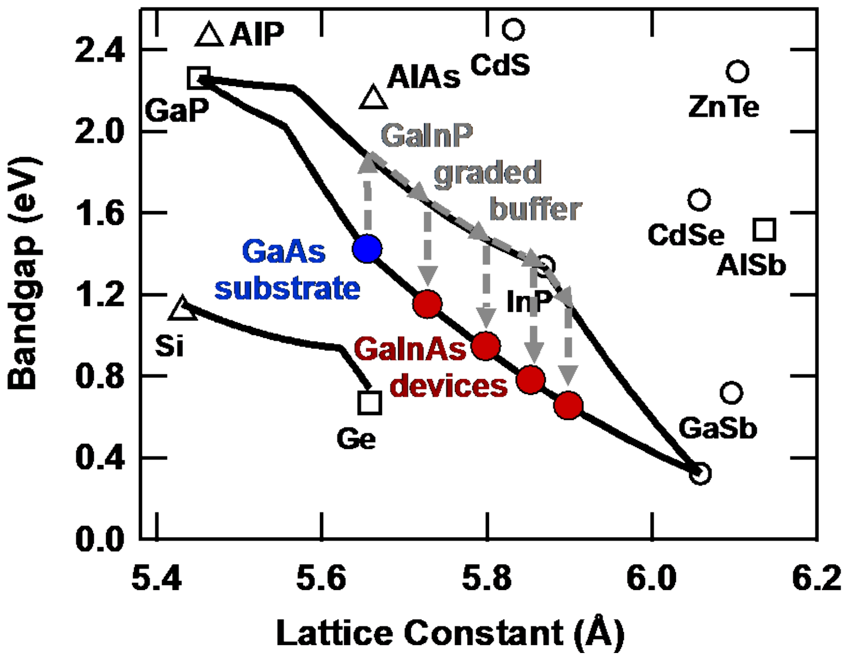
High performance optically-thick QW devices

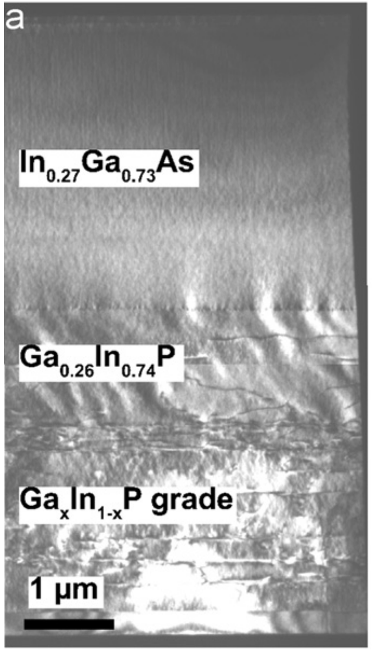
- Jsc increase wrt GaAs of 2.5 mA/cm^2 AM1.5G and 3.1 mA/cm^2 AM0
- Max 1J QW efficiency of 27.5% AM1.5G and 23.9% AM0
- 50% ERE for planar device



Demonstrated optically-thick QW device with excellent performance

Metamorphic solar cells



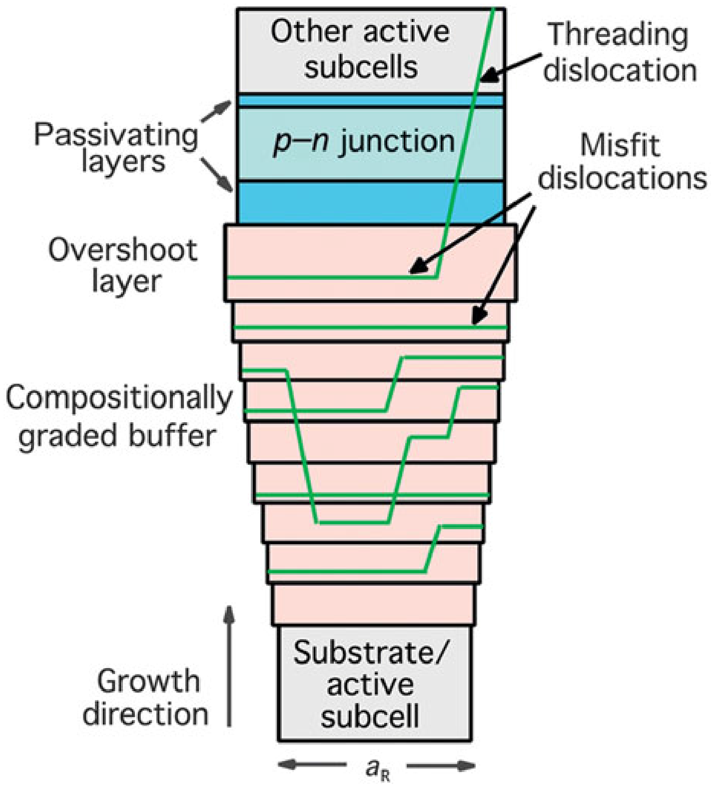


1.0 eV GaInAs solar cell

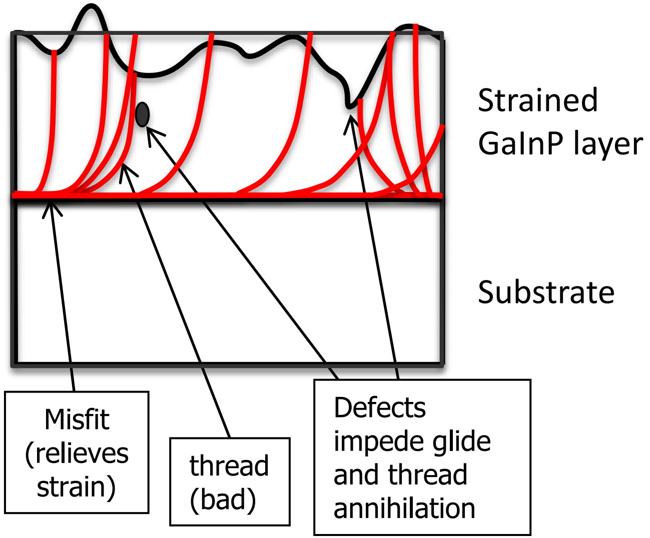
GaInP graded buffer

GaAs substrate

Metamorphic Material



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



Dislocation glide

Dislocation glide kinetics

$$\rho_t = \frac{R_g R_{gr} e^{U/kT}}{C\varepsilon_{eff}^m}$$

ρ_t = threading dislocation density

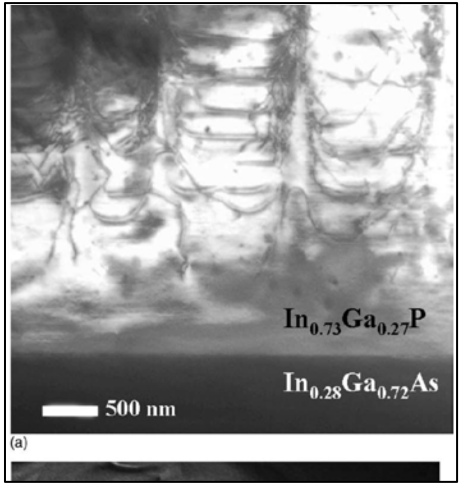
ε_{eff} = effective stress = $\varepsilon_{line} - \varepsilon_{misfit}$

R_g = growth rate (um/hr)

R_{gr} = misfit grade rate (%/um)

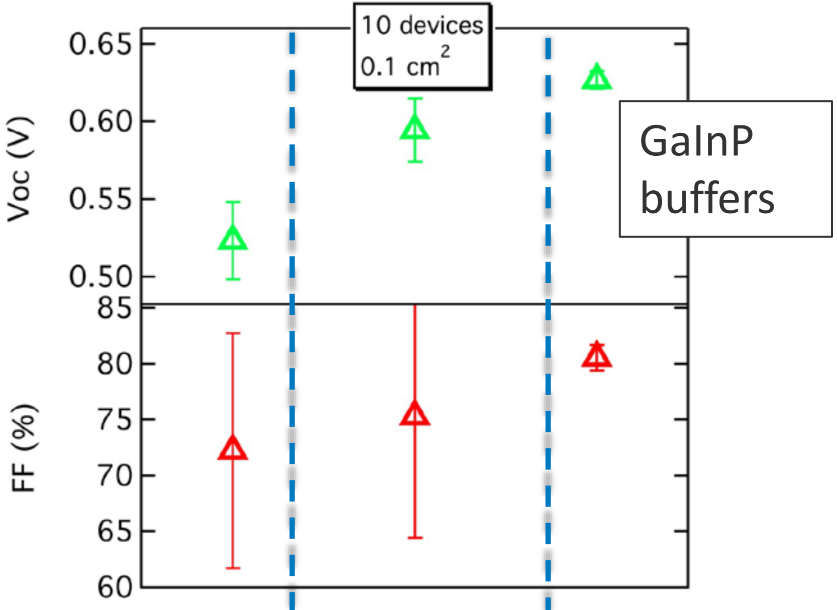
Dislocation pinning: Phase separation

GaInP buffer



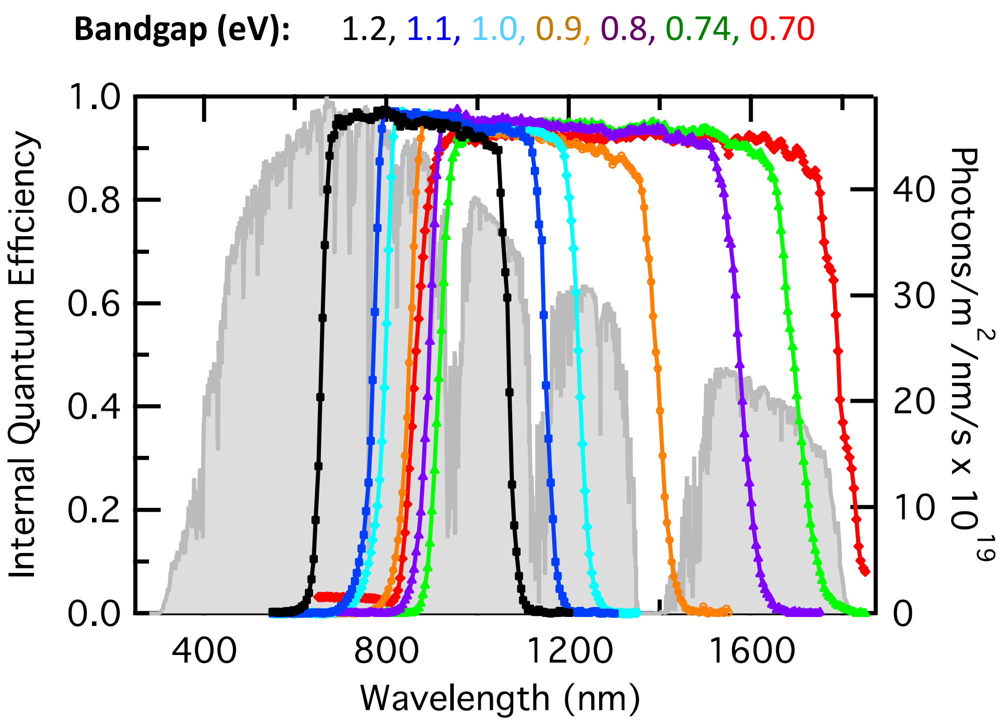
N. Quitoriano et al., J. Appl. Phys. **102**, 033411 (2007)

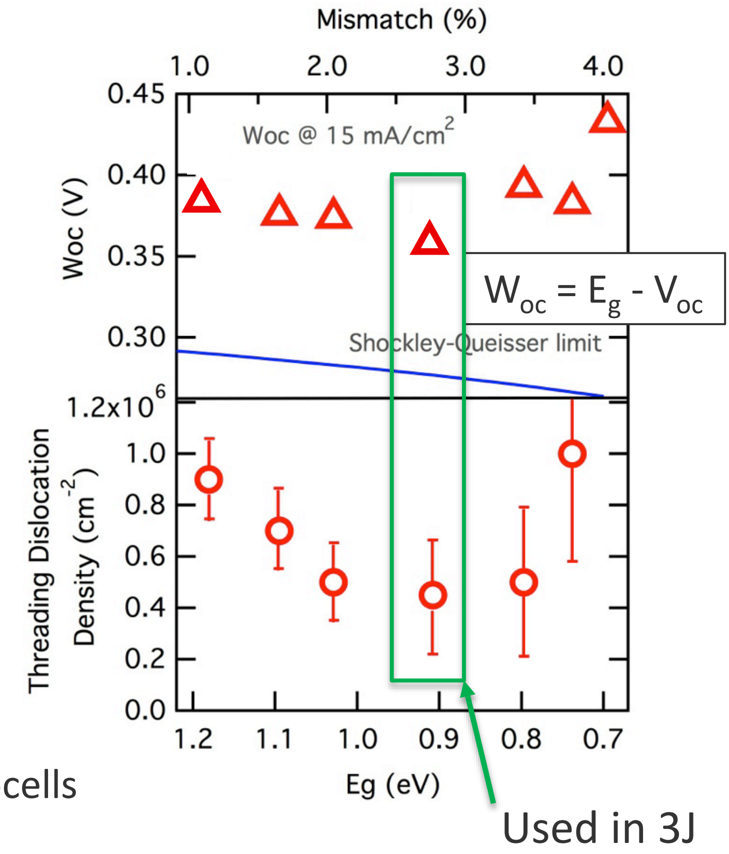
1.0 eV GaInAs cells with varied growth conditions



Unoptimized conditions	**Reduce glide limitations**	**Enhance ideal glide**
620°C	620°C	675°C
Mid V/III, 180	High V/III, 320	High V/III, 320
Mid GR, 4.4	High GR, 7	High GR, 7

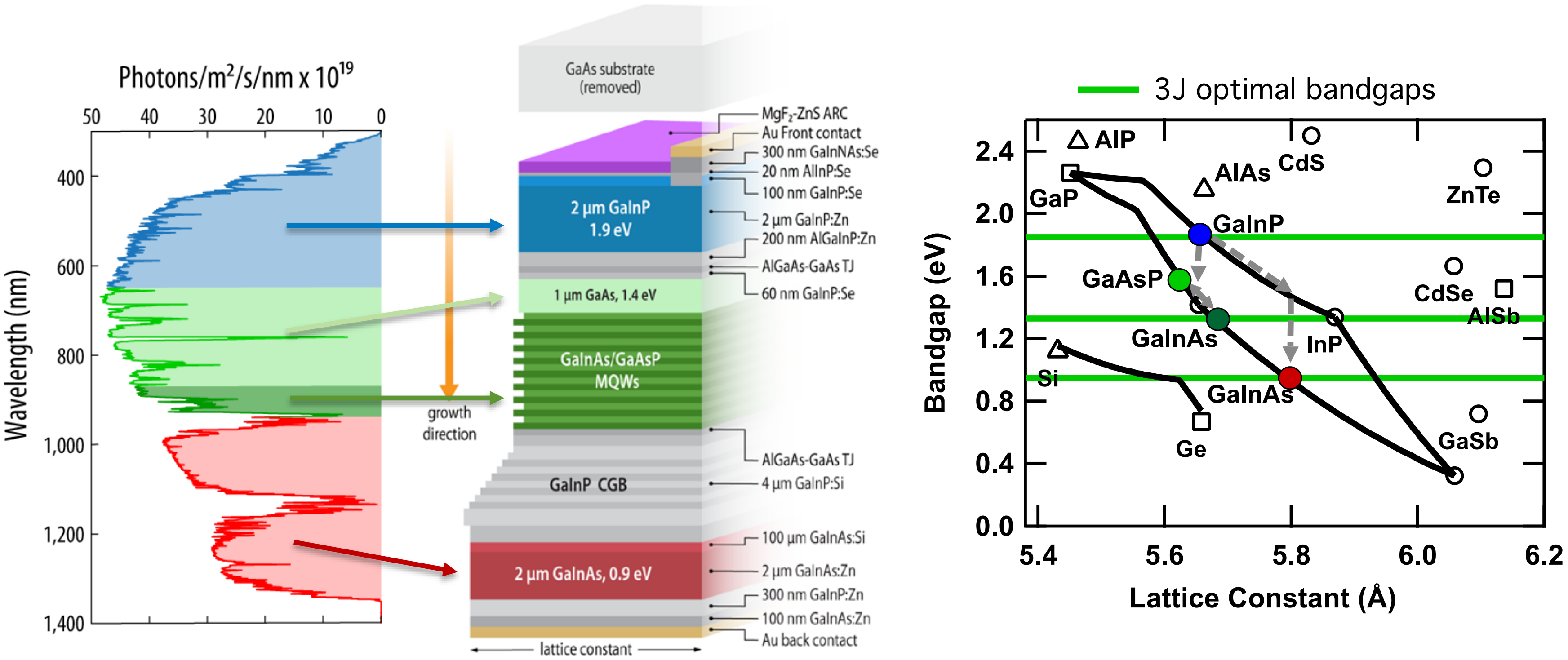
Metamorphic GaInAs cell performance



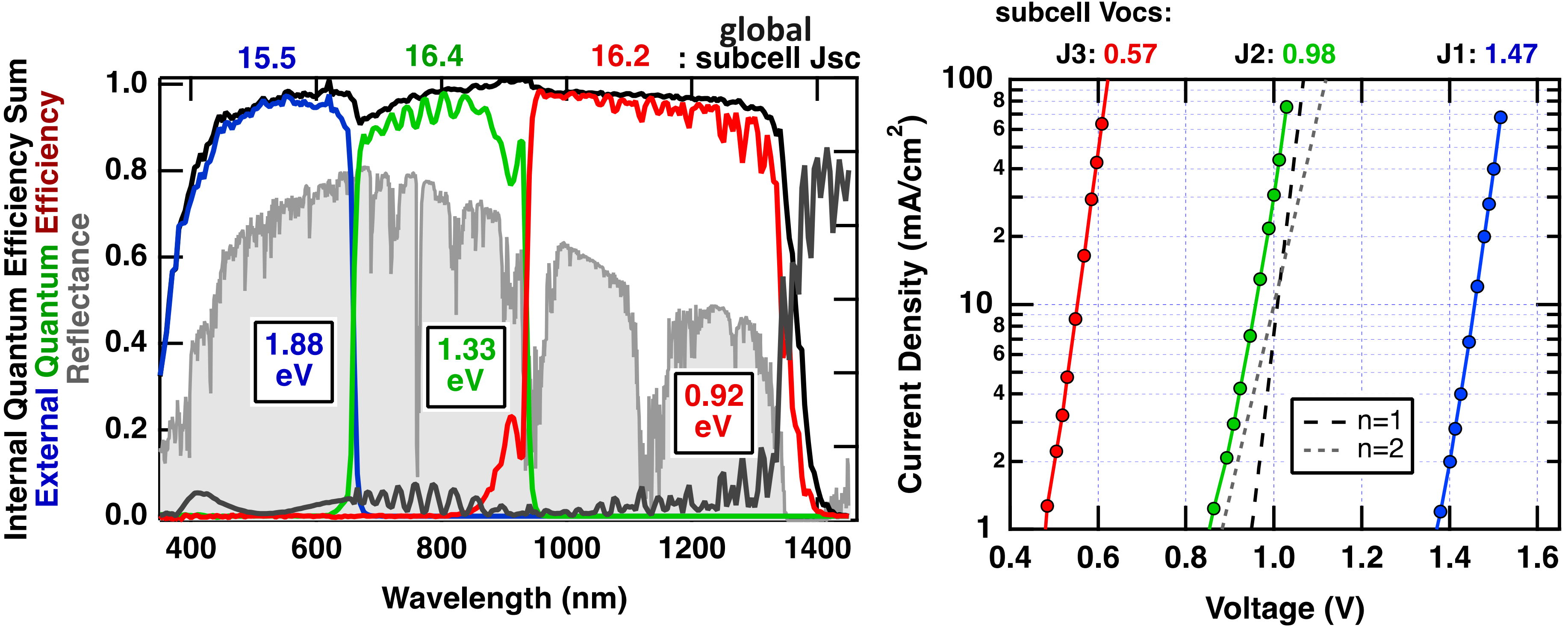


Graded buffers can be used for lattice-mismatched GaInAs subcells with collection spanning large portion of solar spectrum

3-junction Multijunction cell results



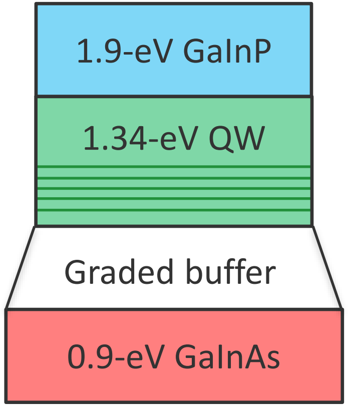
3-junction cell results: subcell analysis



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

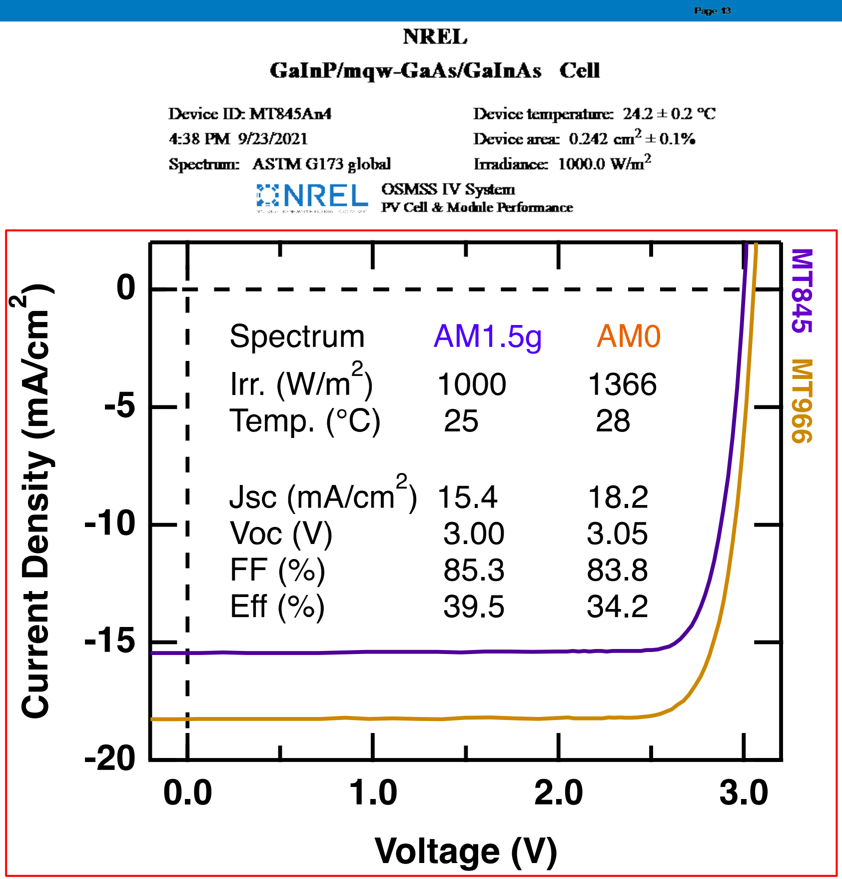
3J structure



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

AM1.5G efficiency = 39.5%

AM0 efficiency = 34.2%



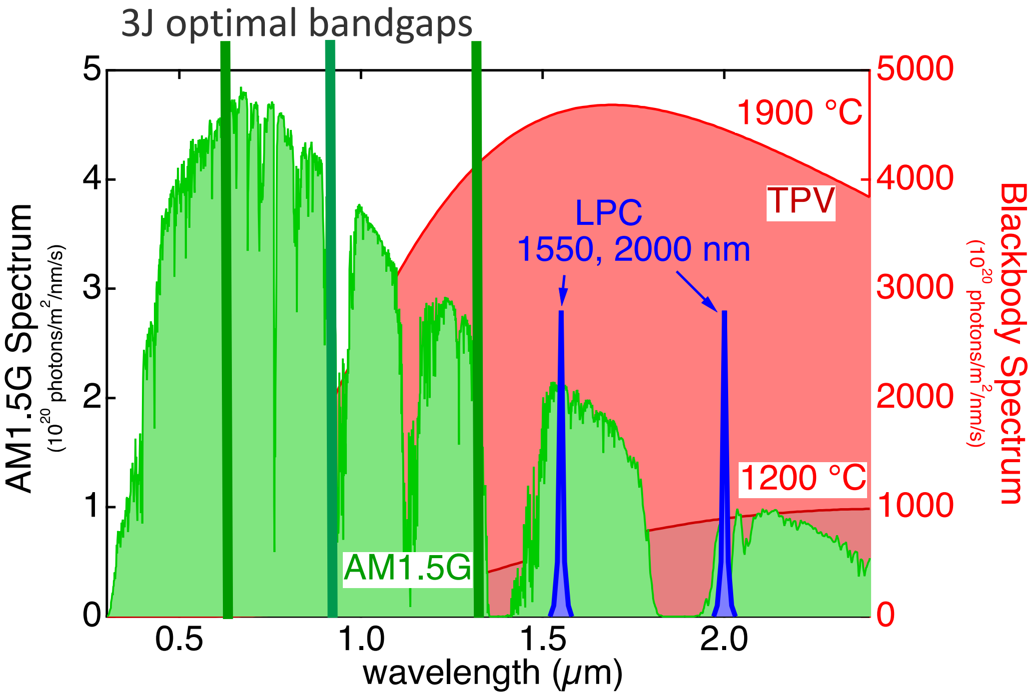
France *et al.*, Joule, 6, 1121, (2022)

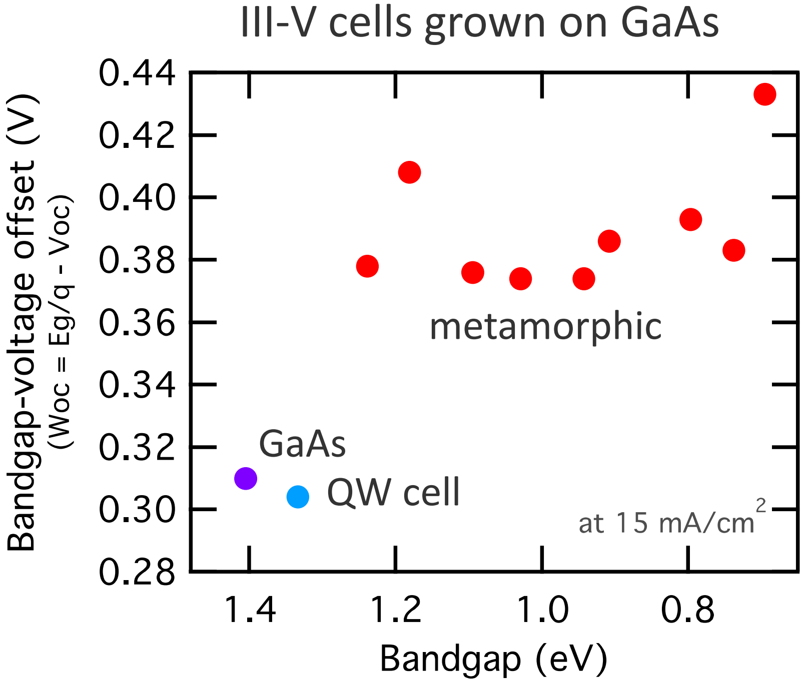
Green *et al.*, Prog. Photovolt., 30, 3, (2022)

New world record!

Other applications of III-V MJ components

- Area-constrained applications, concentrators, space PV
- Thermophotovoltaics (TPV), laser power converters (LPC), other optoelectronics





Thermophotovoltaics

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]✉

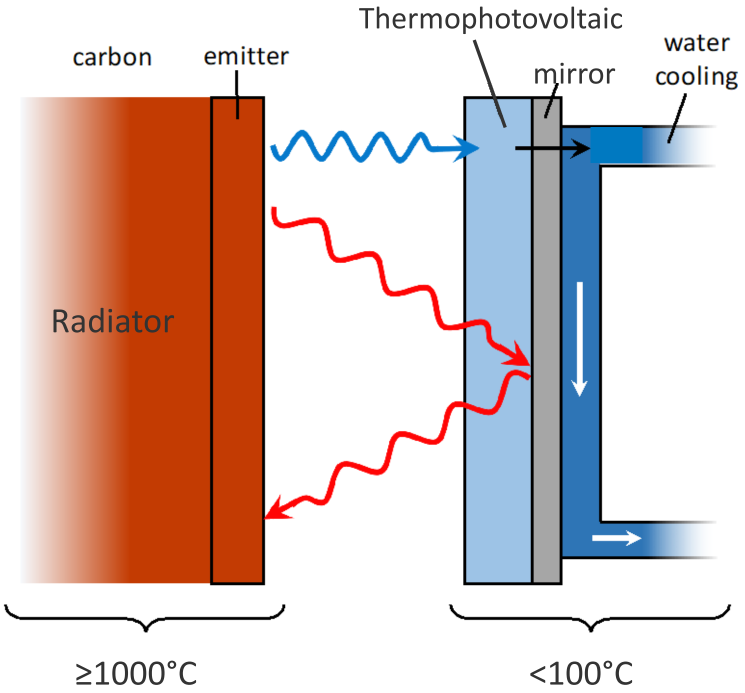
Joule

Article

Efficient and scalable GaInAs thermophotovoltaic devices

Eric J. Tervo,[1,4] Ryan M. France,[1] Daniel J. Friedman,[1] Madhan K. Arulanandam,[1,2] Richard R. King,[2]
Tarun C. Narayan,[3] Cecilia Luciano,[3] Dustin P. Nizamian,[3] Benjamin A. Johnson,[3] Alexandra R. Young,[3]
Leah Y. Kuritzky,[3] Emmett E. Perl,[3] Moritz Limpinsel,[3] Brendan M. Kayes,[3] Andrew J. Ponec,[3]
David M. Bierman,[3] Justin A. Briggs,[3] and Myles A. Steiner[1,5,*]

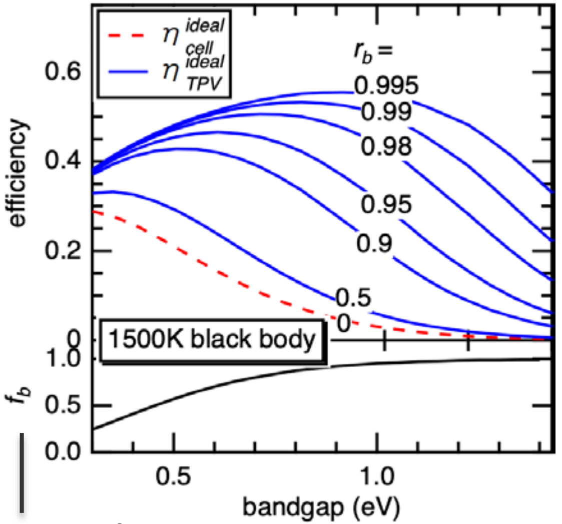
$$\text{TPV Efficiency} = \frac{\text{Power Output}}{\text{Power Incident} - \text{Power Reflected}}$$



Thermophotovoltaics

Single junction Efficiency

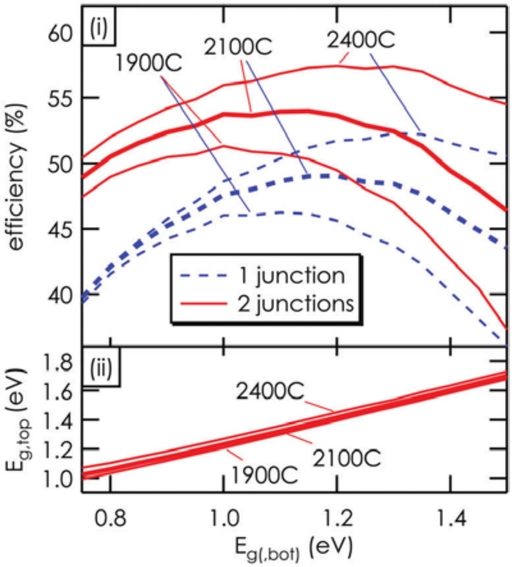
Dependence on reflectance

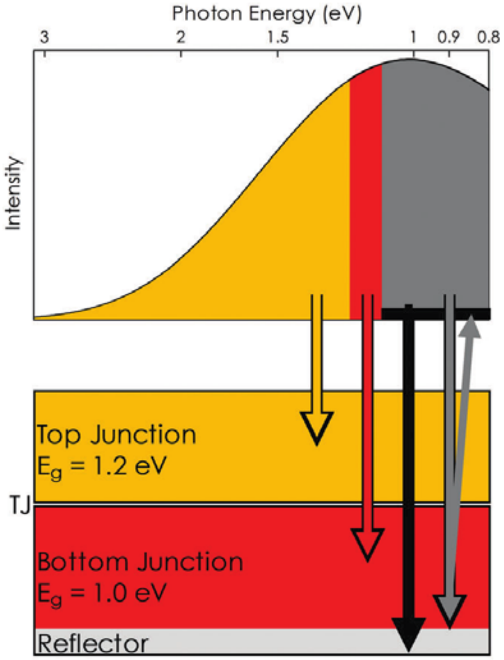


Portion of spectrum below bandgap

2-junction efficiency

Emitter temperature





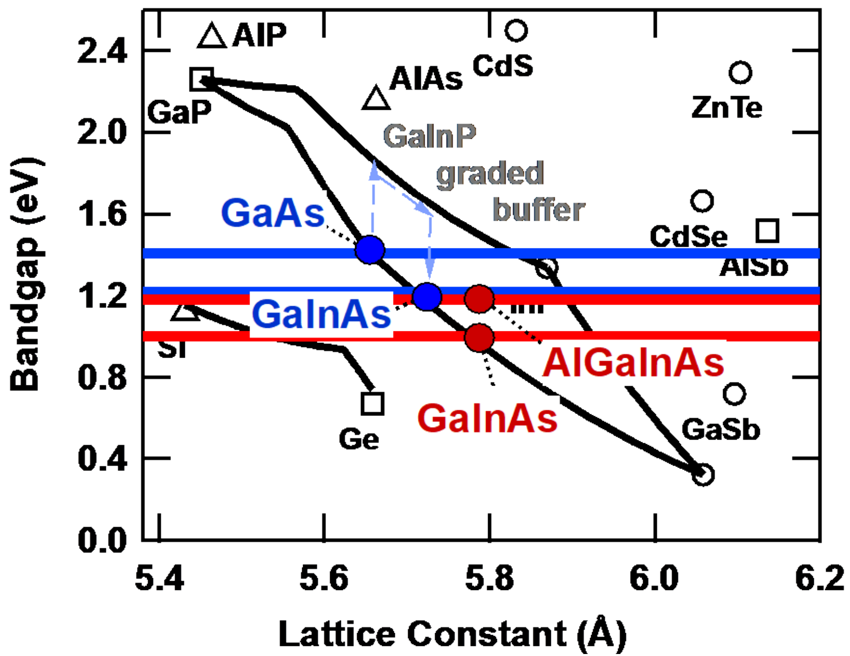
Cell Design Requirements:

- Highly reflective back mirror
- Low parasitic absorption in cell, all wavelengths
- Material bandgaps optimized for emitter temperature, reflectance, and required power density
- Management of resistive power loss

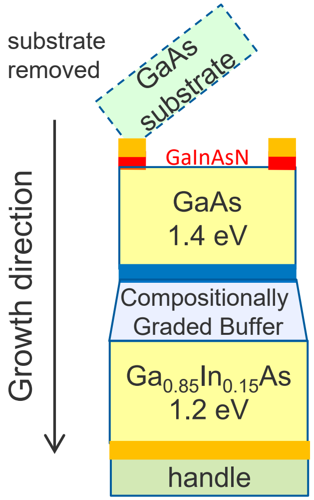
Friedman and Steiner,
PVSC proc. pp 3215. (2019)

Two MJ Device Strategies

Optimal 2-junction cell targets
2400°C emitter
1900°C emitter

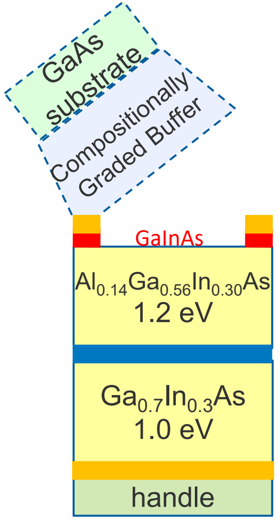


1.4 eV/1.2 eV



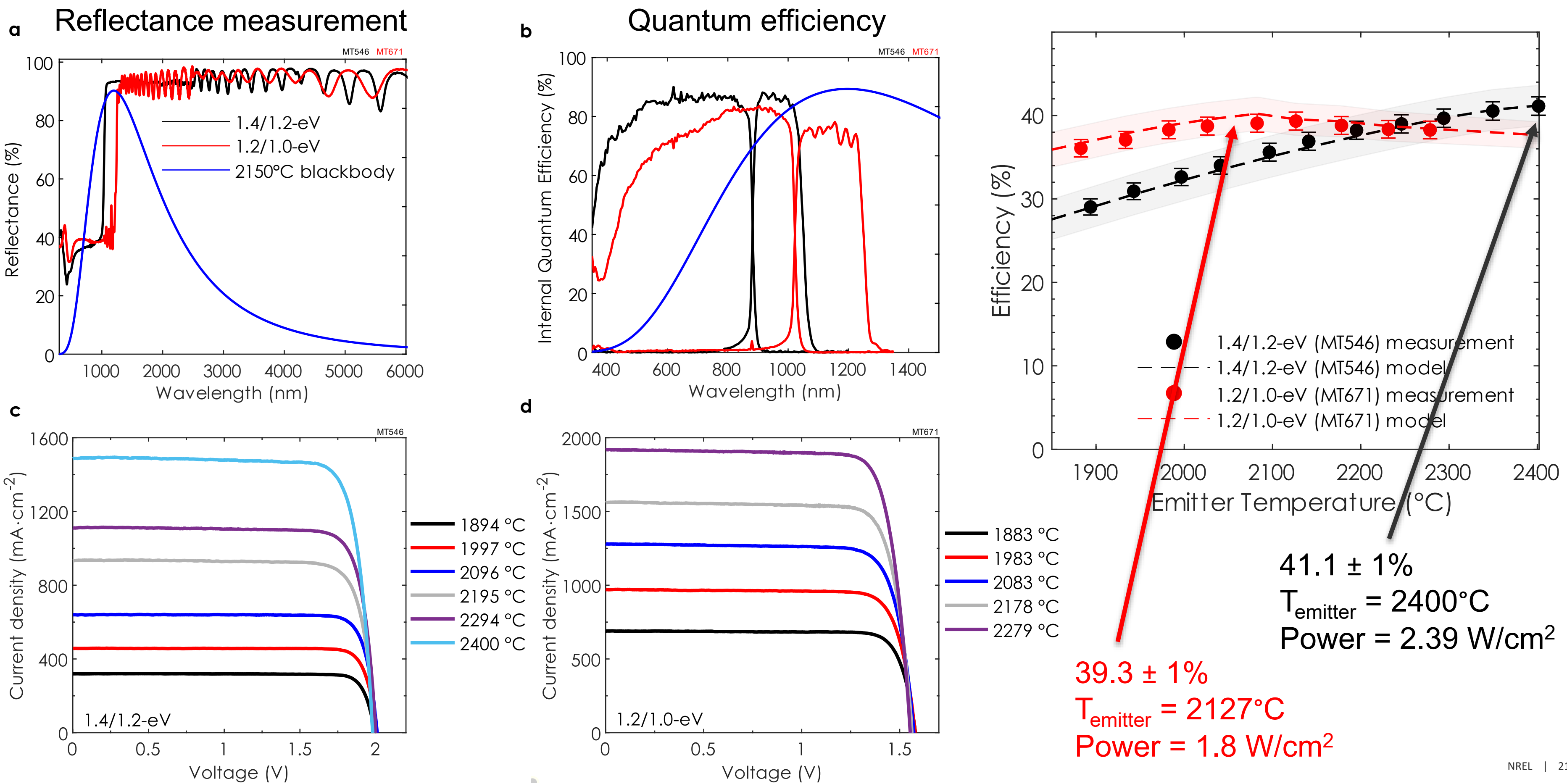
- Lower current minimizes I^2R losses, but lower power output
- Grade left inside, could parasitically absorb

1.2 eV/1.0 eV



- Higher current and power, but resistive losses could dominate
- Grade removed

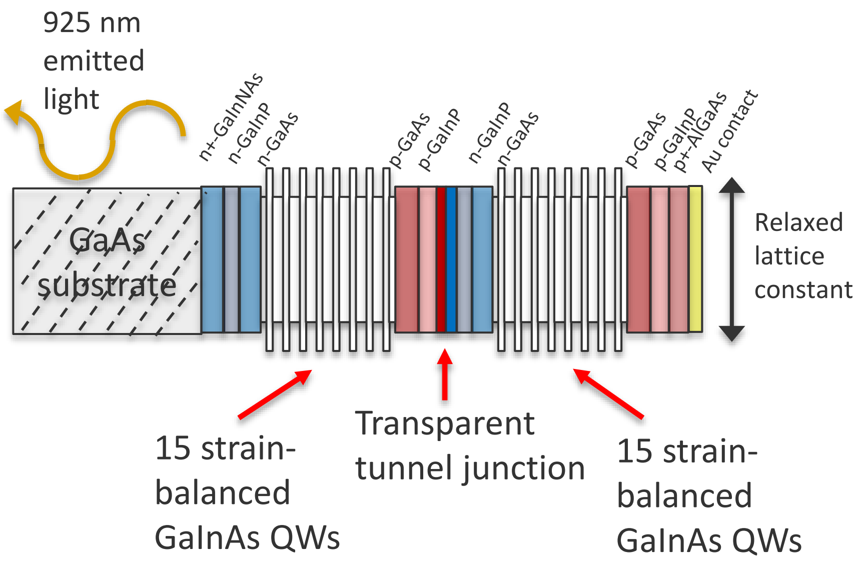
TPV characterization

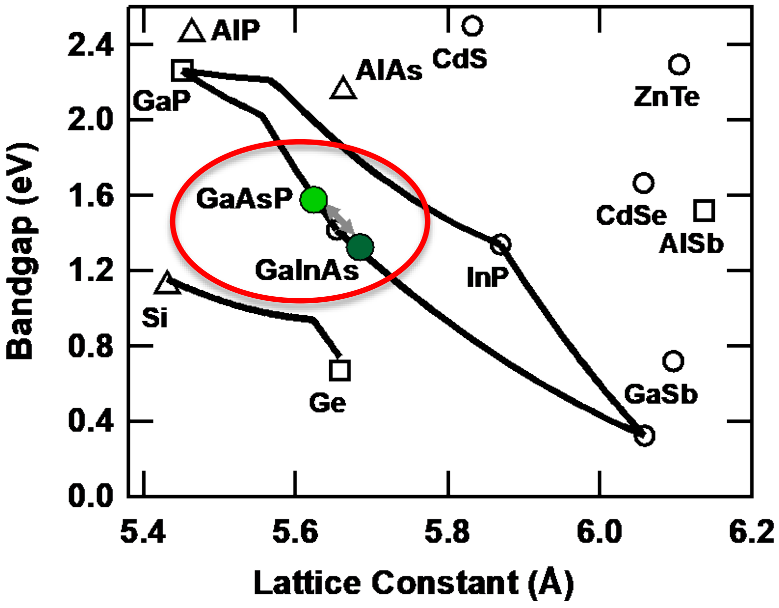


41.1 ± 1%
$T_{emitter}$ = 2400°C
Power = 2.39 W/cm^2

39.3 ± 1%
$T_{emitter}$ = 2127°C
Power = 1.8 W/cm^2

Multijunction LEDs





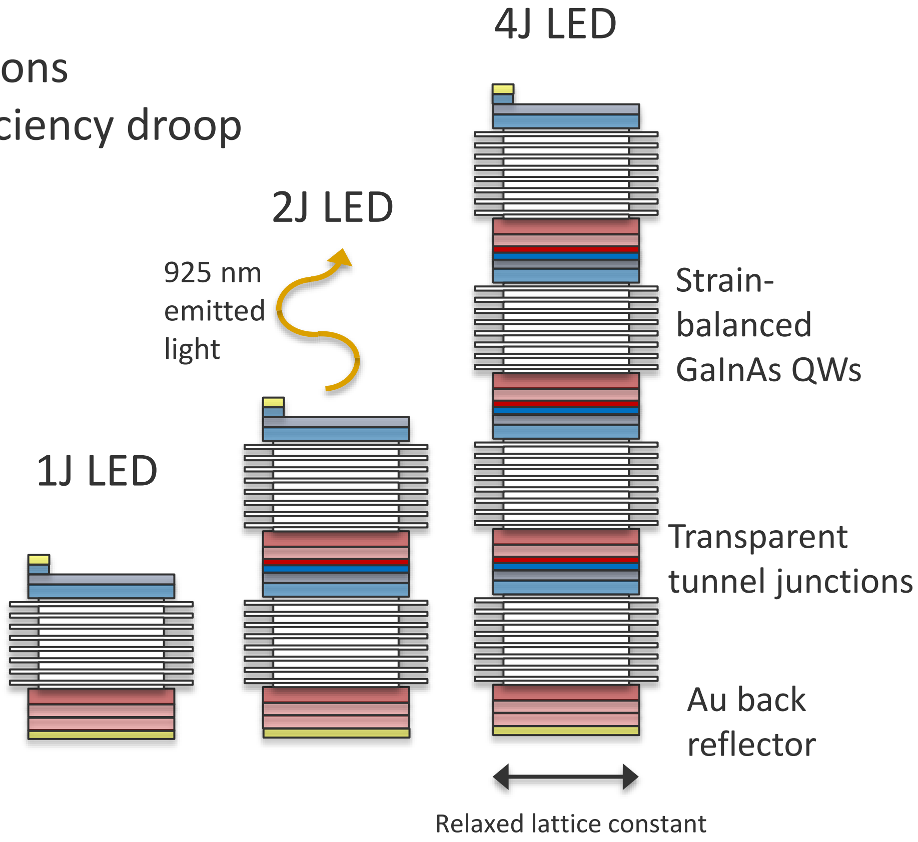
Multijunction LEDs

Benefit of Multijunction LEDs:

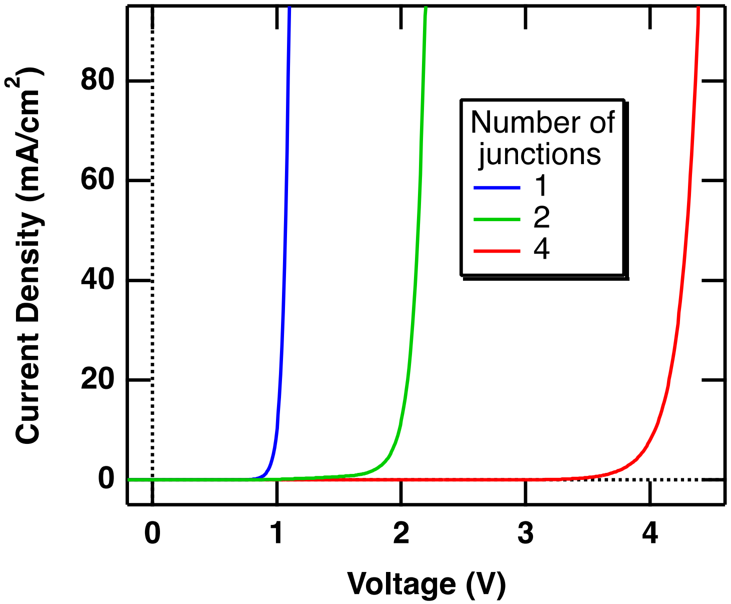
- Reduce current for a given # of emitted photons
- Reduce series resistance losses, heating, efficiency droop
- Increase voltage (system integration)

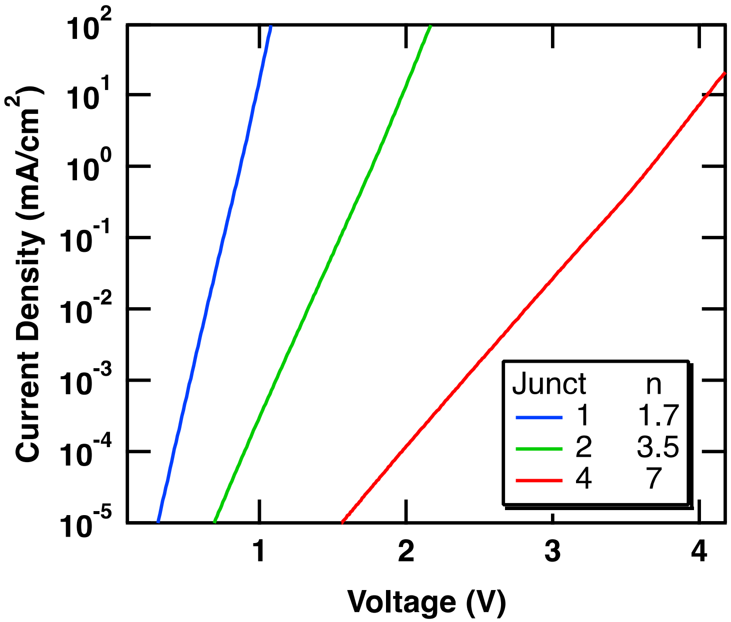
Experiment:

- Compare from 1-junction, 2-junction, and 4-junction GaInAs emitters at 925 nm
- Any major loss mechanisms introduced with extra junctions?
- EQE of 4 J> 2J > 1J?



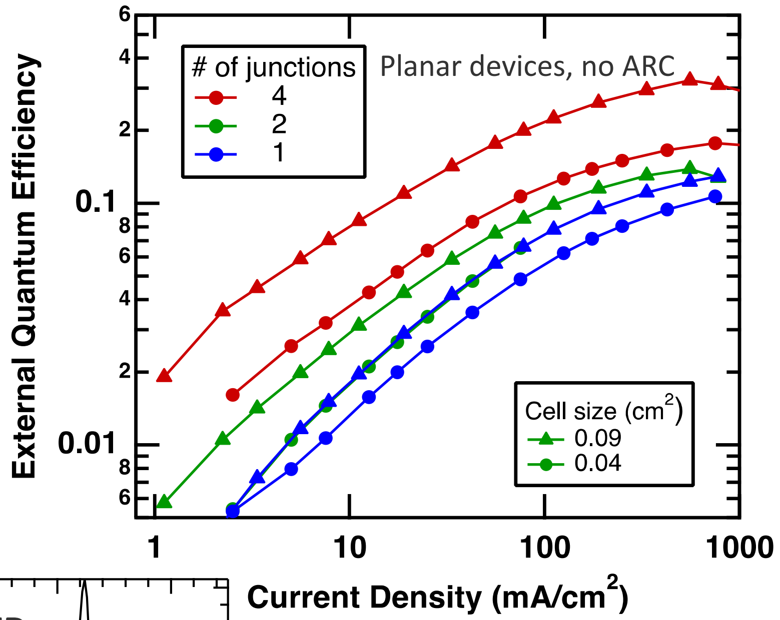
Multijunction LEDs

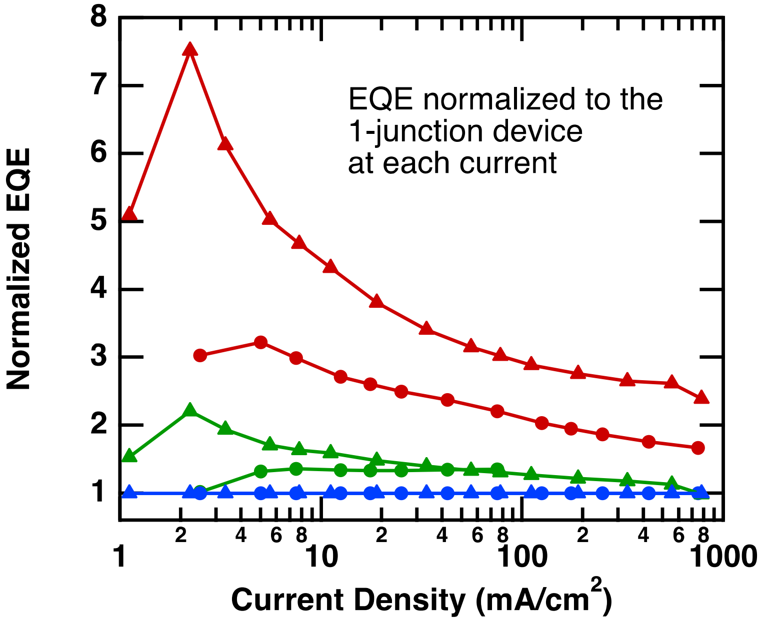


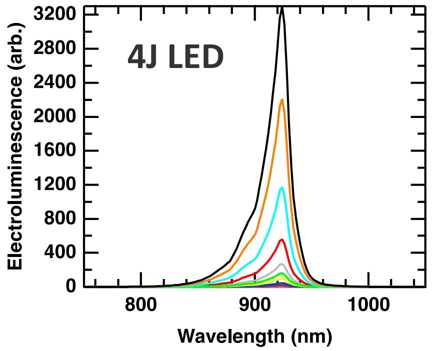


- High operating voltage, low current 4-junction GaInAs device
- Ideality factors add → no major extra loss introduced

Multijunction LEDs







- High EQE is possible with MJ LEDs
- EQE addition observed, but varies w/ injection current → multijunction LEDs emit more photons at a given current

Conclusions

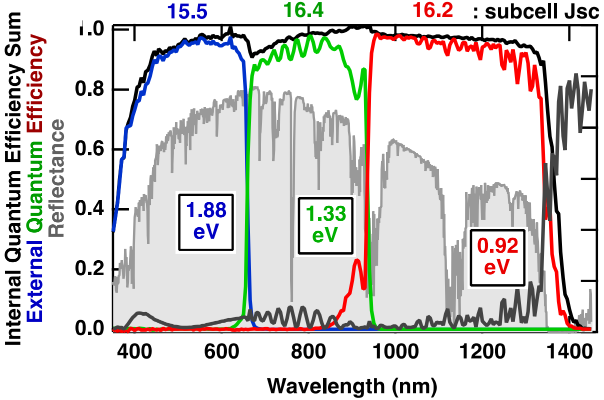
Component development

- QW solar cells
- Lattice-mismatched solar cells

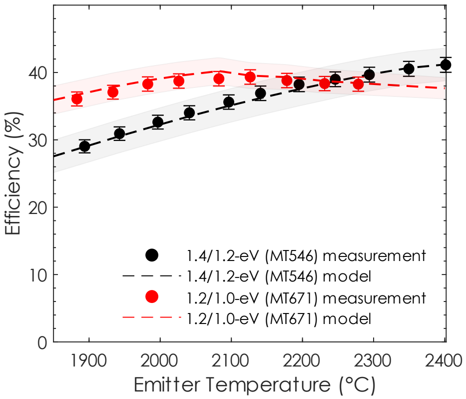
Multijunction (MJ) Devices demonstrations for PV/non-PV applications

- Terrestrial/space PV: 3-junction MJ
    - 39.5% / 34.2% PV efficiency
- Thermophotovoltaics
    - 41% TPV efficiency
- Multijunction LEDs
    - EQE addition, no major losses

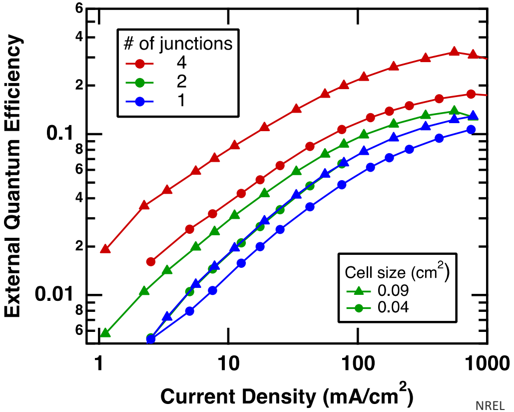
MJ for terrestrial/space PV



MJ for TPV



MJ LEDs



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- Alina LaPotin (MIT)
- Brendan Kayes (Antora Energy)
- Leah Kuritzky (Antora Energy)
- Emmett Perl (Antora Energy)

Thank you!

Ryan.France@nrel.gov

Postdoc opening!
III-V group: R10217
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