PV ACADEMY

TANDEM SOLAR CELLS PART 1

AUTHOR:

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Milan, 25 Sept. 2022

Outline

TANDEM SOLAR CELLS

Part 1

- Multijunction basics
  - Why multijunction? Efficiency!
  - Operation and characterization
- III-V Multijunctions
  - Materials, components, integration
  - MJ pathways, applications and current topics

Part 2

- Introduction to perovskites
- 4-terminal perovskite/silicon tandems
- 2-terminal perovskite/silicon tandems
- Current challenges and outlook
- Other tandems ?

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NREL

Prof. Christophe Ballif
EPFL

Introduction

PHOTOVOLTAIC TECHNOLOGIES

Silicon PV

1st generation

22-25 % efficiency

→ efficient, low cost

95 % of market

Thin film

2nd generation

~20-22 % efficiency

→ cheap, large areas

III-Vs and tandems

3rd generation

30-47 % efficiency

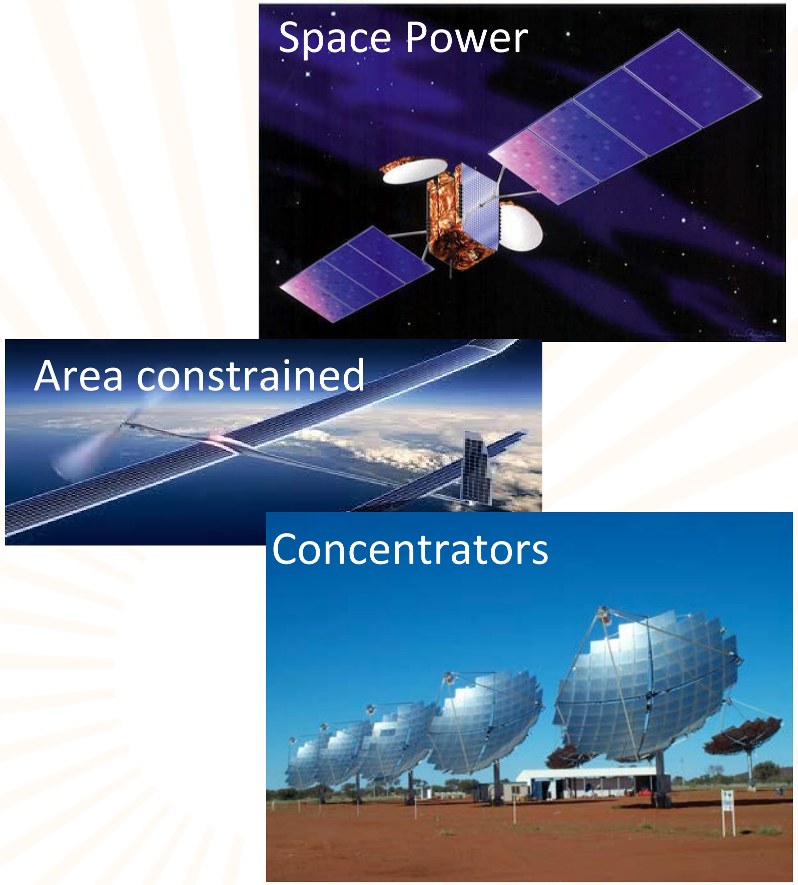
→ highest efficiency and cost

Can we also make these high efficiency cells affordable?

Introduction

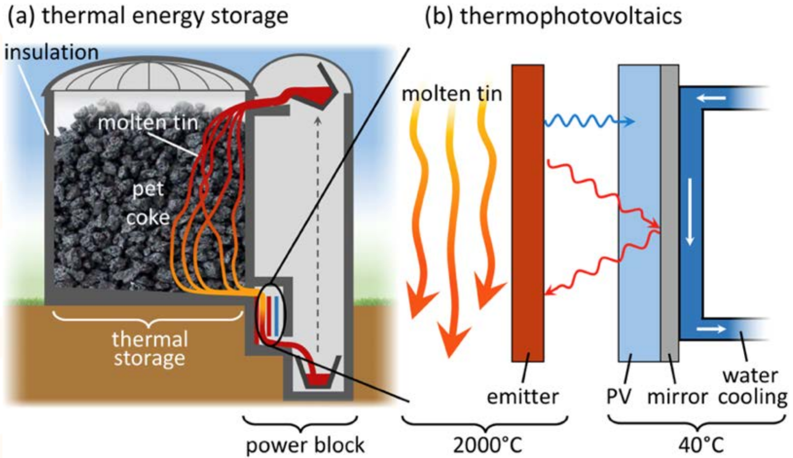
HIGH EFFICIENCY APPLICATIONS

Photovoltaic

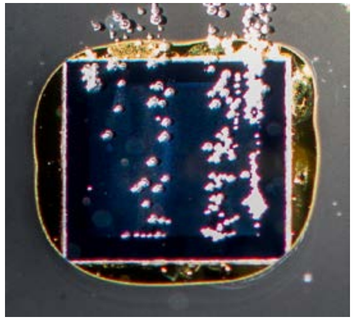


Energy storage applications

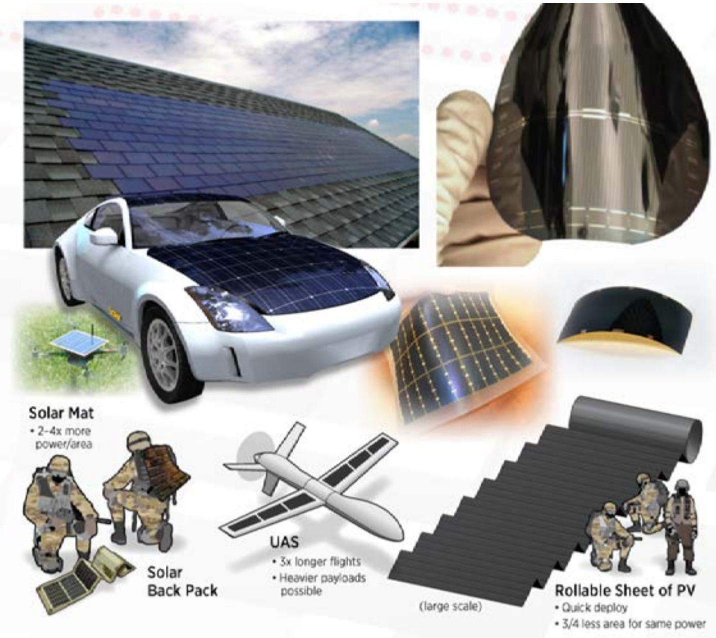
Thermophotovoltaics



Hydrogen Production

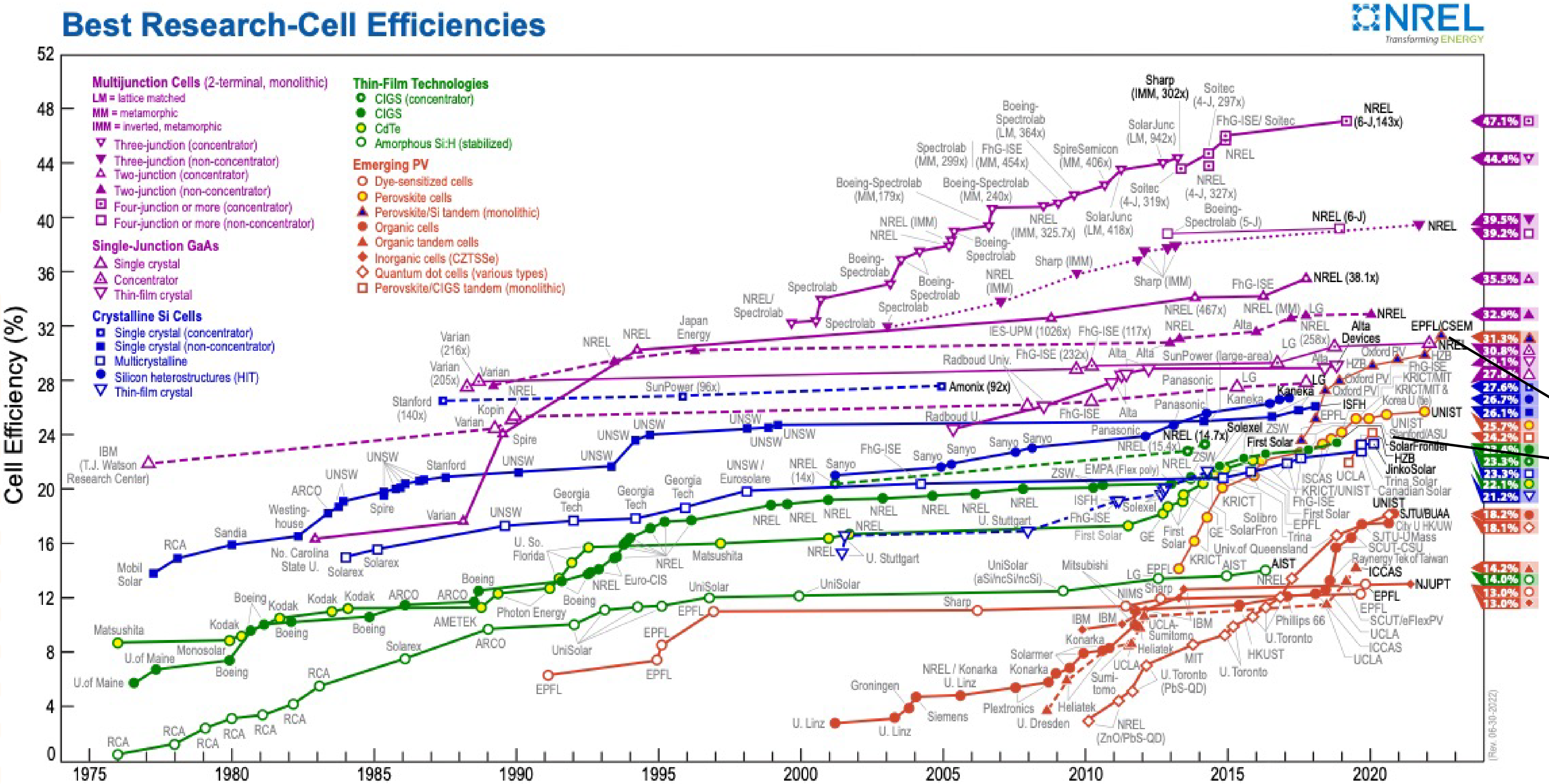


Other future applications



Introduction

PHOTOVOLTAIC TECHNOLOGIES



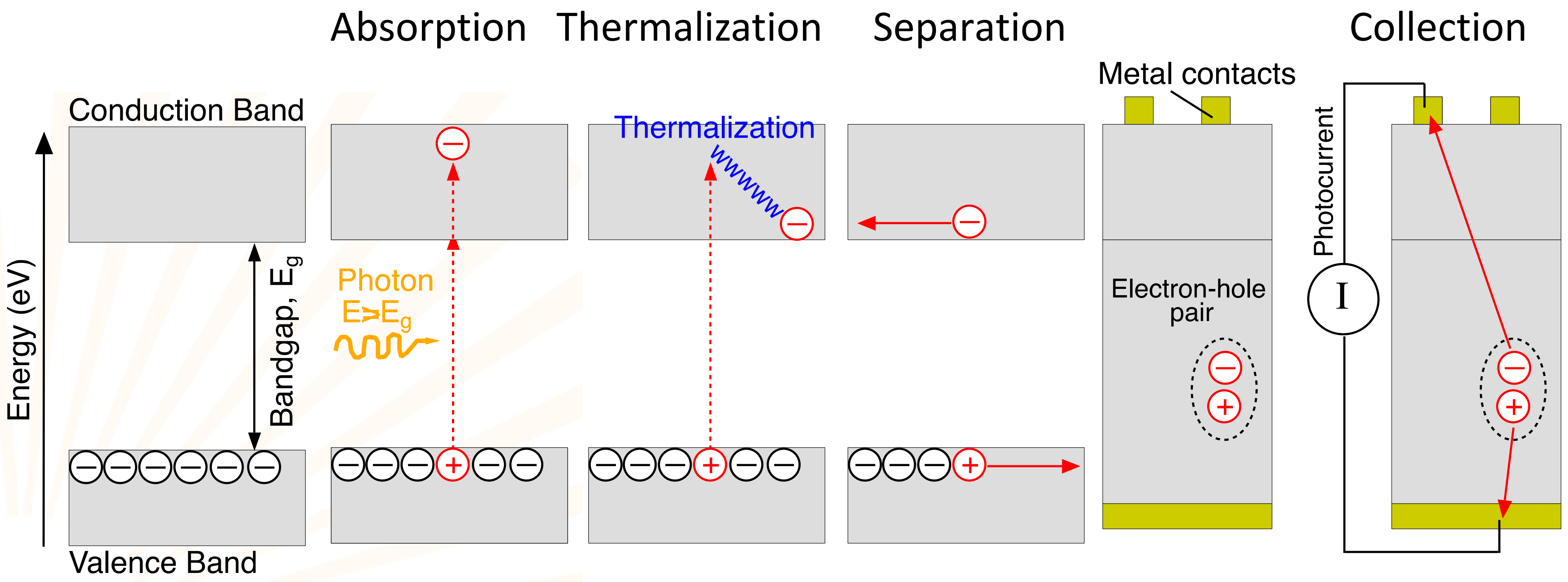
III-Vs

Perovskite-based tandems

Tandems are no longer just made of III-Vs

Multijunction background

SOLAR CELL FUNDAMENTALS



- Current is proportional to the number of absorbed photons
- Voltage varies approx. linearly with the bandgap: $V_{oc} \approx E_g/q - 0.4$
- Power = Current x Voltage

Multijunction background

BROADBAND SOLAR SPECTRUM

The sun is not a laser

Multijunction background

BROADBAND SOLAR SPECTRUM

Blackbody, ~5800K

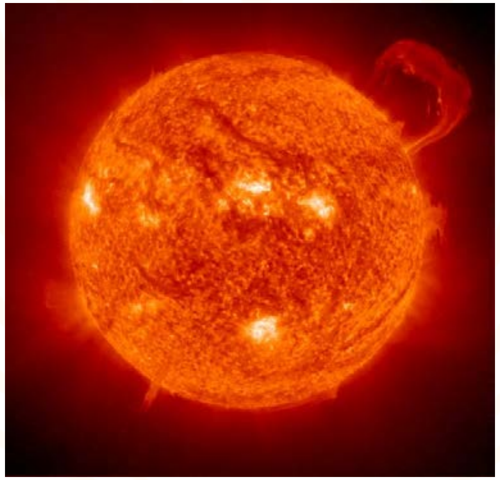
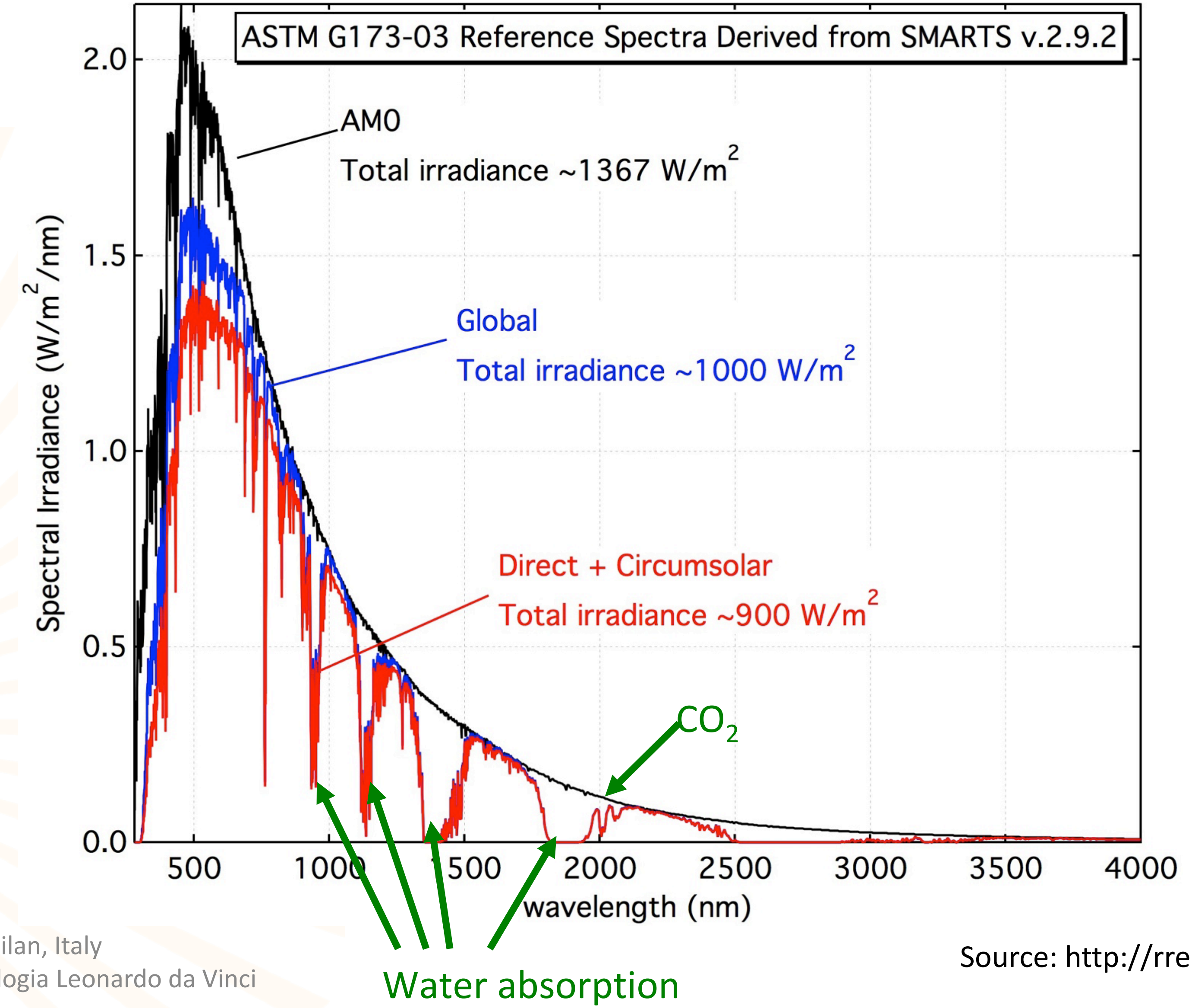


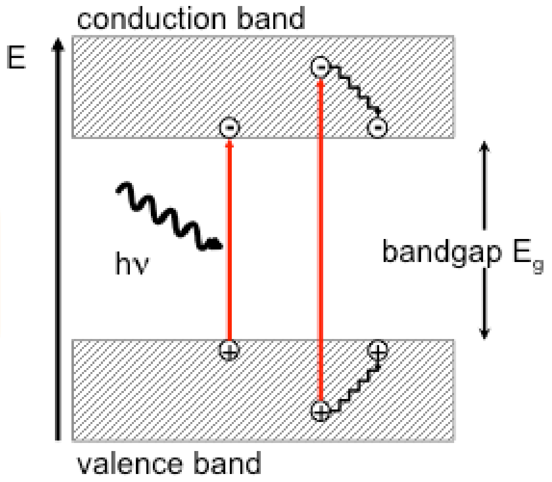
Image Credit: ESA/NASA/SOHO
https://photojournal.jpl.nasa.gov/catalog/PIA03149



Source: http://rredc.nrel.gov/solar/spectra/am1.5/

Multijunction background

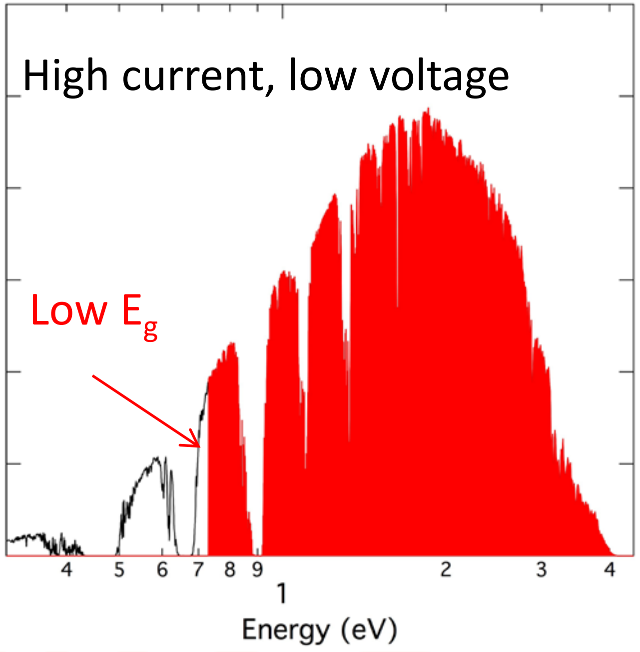
SINGLE JUNCTION LOSSES

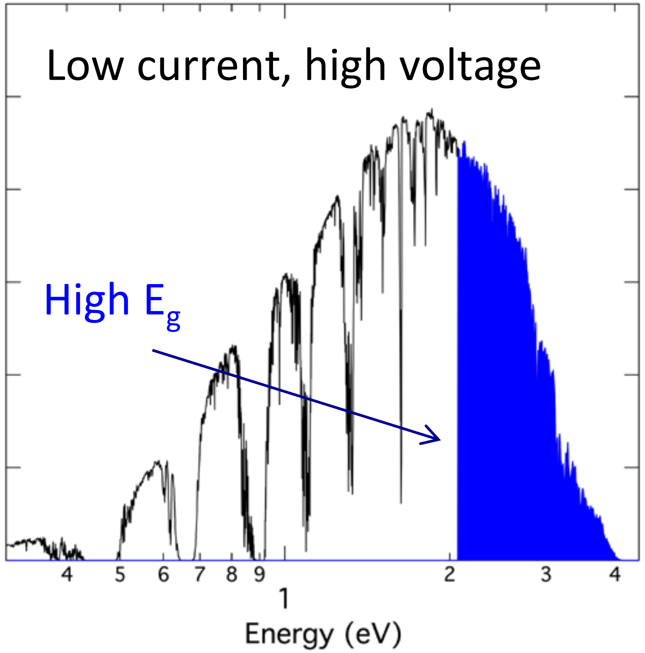


Conventional, single-junction cells have two unavoidable losses which put a fundamental ceiling on cell efficiency:

- Absorption losses
- Thermalization losses

$P = IV$

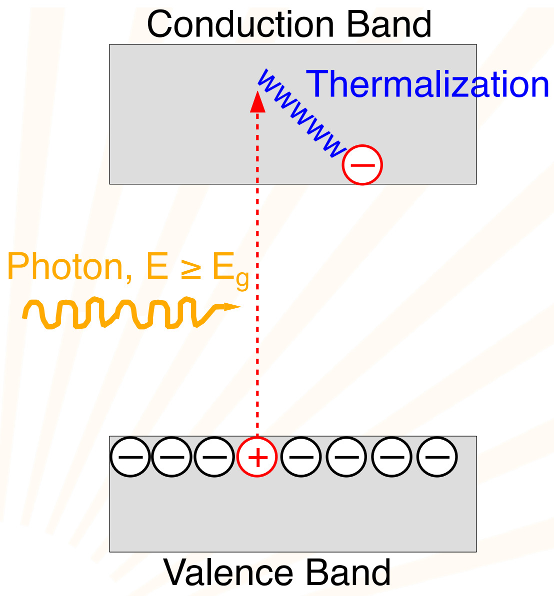

High current, low voltage


Low current, high voltage

Higher energy photons (shorter wavelength) →

Multijunction background

FUNDAMENTAL LOSSES



Two fundamental losses in a solar cell:

1) Photons with $E < E_g$ do not get absorbed

→ Extend the range of absorption

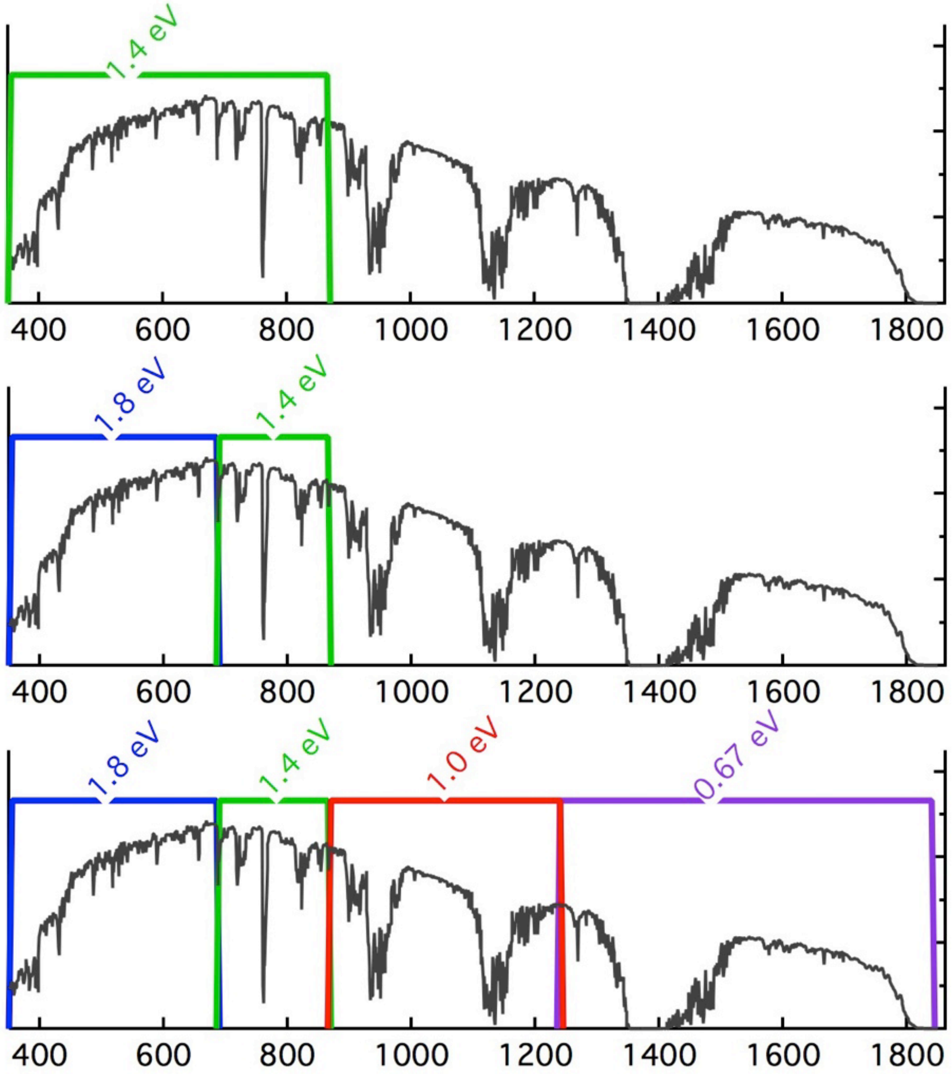
2) Energy in excess of E_g is lost to thermalization

→ Divide the absorption into smaller bands to reduce the thermalization losses

Multijunction background

MULTIJUNCTION ADVANTAGES

Global spectrum (photons/m^2/nm/s)



Single junction, optimal bandgap

↓

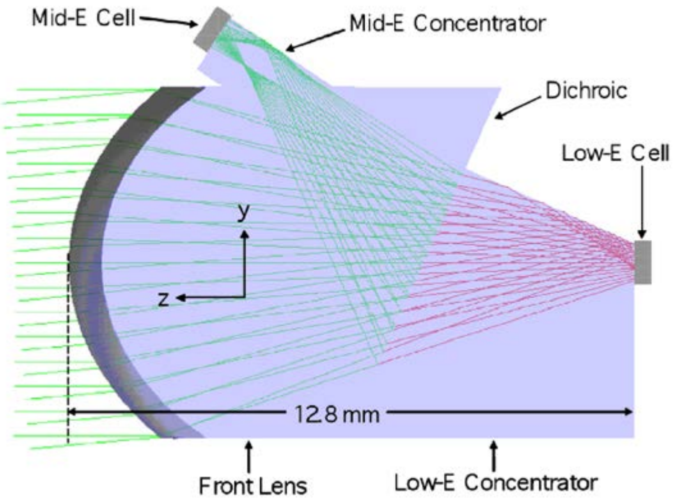
Reduced thermalization losses

↓

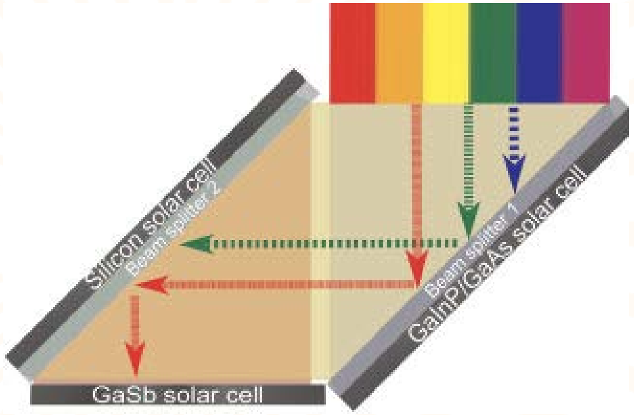
Increased voltage from additional cells

Multijunction background

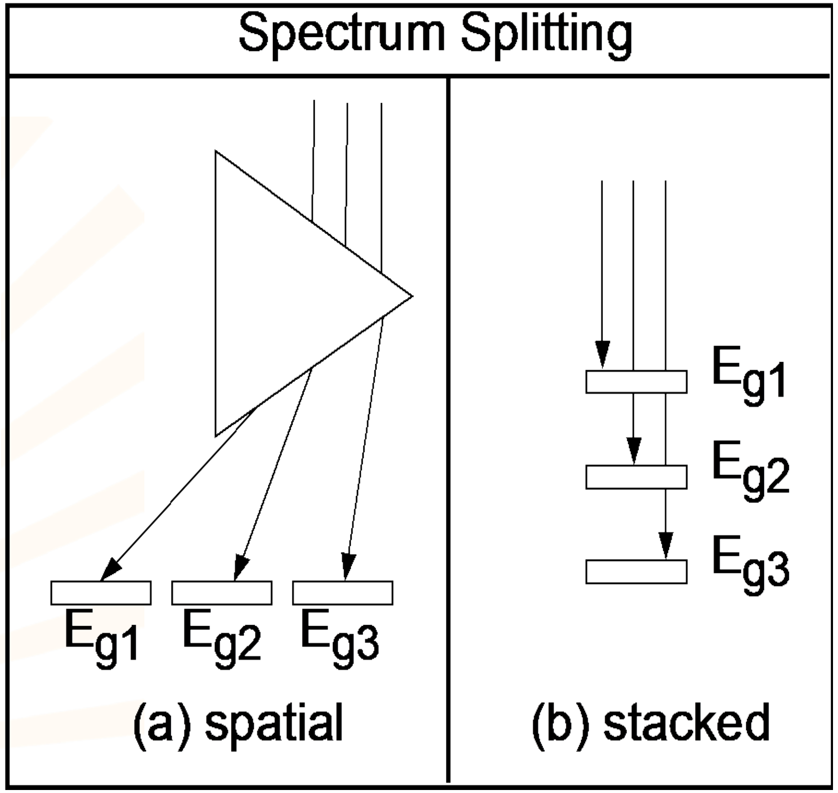
DIVIDING THE SOLAR SPECTRUM

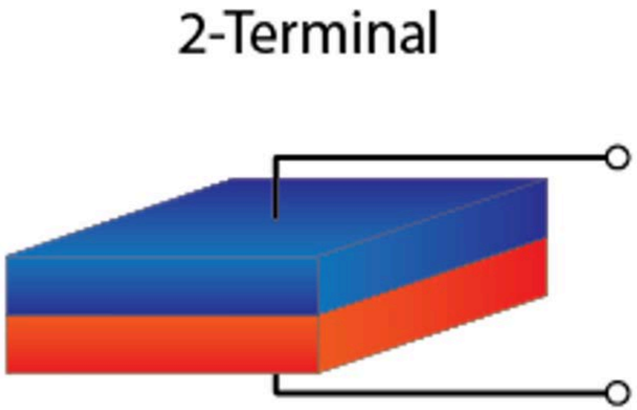


McCambridge *et al.*, Progress in PV (2010)

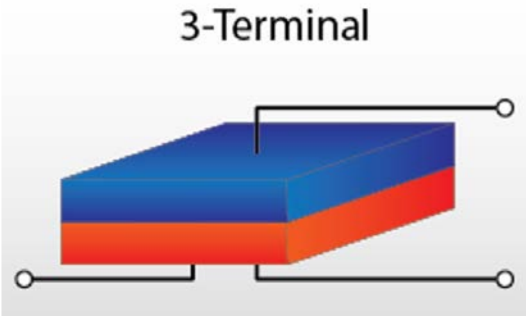


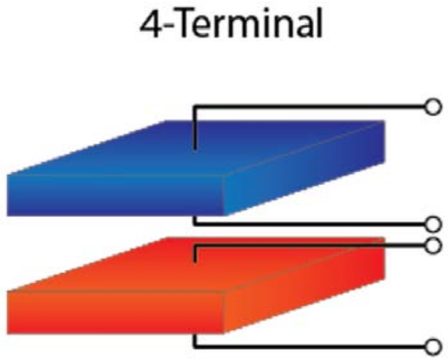
Mitchell *et al.*, Progress in PV (2010)





- Requires current matching
- Sensitive to spectral variations



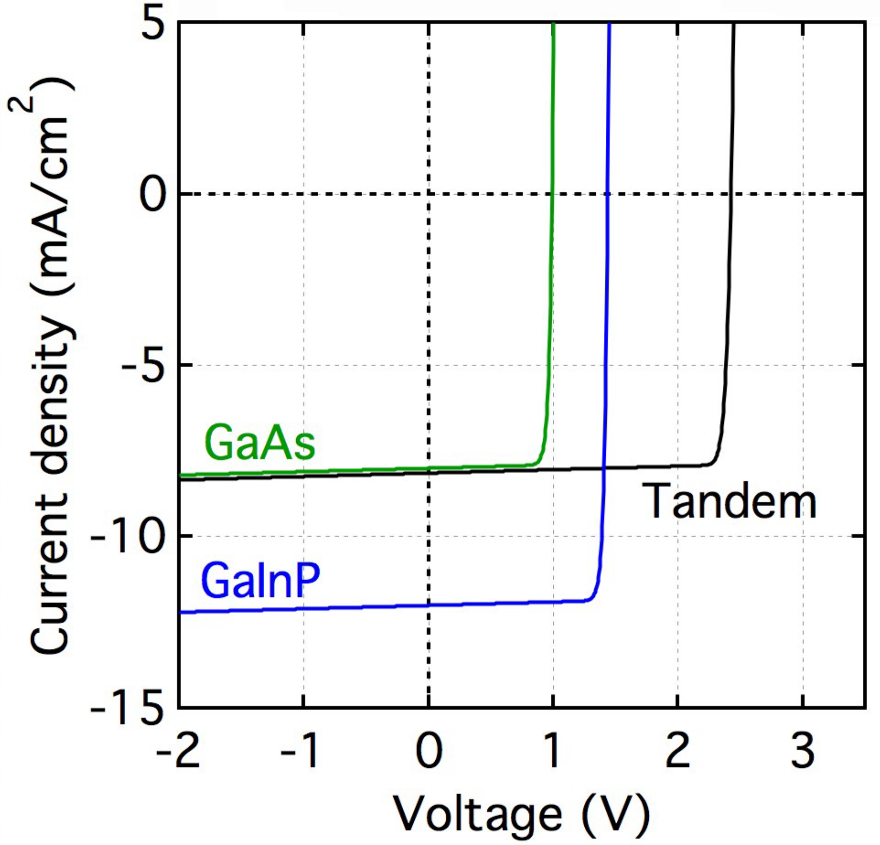


Multijunction operation

SERIES-CONNECTED TANDEMS

Continuous current through the device: sum the voltage at every current

$$V(J) = \sum_{i=1}^{N} V_i(J)$$

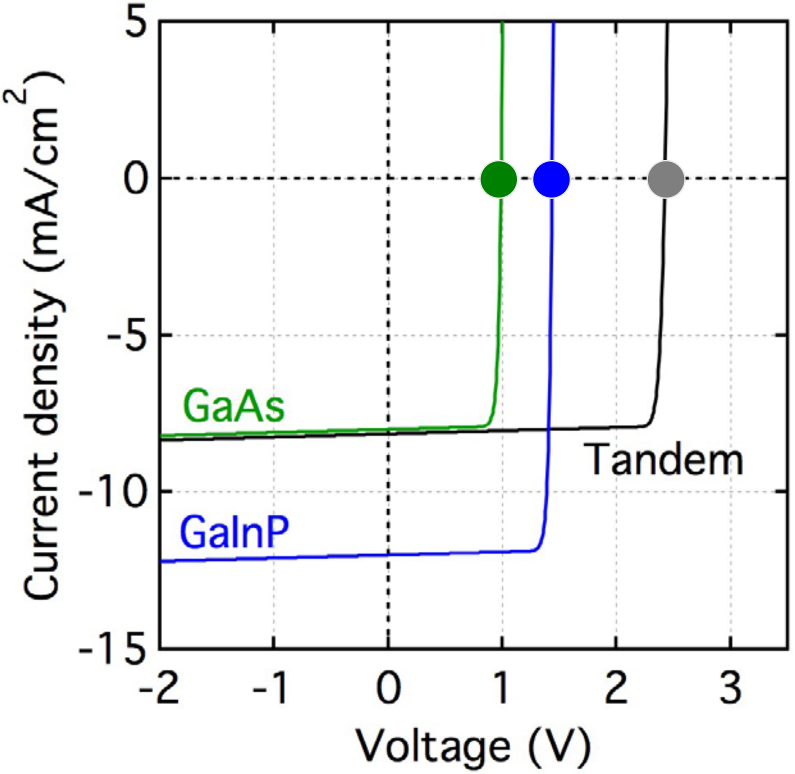


SERIES-CONNECTED TANDEMS

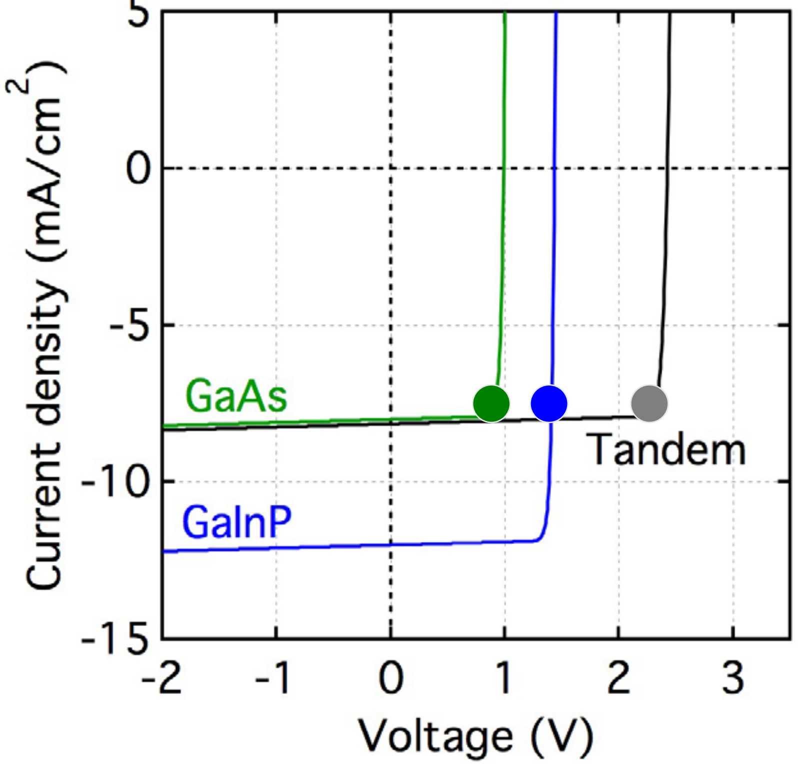
Continuous current through the device: sum the voltage at every current

$$V(J) = \sum_{i=1}^{N} V_i(J)$$

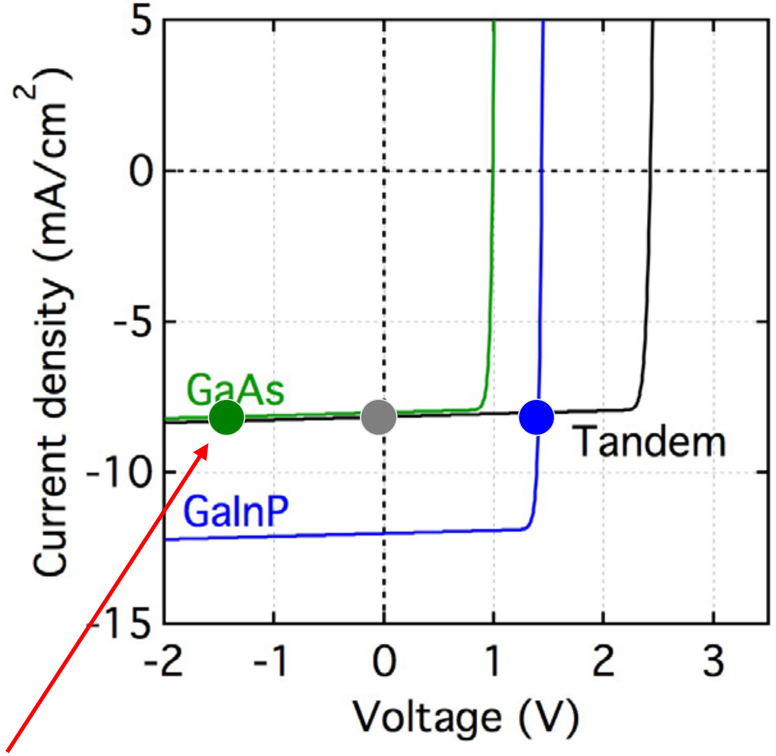
V_{oc}



V_{mpp}



J_{sc}

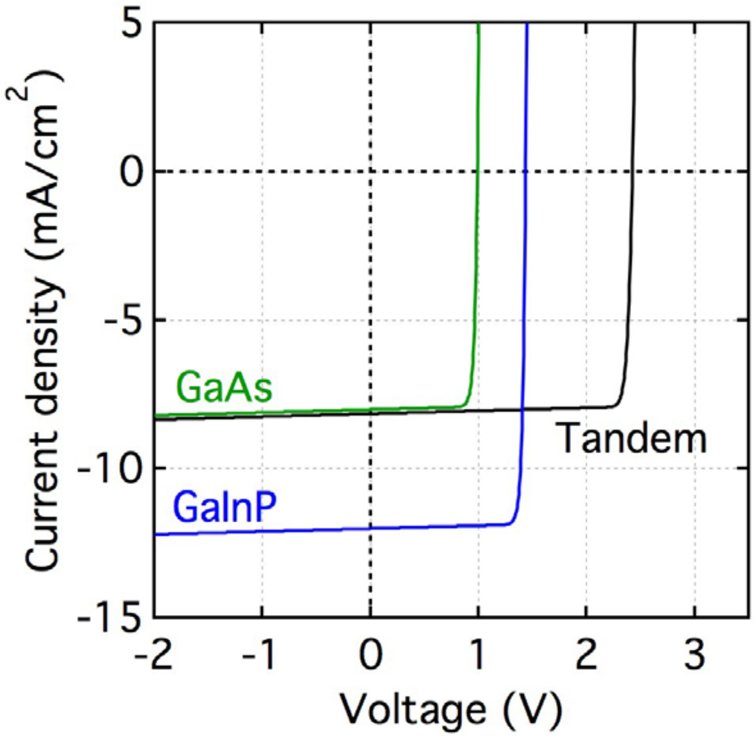


Note that the limiting cell is in reverse bias

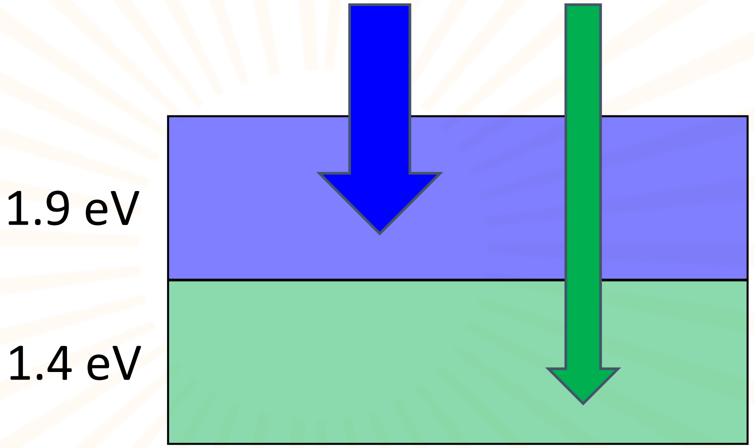
Multijunction design

CURRENT MATCHING

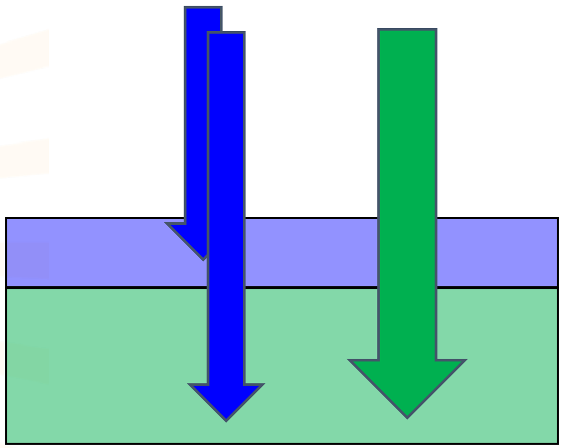
Pretend you’ve designed a 2-terminal multijunction device and the subcell currents are very mismatched. What tactics can be used to make the subcell currents equivalent?



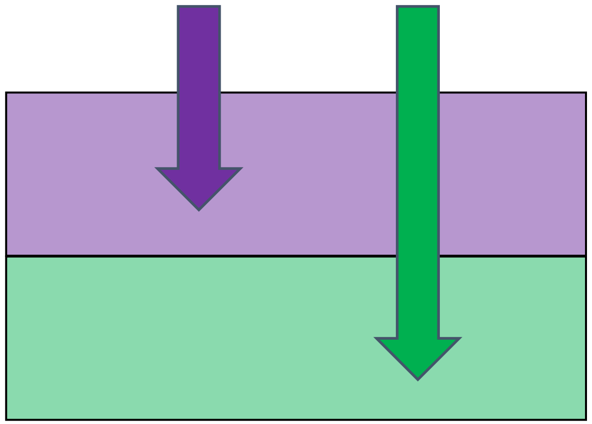
Mismatched current



Adjust thickness



Adjust bandgaps

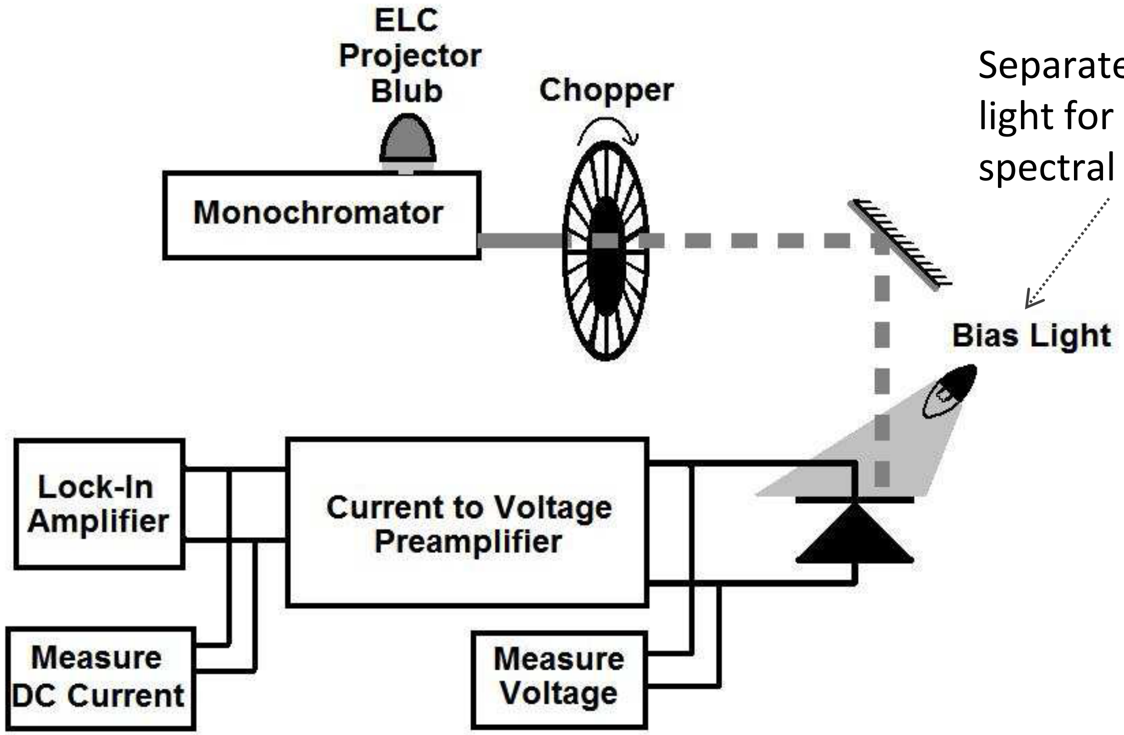


Multijunction device characterization

QUANTUM EFFICIENCY

Quantum Efficiency = # of electrons collected / # of incident photons

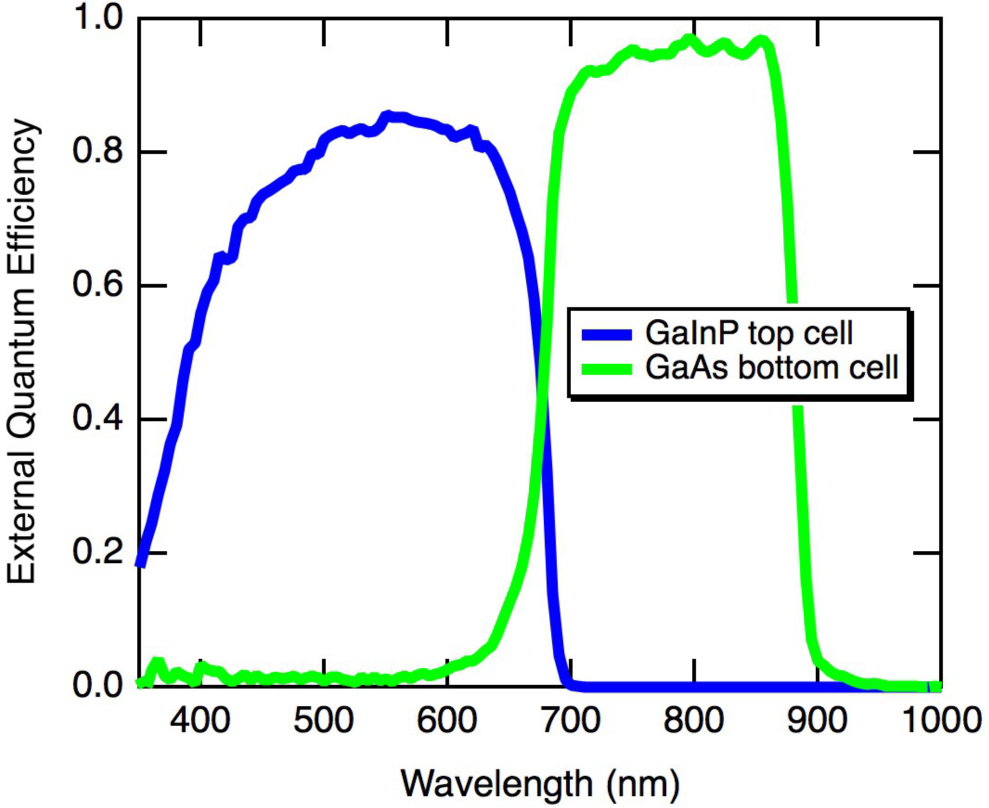
- Scan one wavelength at a time and compare current response to calibrated device
- Multijunction devices: use monochromated AC light for QE measurement
  - Use DC bias light to force current to be limited by one particular subcell



Separate DC bias light for each subcell spectral range

Image from: Timothy Nagle, Ph.D. Thesis 2007

MJ QE enables subcell Jsc to be measured

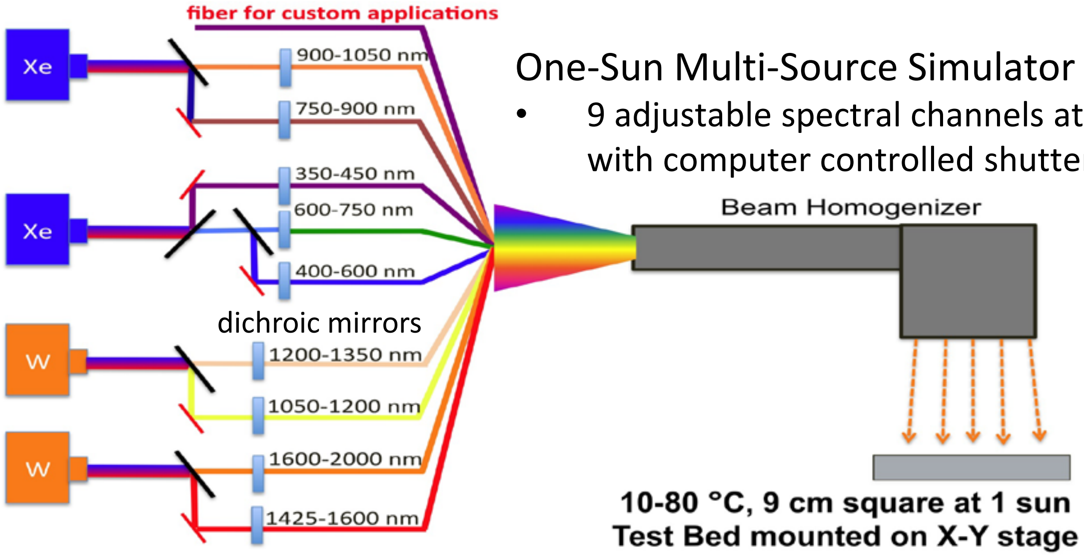


Multijunction device characterization

J-V FOR DEVICE EFFICIENCY

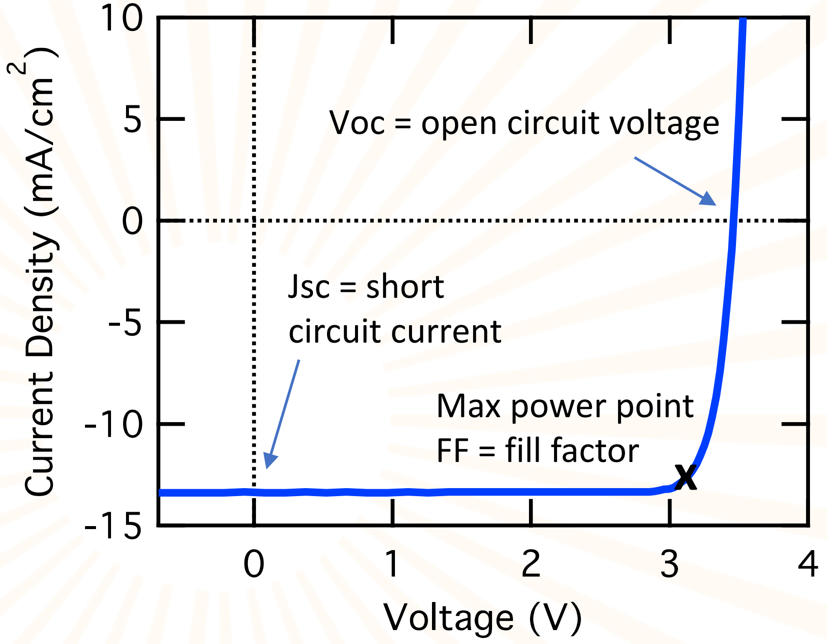
Illuminated J-V curve

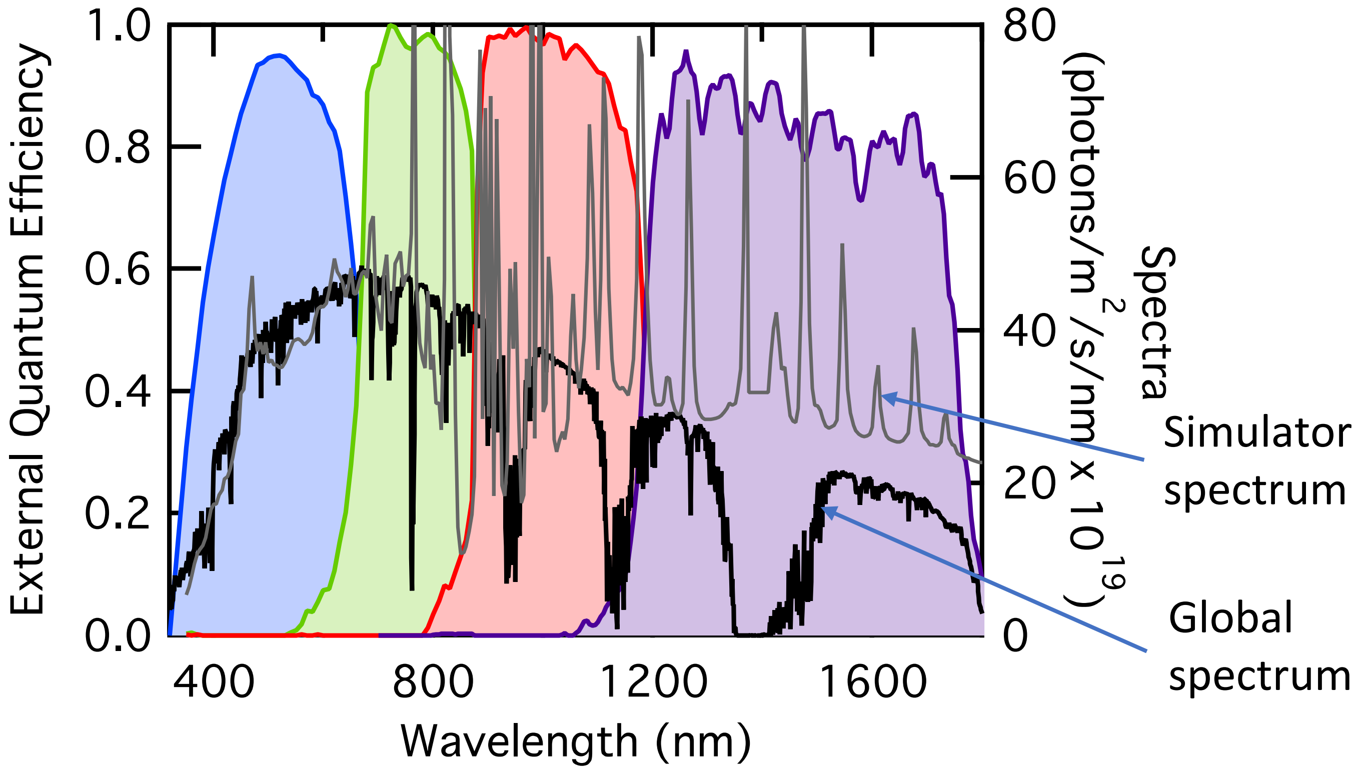
- Illuminate solar cell with simulated solar spectrum, scan voltage and collect current to determine power
- Multijunction measurement requires adjustable solar simulators!



One-Sun Multi-Source Simulator (OSMSS)

- 9 adjustable spectral channels attenuated with computer controlled shutter



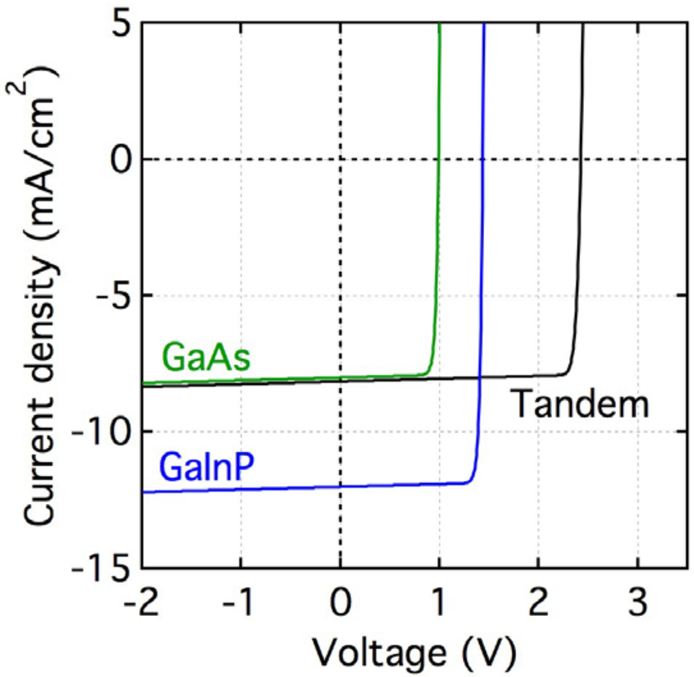


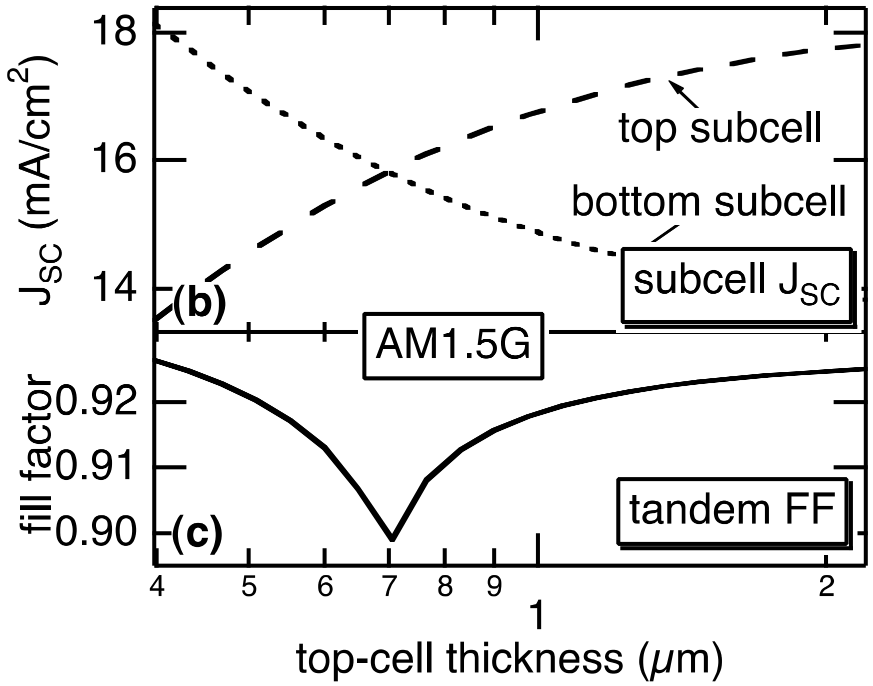
Break

Q&A

What happens to the fill factor of the tandem as the subcell currents become matched?

What happens to the fill factor of the tandem if the JV solar simulator is not correctly balanced between junctions?





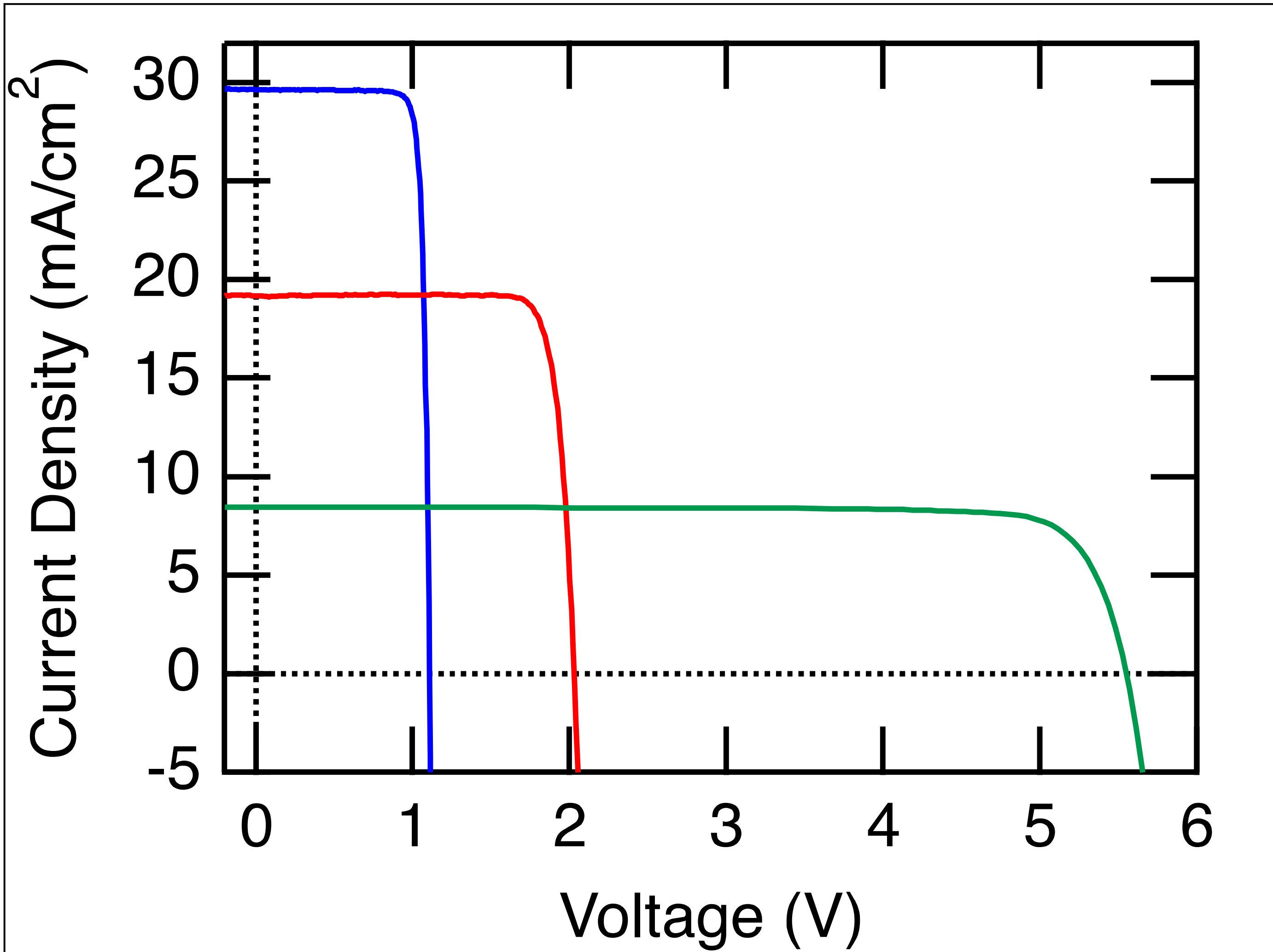
Olson, Friedman, Kurtz, handbook of photovoltaic science and engineering, 2003

Break

Q&A

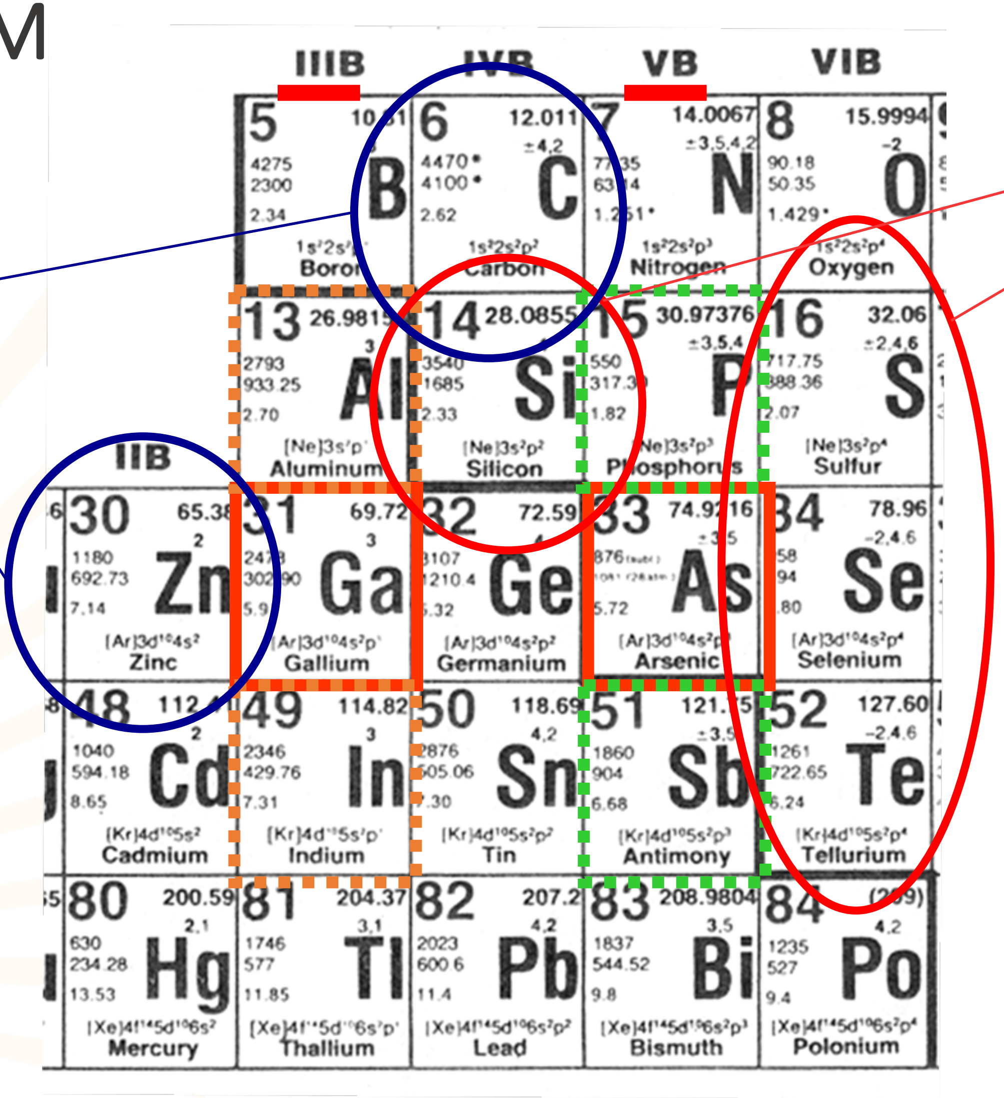
- What happens when you shine a laser on a multijunction solar cell?

- These are the JV curves of record efficiency multijunction devices with a different number of junctions. Can you determine the number of junctions in each?



III-V Introduction

III-V MATERIAL SYSTEM



Typical p-type dopants

Typical n-type dopants

- Wide variety of materials and bandgaps
- P- and N- type dopants available

III-V Introduction

EPITAXY

The deposition of an overlayer on a crystalline substrate, <u>where the overlayer is in registry with the substrate</u>

Metalorganic vapor phase epitaxy (MOVPE / MOCVD)

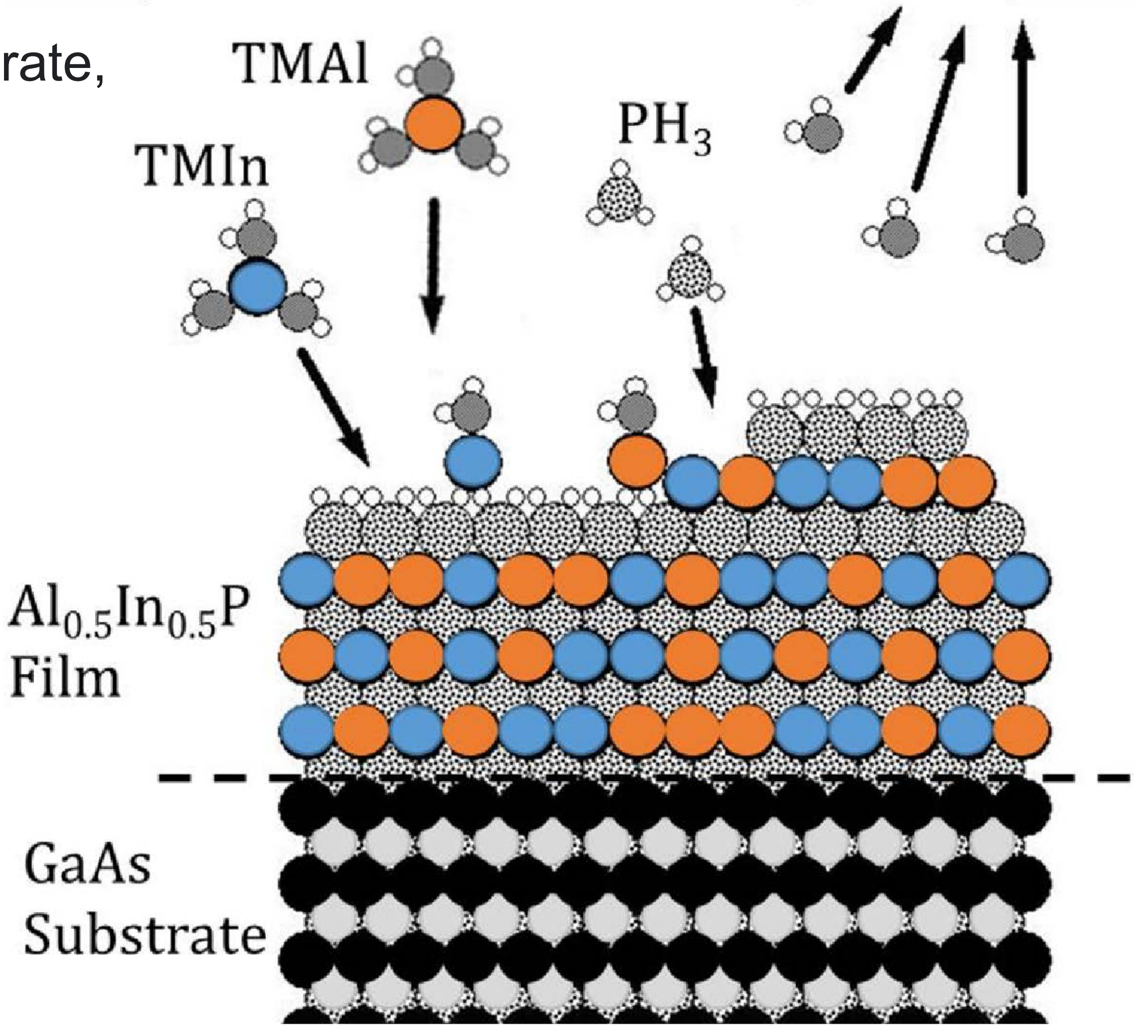
- Expensive organometallic and hydride sources
- ~ 10-60 µm/hr
- Industry standard

Molecular beam epitaxy (MBE)

- Elemental sources
- ~ 1 µm/hr
- Ultrahigh vacuum

Hydride vapor phase epitaxy (HVPE)

- Metallic and hydride sources
- >500 µm/hr for some materials



From K. Mukherjee, Thesis, adapted from Pinzone.

III-V components

SERIES CONNECTED 2-JUNCTION DEVICE

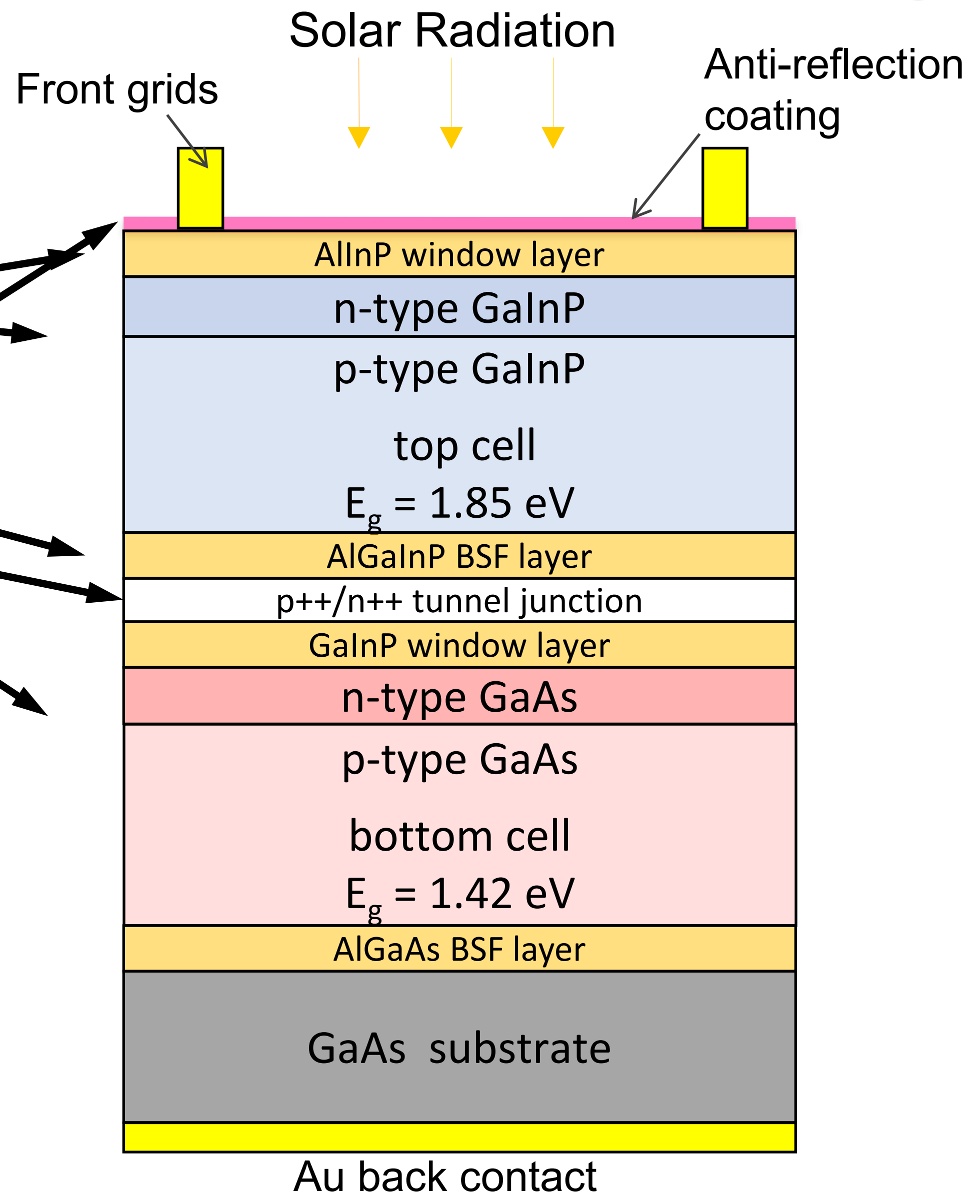
Components

p-n junctions

cladding layers

tunnel junction

anti-reflection coating



Solar Radiation

Front grids

Anti-reflection coating

AlInP window layer

n-type GaInP

p-type GaInP

top cell

E_g = 1.85 eV

AlGaInP BSF layer

p++/n++ tunnel junction

GaInP window layer

n-type GaAs

p-type GaAs

bottom cell

E_g = 1.42 eV

AlGaAs BSF layer

GaAs substrate

Au back contact

- Bandgaps are extremely important!
  - Highest efficiency when each junction produces the same current
- Material quality must be high!
  - Limit structural defects upon subcell integration

III-V Introduction

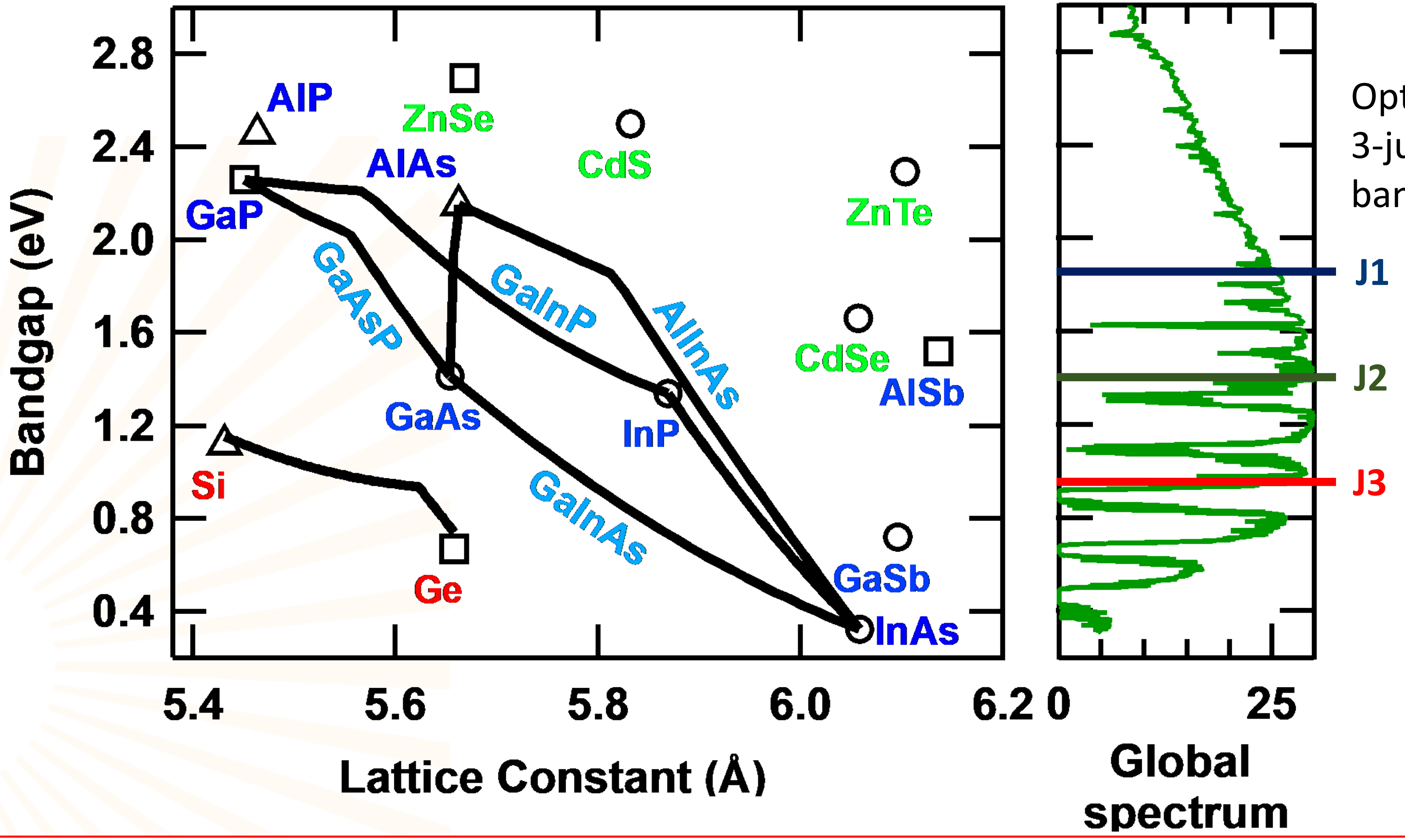
WIDE BANDGAP RANGE

III-V binary

III-V ternary

II-VI

IV



Optimal 3-junction bandgaps

Can you foresee a challenge integrating 3 optimal III-V materials together?

III-V Introduction

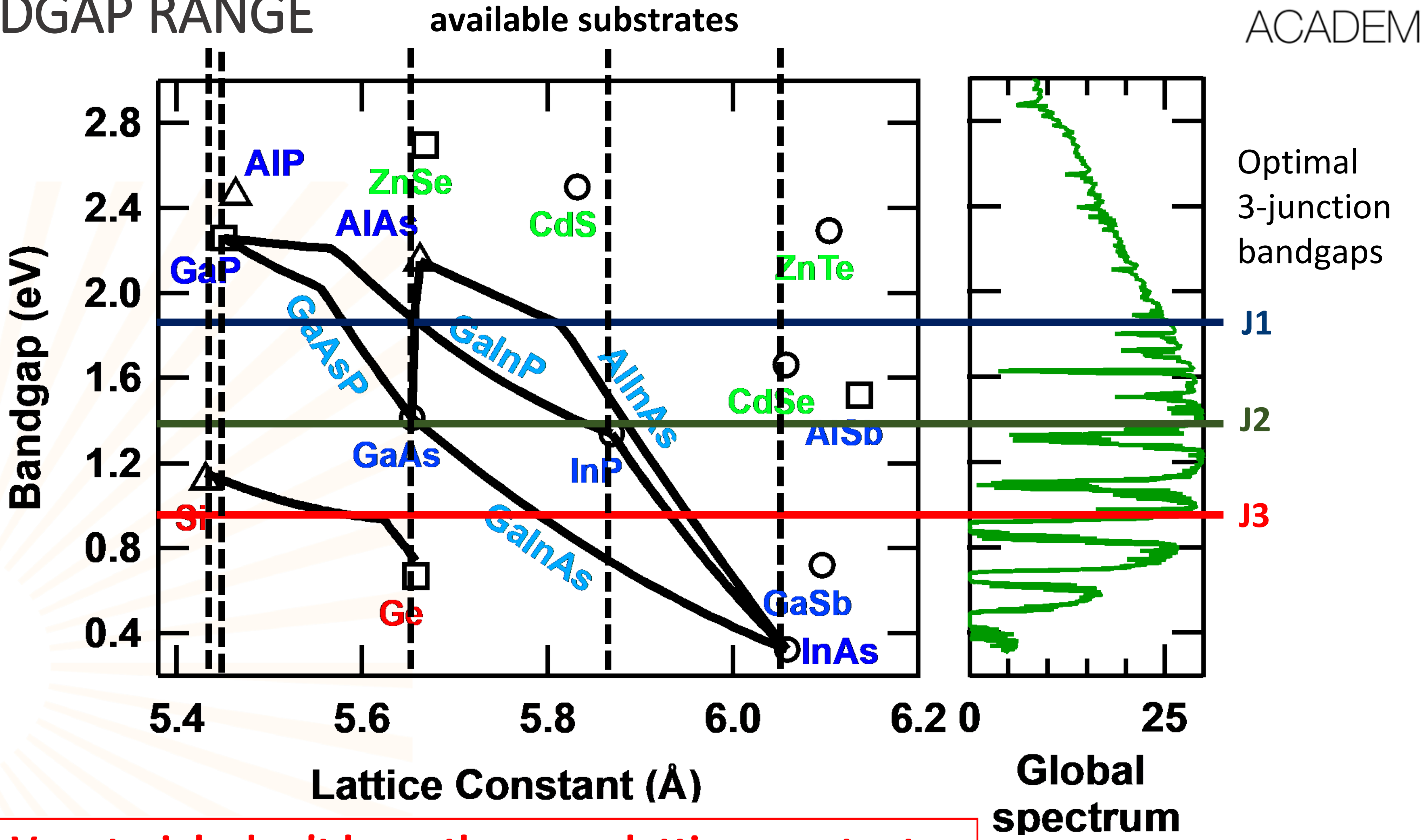
WIDE BANDGAP RANGE

III-V binary

III-V ternary

II-VI

IV



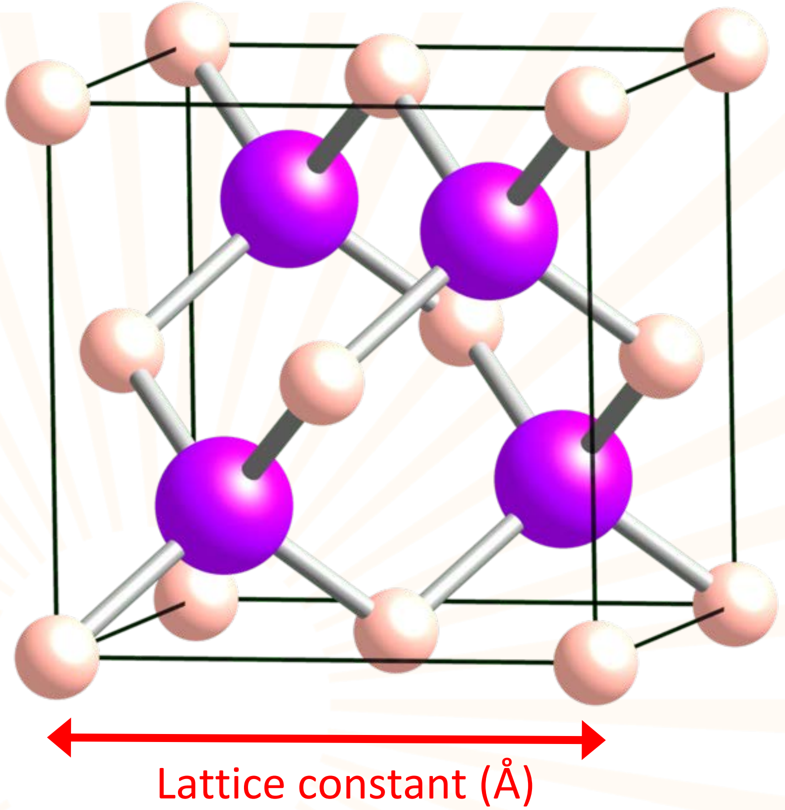
Optimal III-V materials don’t have the same lattice-constants

Material integration challenges

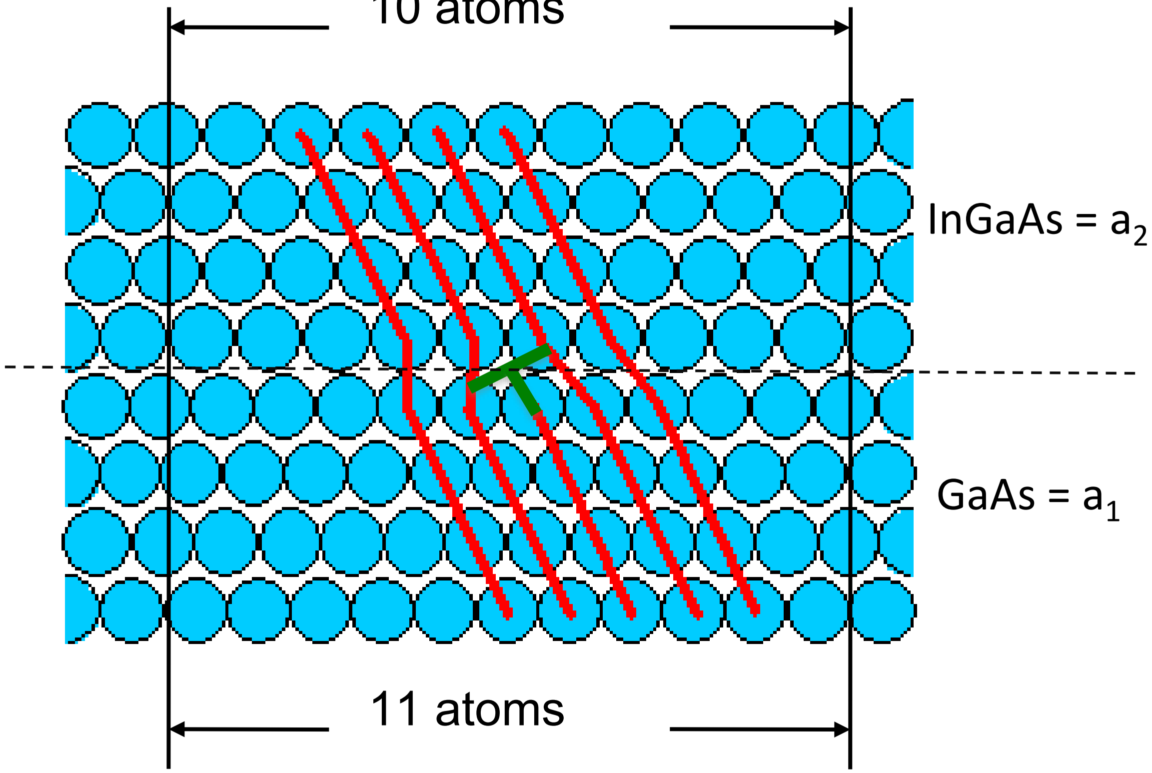
III-V CRYSTAL STRUCTURE

Zincblende crystal structure

Unit cell contains 4 Ga and 4 As atoms



Lattice-mismatched InGaAs on GaAs

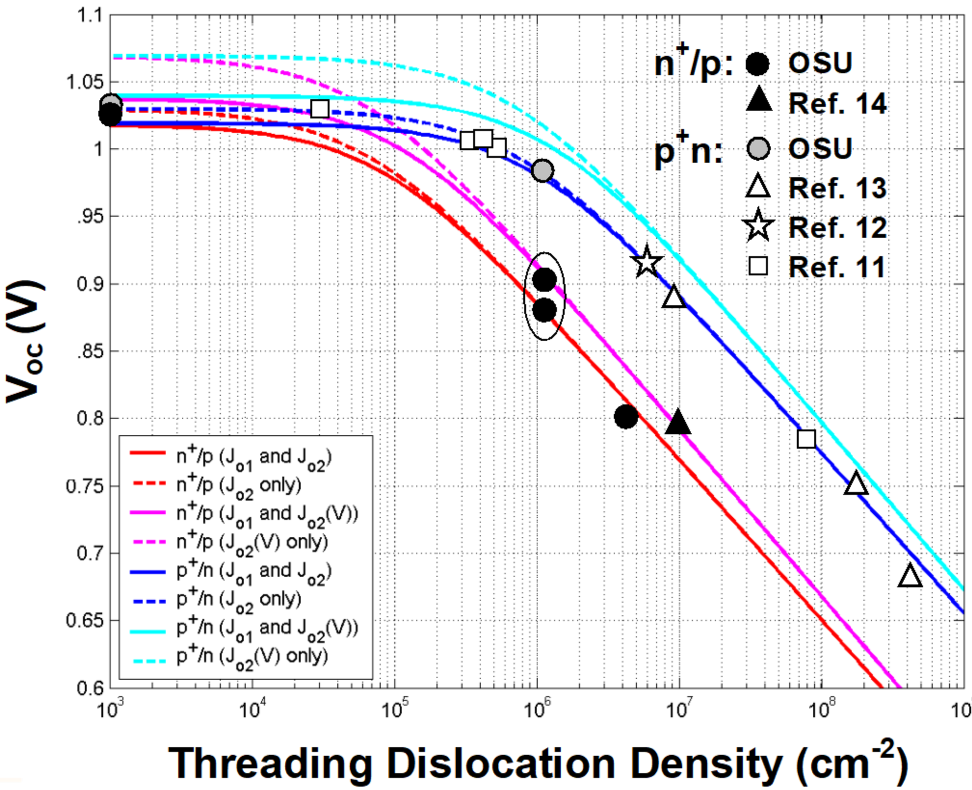


Lattice constants : $a_2 > a_1$

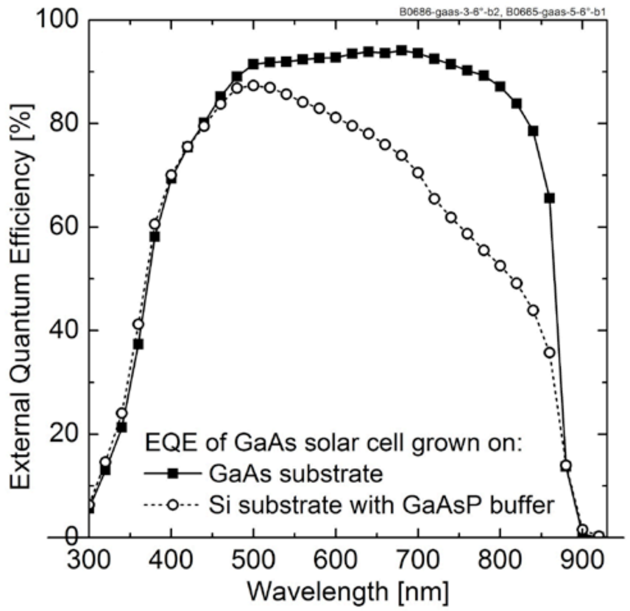
Excellent crystalline material quality when all materials have the same lattice constant

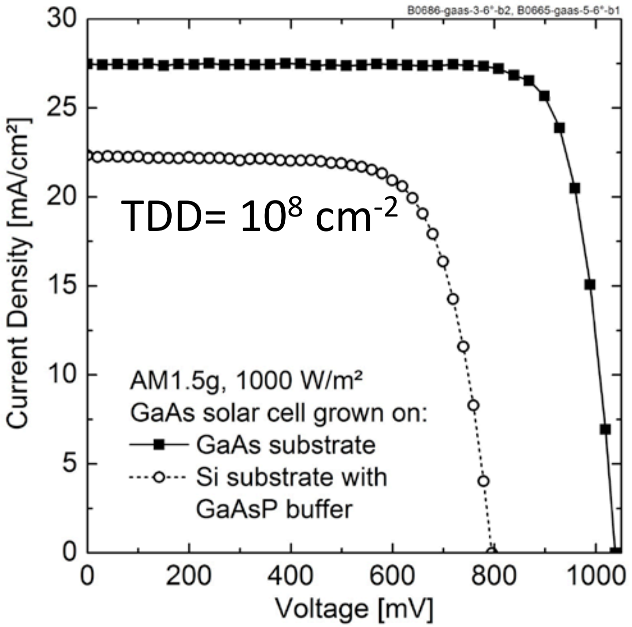
Material integration challenges

LATTICE-MISMATCHED MATERIALS

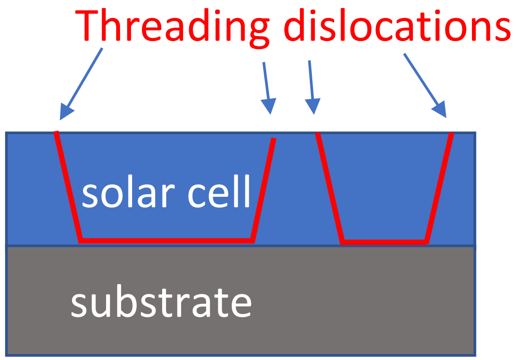


- Threading dislocation density (TDD) < 10^6 cm^{-2} needed for good solar cell performance





TDD= 10^8 cm^{-2}

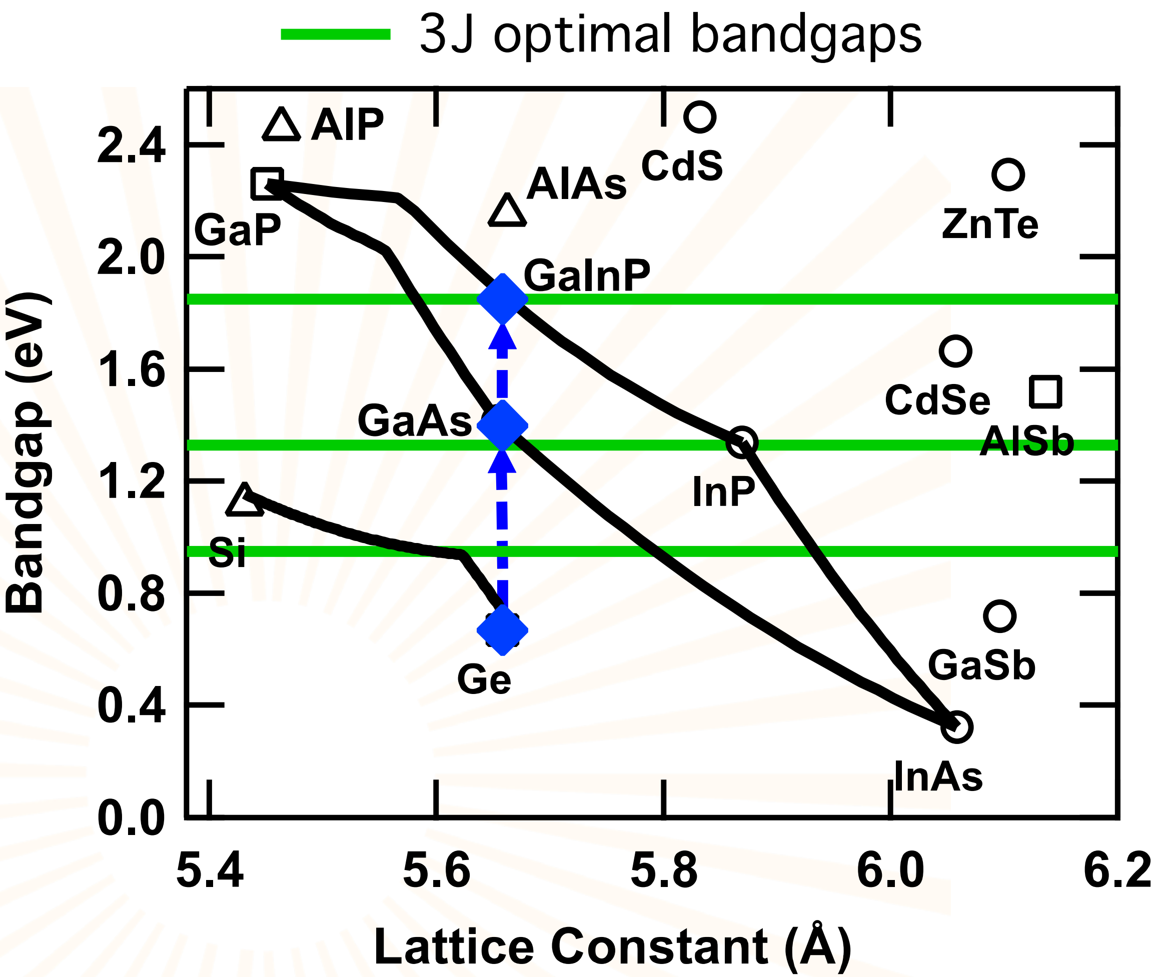


Lattice mismatched layers can only be included when the TDD is low

Theoretical : C. Andre, PhD Thesis, Ohio State University (2004).
Experimental: T. Roesener, PhD Thesis, Universität Konstanz, Germany (2013

High efficiency devices

III-V MULTIJUNCTION PATHWAYS



Lattice-matched approaches

◆ Standard Ge-based

Quaternary GaInNAs

Wafer bonded

Lattice-mismatched approaches

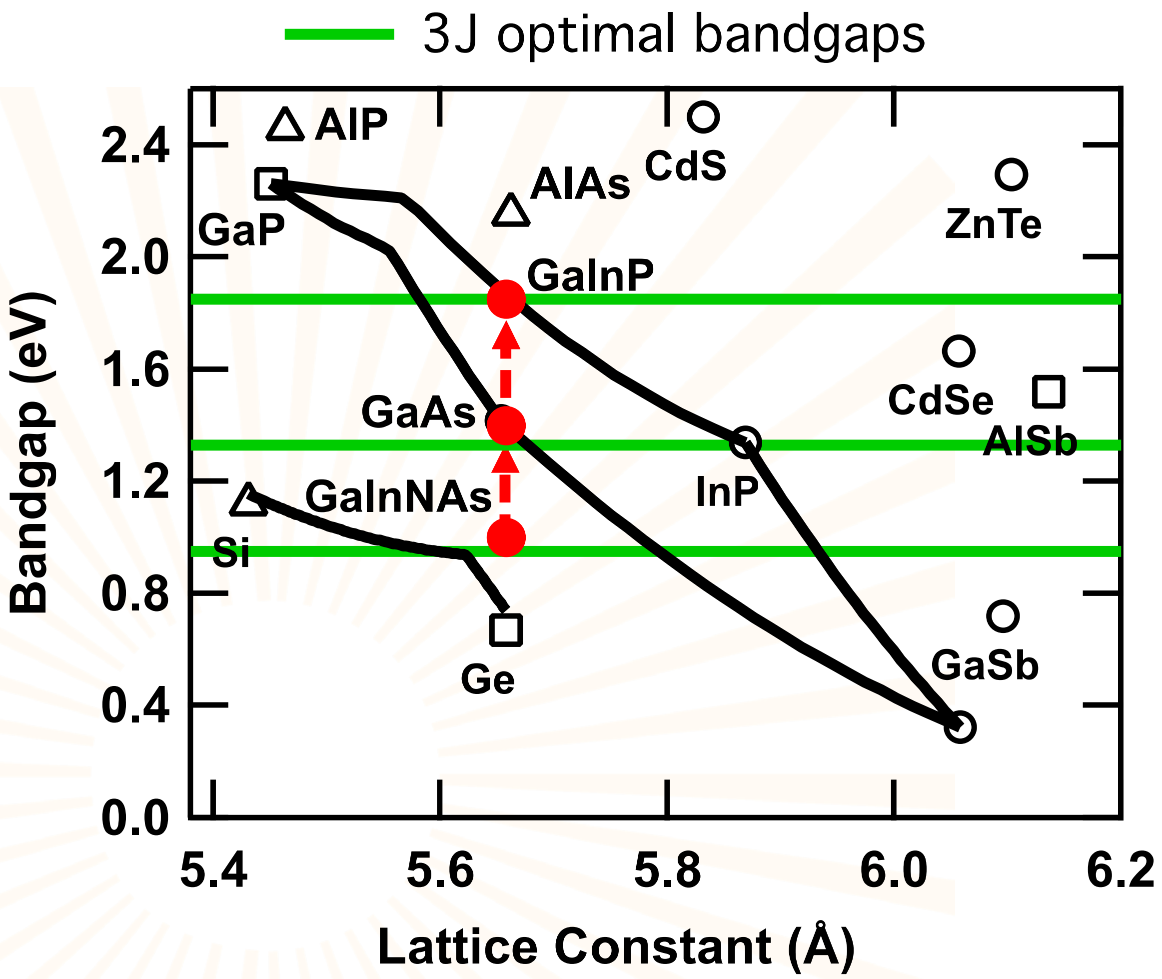
Upright Metamorphic

Inverted Metamorphic

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

High efficiency devices

III-V MULTIJUNCTION PATHWAYS



Lattice-matched approaches

Standard Ge-based

🔴 Quaternary GaInNAs

Wafer bonded

Lattice-mismatched approaches

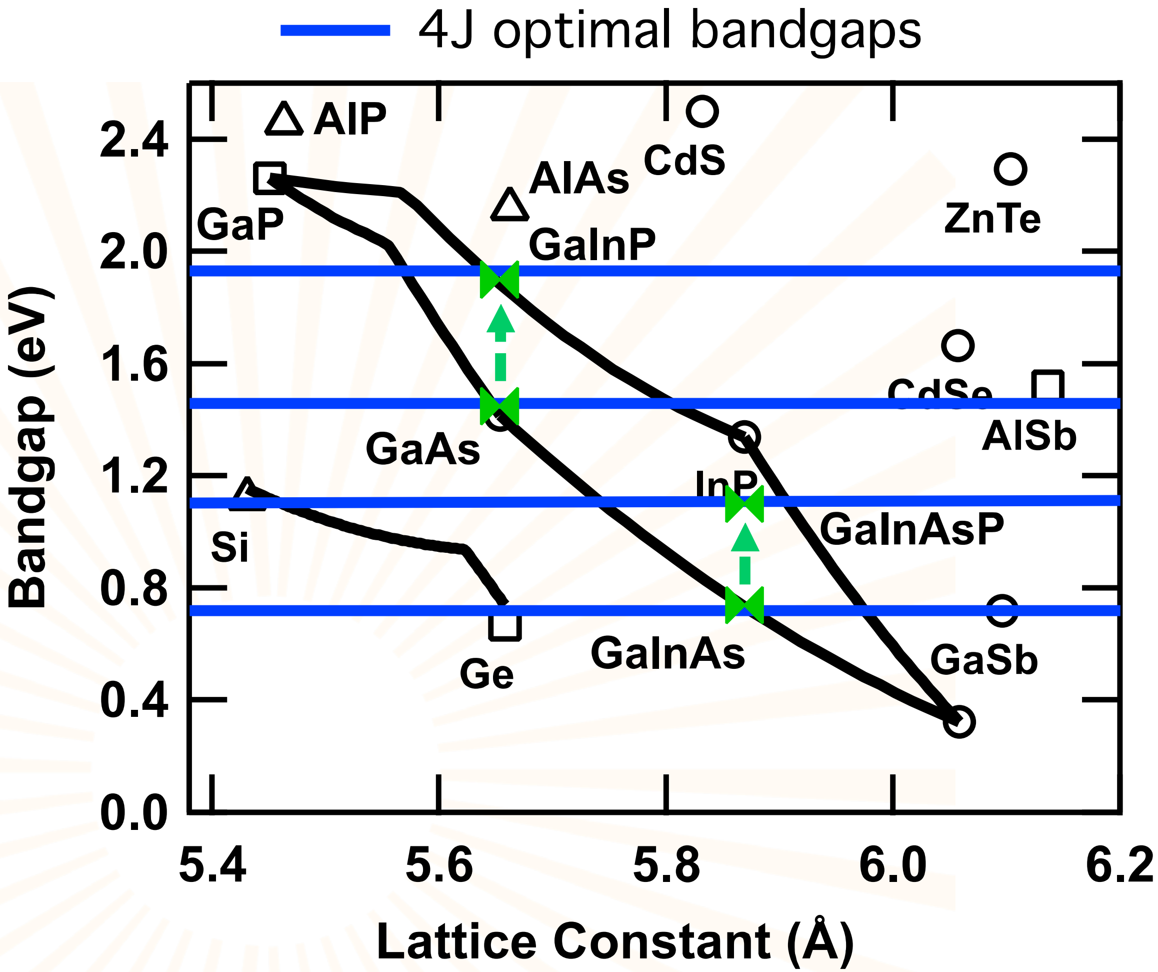
Upright Metamorphic

Inverted Metamorphic

- Lattice-matched, more optimal bandgap combination
- GaInNAs tends to have low diffusion length and high non-radiative recombination

High efficiency devices

III-V MULTIJUNCTION PATHWAYS



Lattice-matched approaches

Standard Ge-based

Quaternary GaInNAs

⋈ Wafer bonded

Lattice-mismatched approaches

Upright Metamorphic

Inverted Metamorphic

- Optimal bandgap combination
- All lattice-matched, high-quality materials
- Requires two growths and bonding

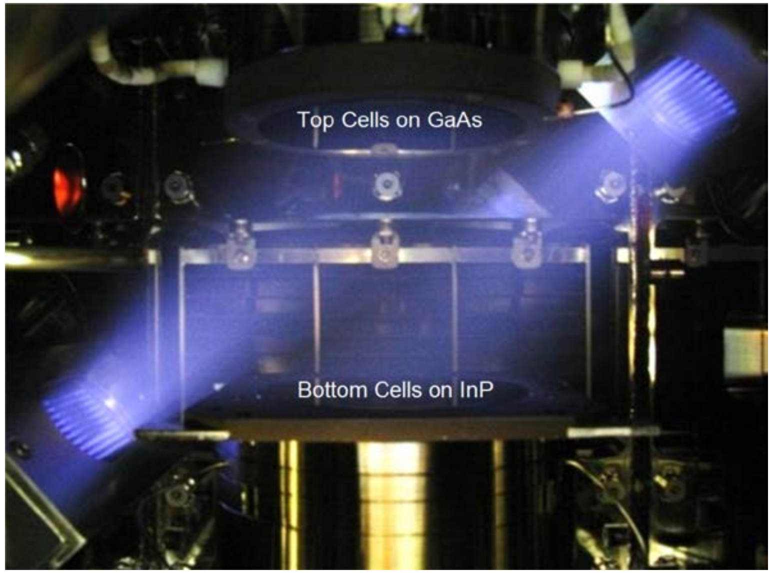
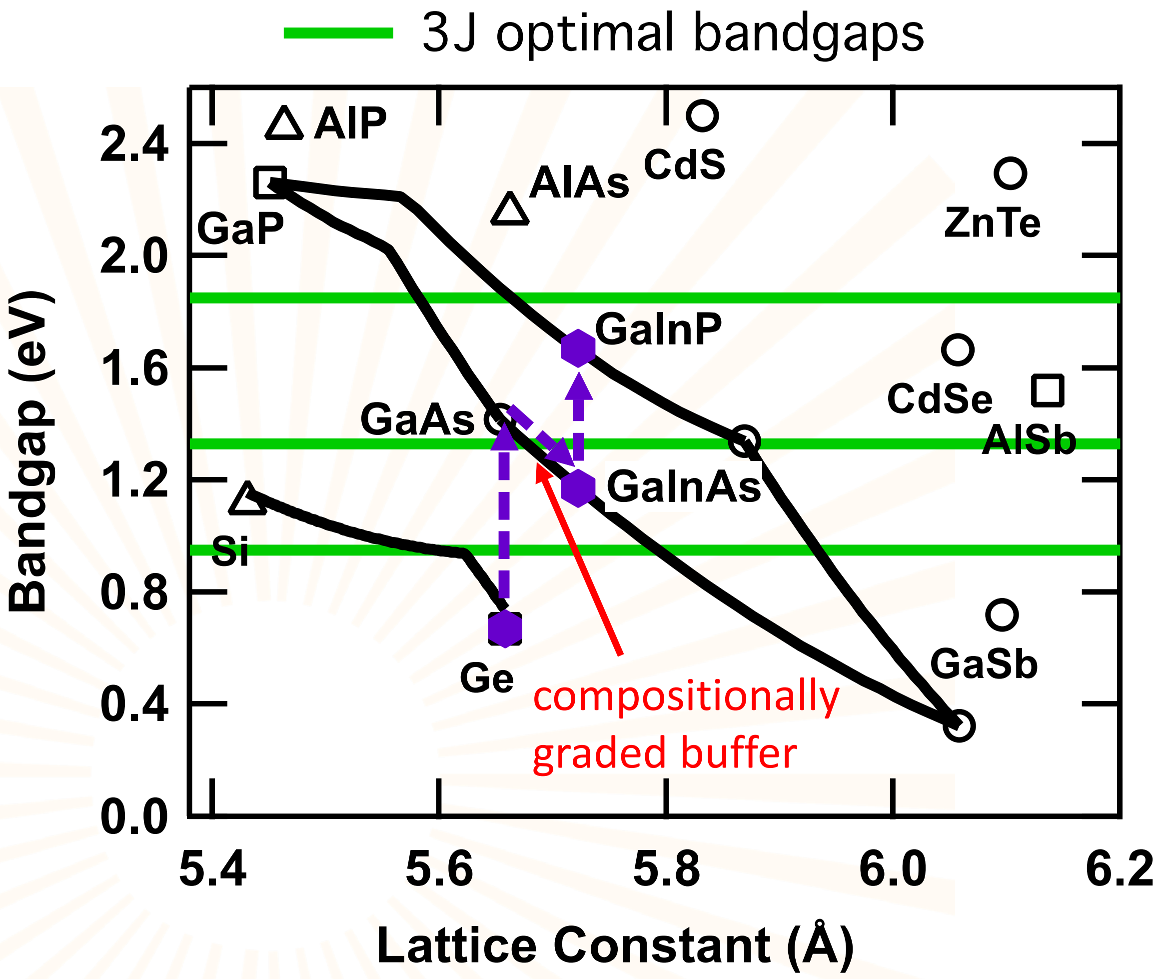


Image credit:
50-percent.de

High efficiency devices

III-V MULTIJUNCTION PATHWAYS



Lattice-matched approaches

Standard Ge-based

Quaternary GaInNAs

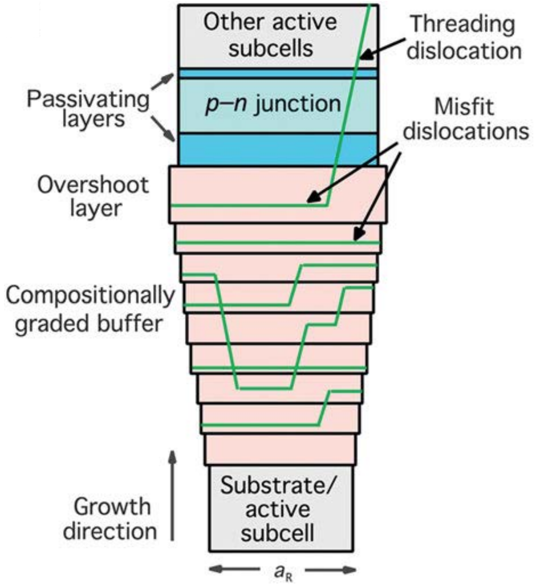
Wafer bonded

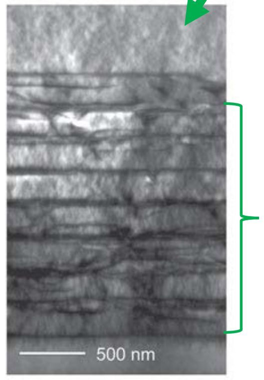
Lattice-mismatched approaches

⬢ Upright Metamorphic

Inverted Metamorphic

- Current-balanced
- Low mismatch buffer ~1.2%
- High efficiency 3J design

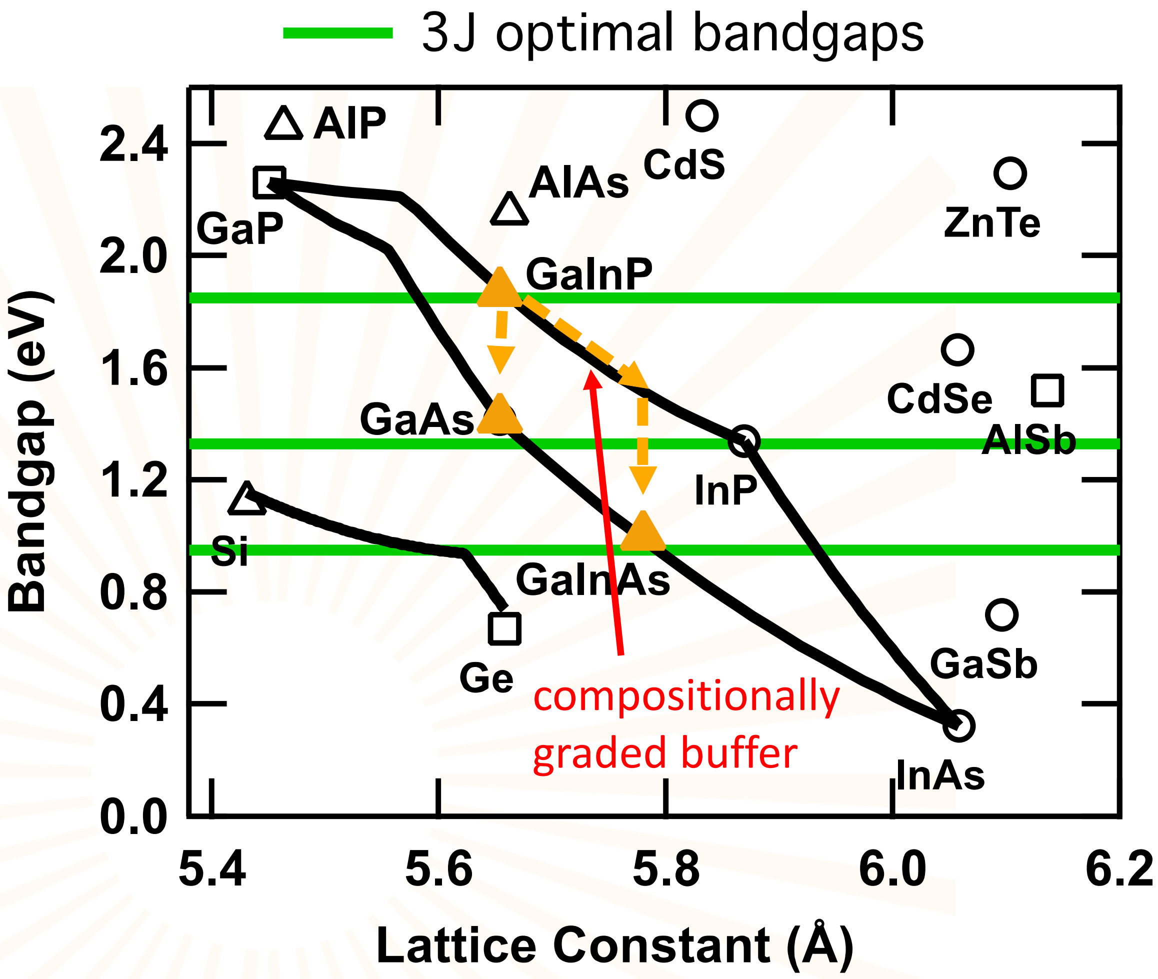




TEM

High efficiency devices

III-V MULTIJUNCTION PATHWAYS



Lattice-matched approaches

Standard Ge-based

Quaternary GaInNAs

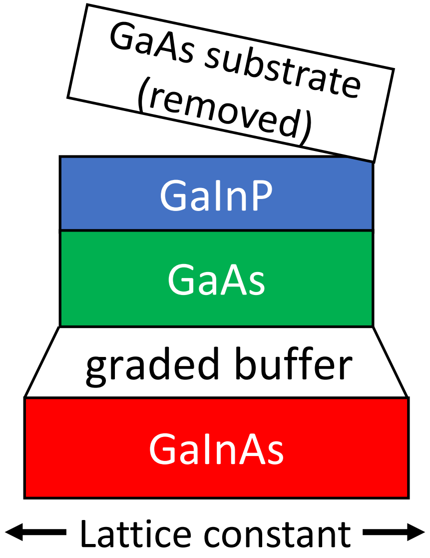
Wafer bonded

Lattice-mismatched approaches

Upright Metamorphic

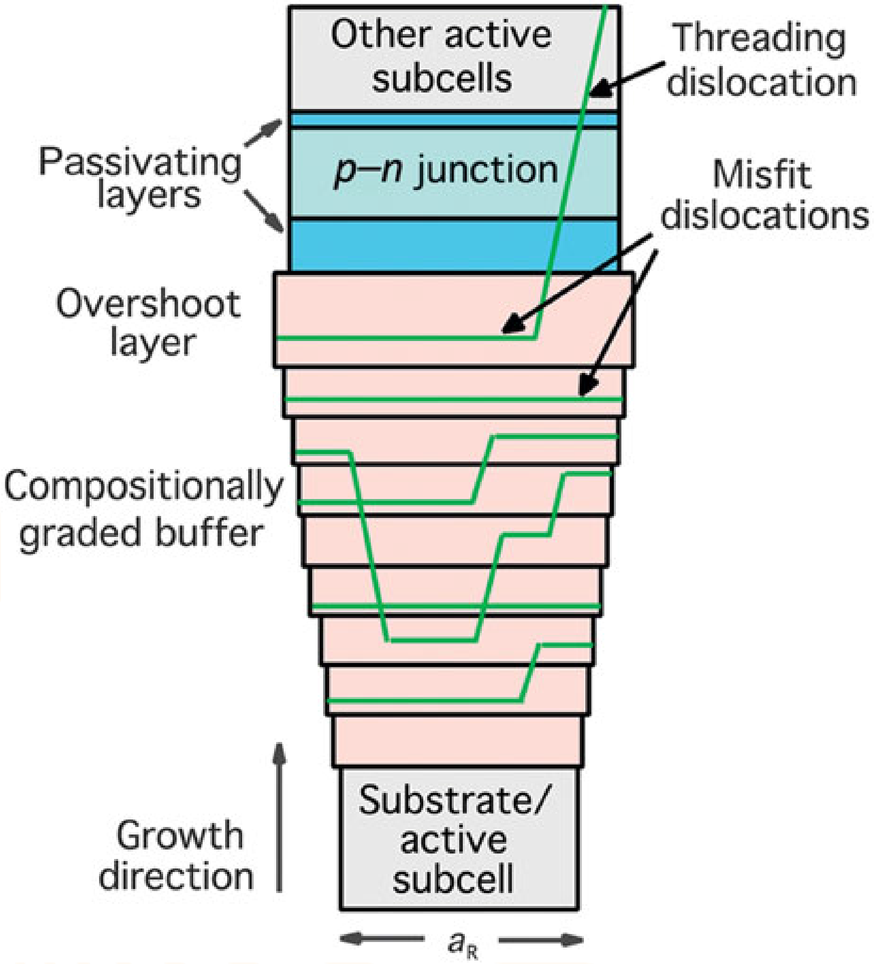
▲ Inverted Metamorphic

- Top cell grown first, substrate removed
- Near ideal bandgap combination
- Flexible design, up to 6 junctions

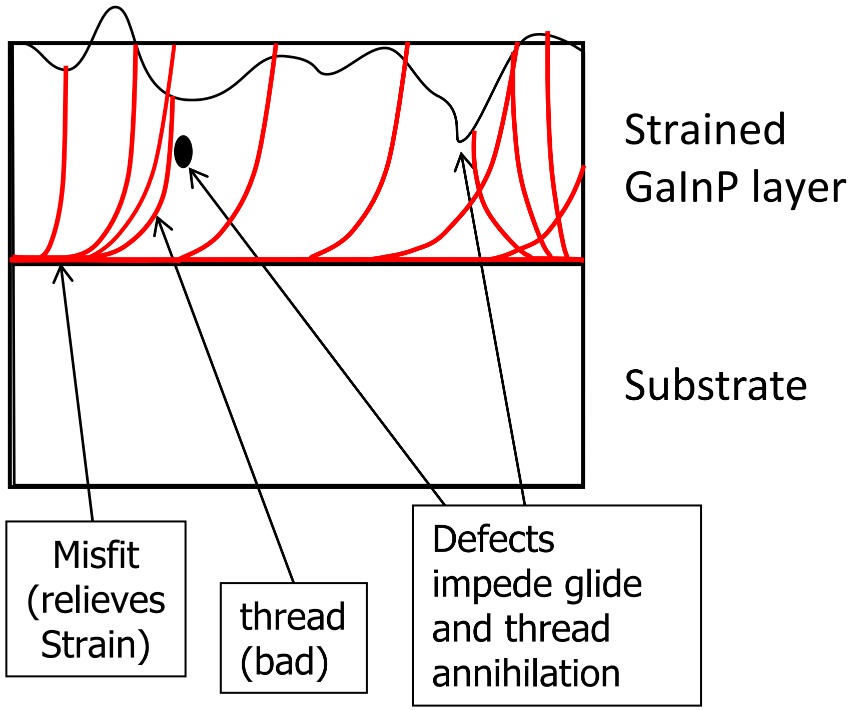


Materials Research

METAMORPHIC MATERIAL



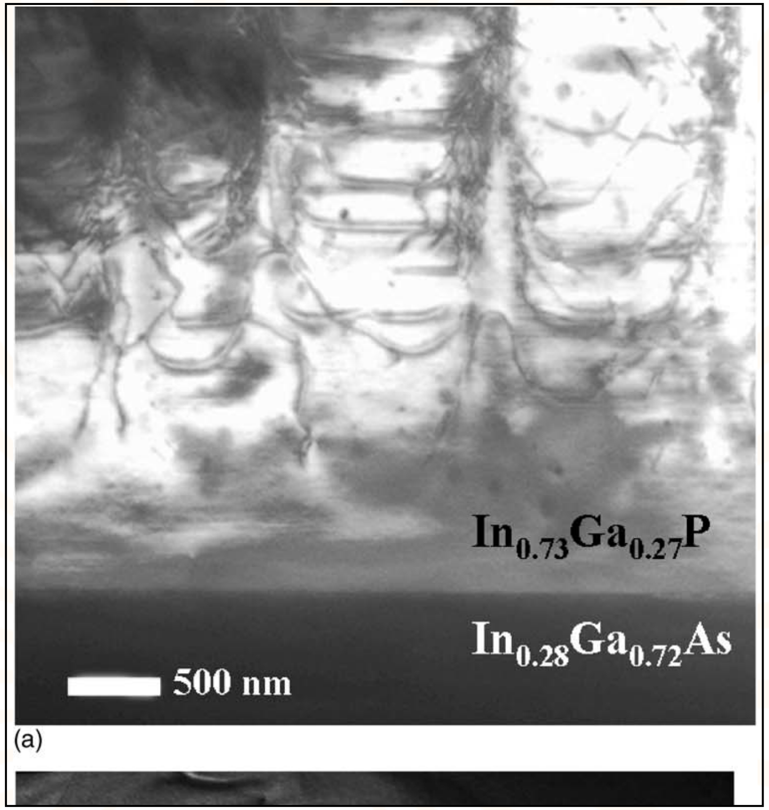
- Intentionally introduce dislocations to alter in-plane lattice constant
- Need to minimize threading dislocation density for performance
- *Maximize dislocation glide*



Materials research

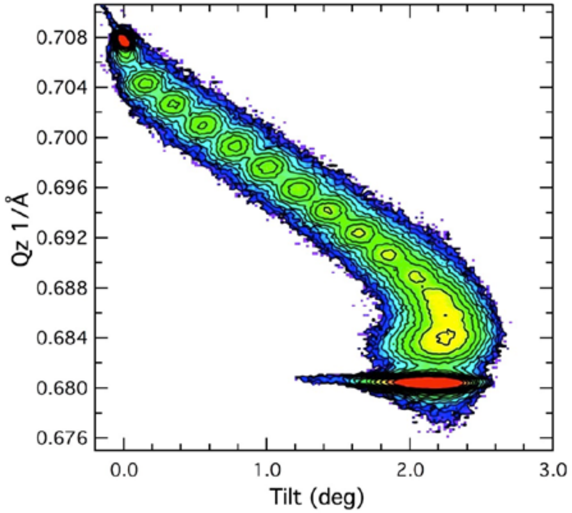
MATERIAL CHARACTERIZATIONS

X-sectional TEM
Material nonuniformities

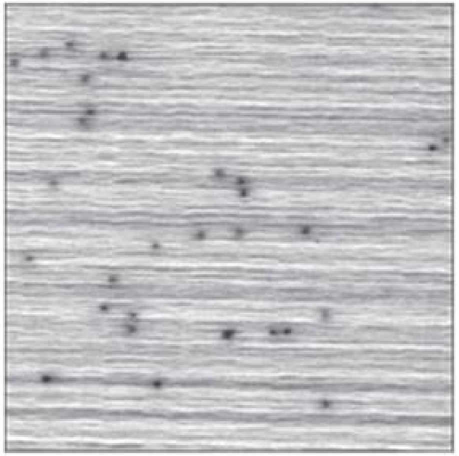


N. Quitoriano et al.,, J. Appl. Phys. **102**, 033411 (2007)
R. France et al., MRS Bulletin, **41**, 202 (2016)
R. France et al., J. Photovolt., **4**, 193 (2014)
S. B. Samavedam et al, J. Appl. Phys. **81**, 3108 (1997).

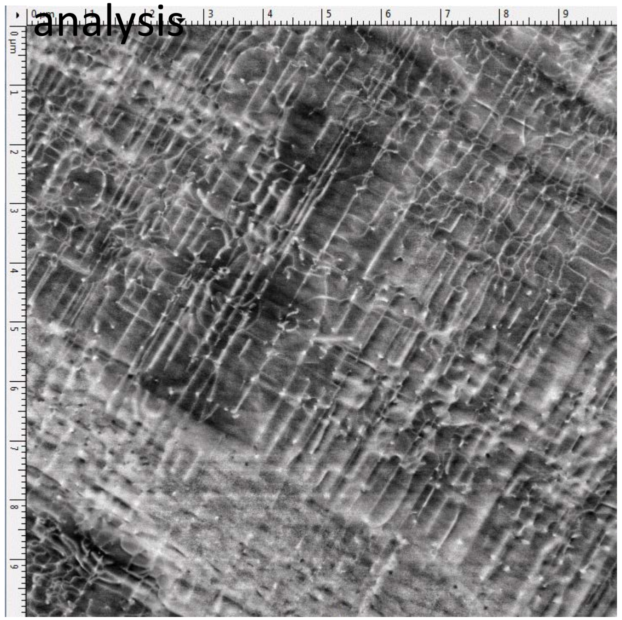
High resolution XRD
Glide dynamics



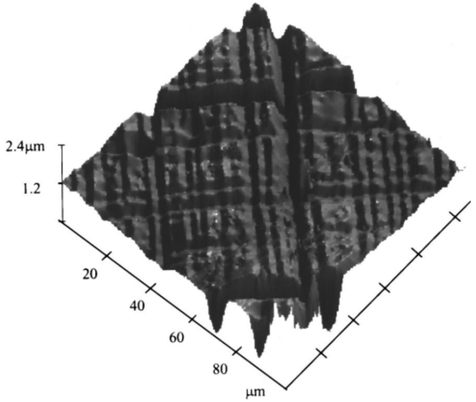
Cathodoluminescence/ EBIC
Threading defect density



Electron channeling contrast imaging
Misfit dislocation analysis

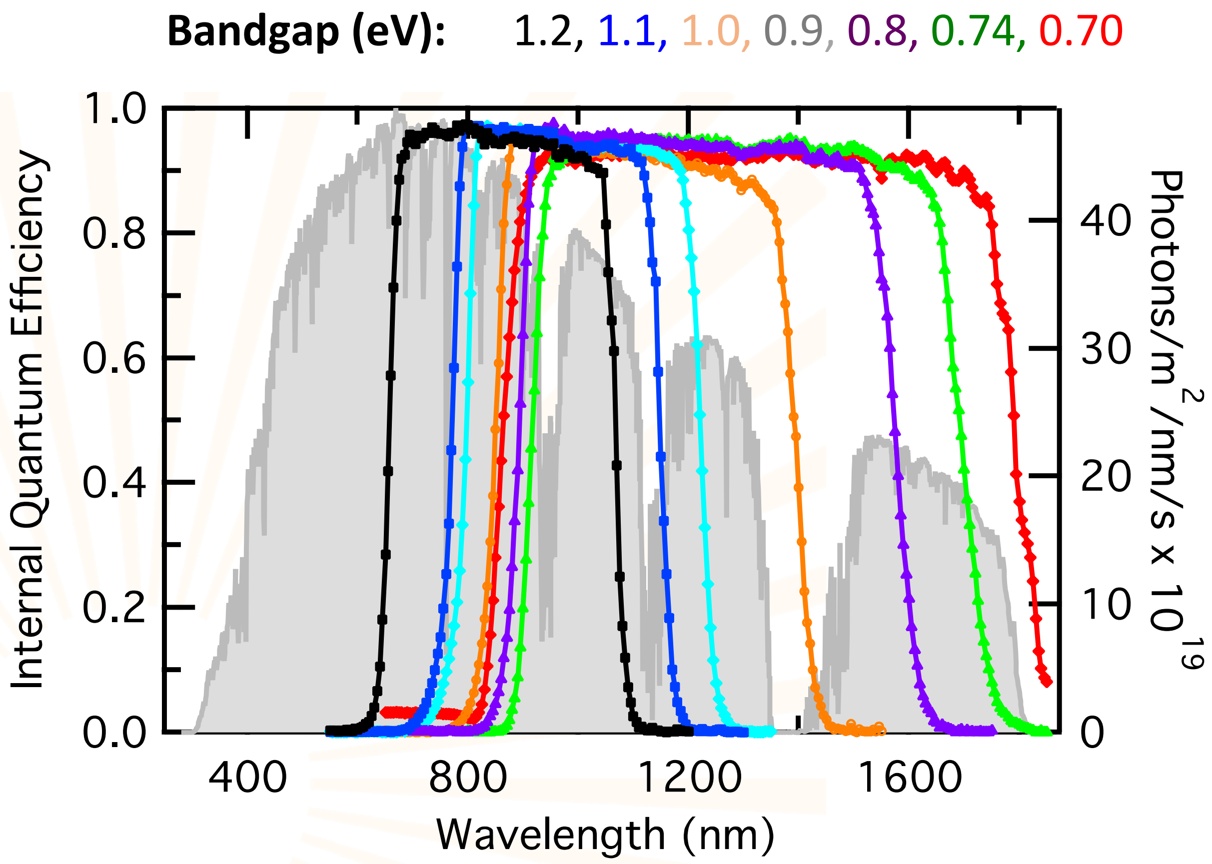


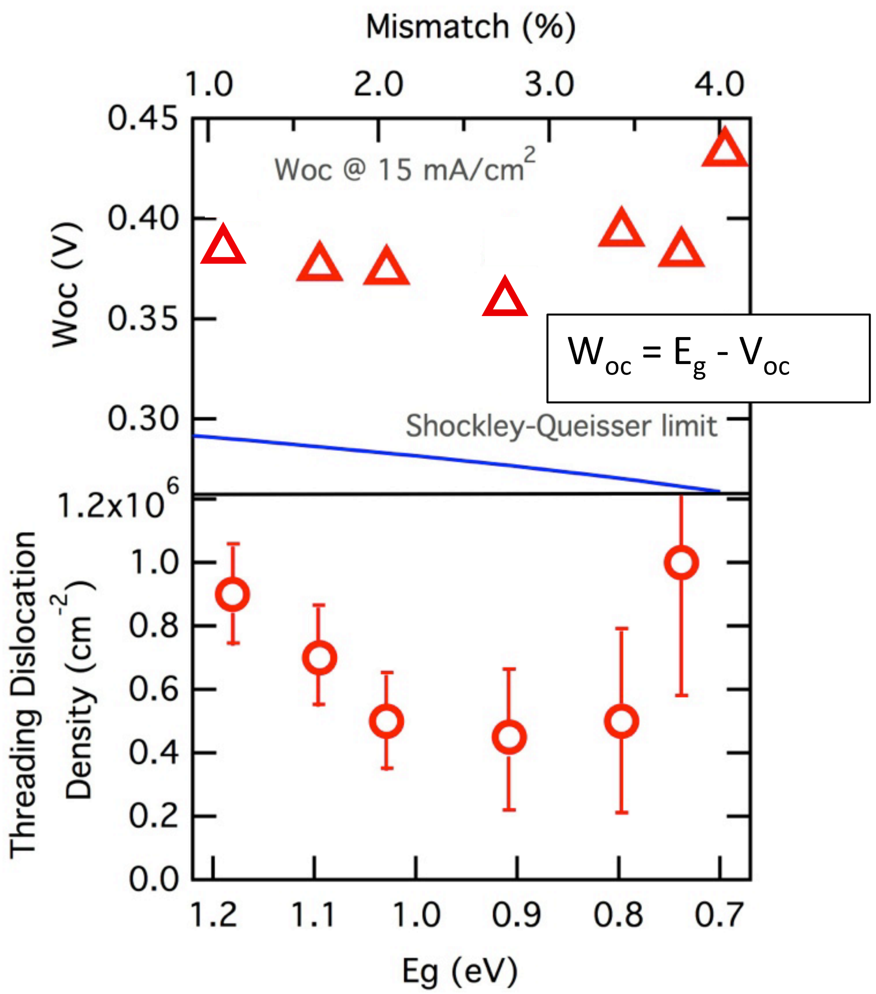
Atomic force microscopy
Surface analysis



Metamorphic devices

METAMORPHIC GAINAS CELL PERFORMANCE



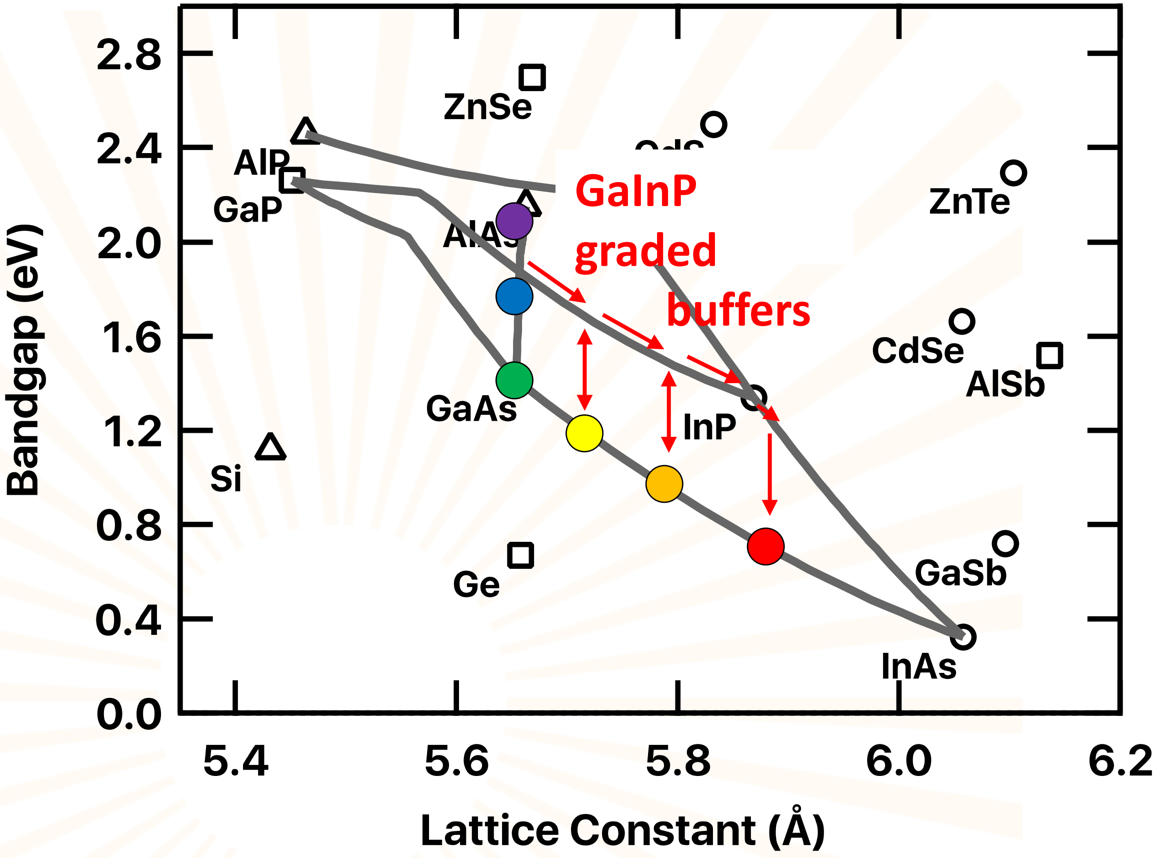


Graded buffers can be used for lattice-mismatched GaInAs subcells with collection spanning large portion of solar spectrum

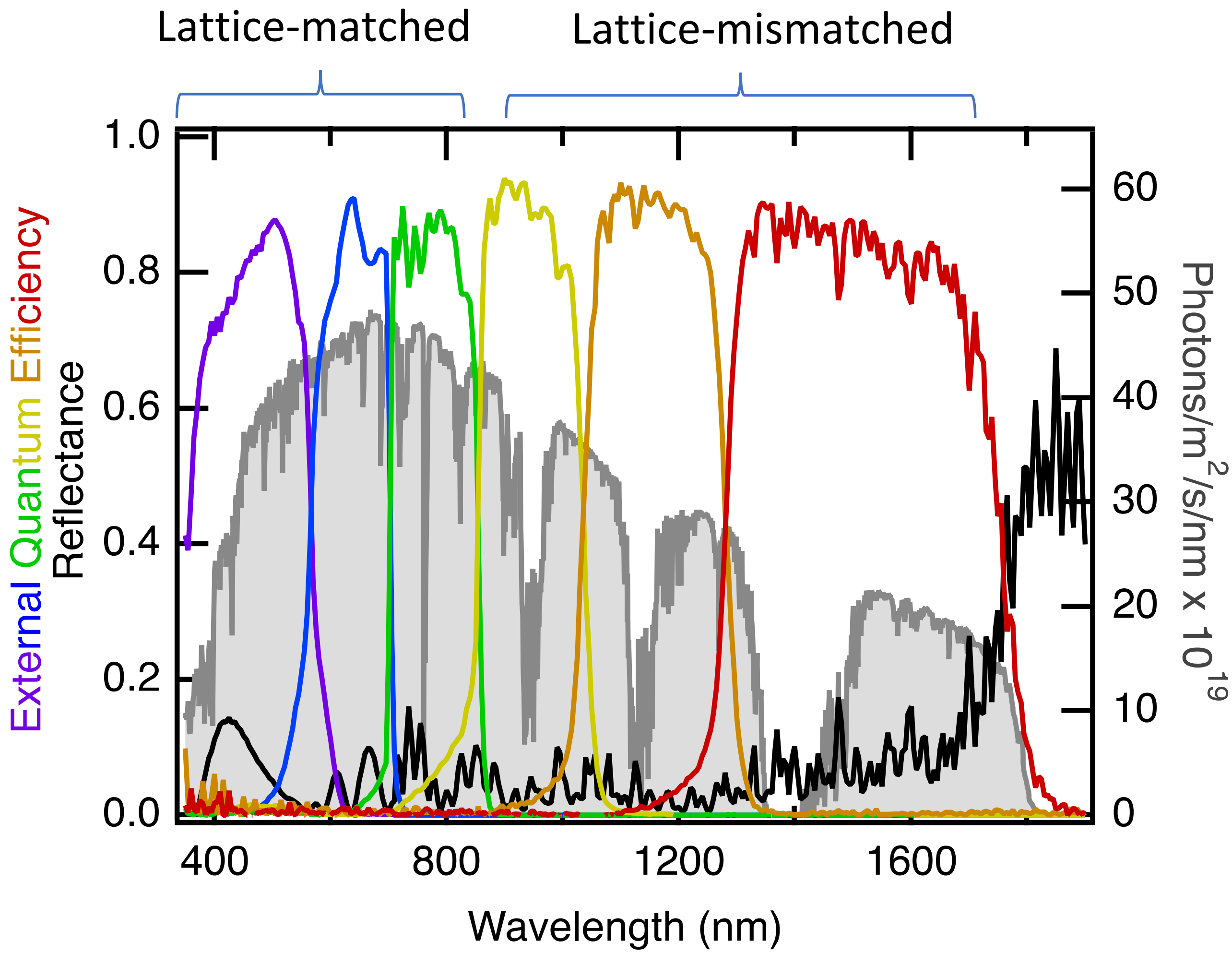
R. France et al., J. Photovolt., **6**, 578 (2016)

Metamorphic devices

6-JUNCTION INVERTED METAMOPRHIC



J. Geisz et al., Nat. Energy., **5**, 326 (2020)



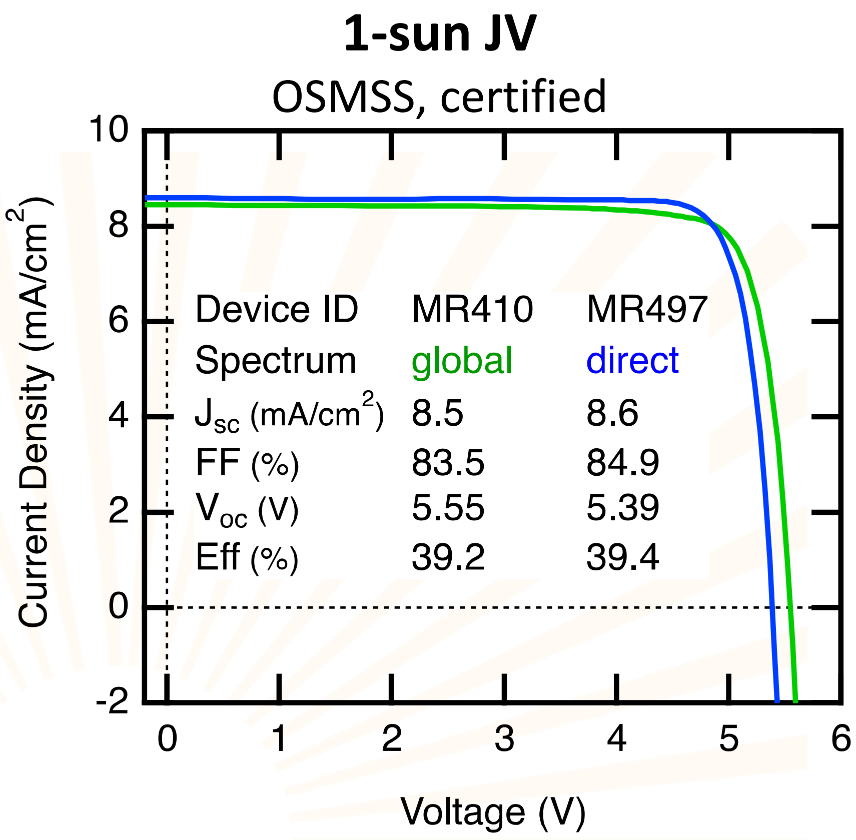
- 3 subcells lattice-matched to GaAs
- 3 independently mismatched GaInAs subcells

Metamorphic devices

HIGH EFFICIENCY RESULTS

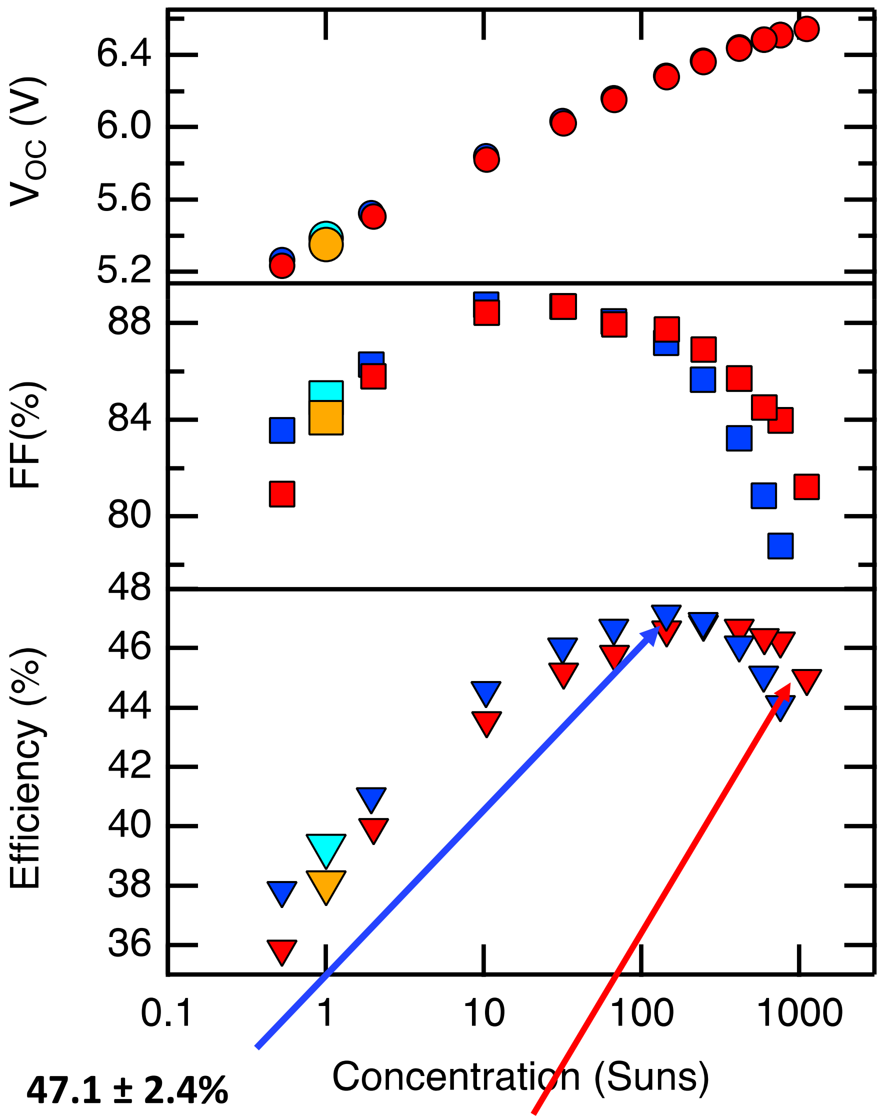
1-sun JV

OSMSS, certified



Device ID	MR410	MR497
Spectrum	global	direct
J_{sc} (mA/cm^2)	8.5	8.6
FF (%)	83.5	84.9
V_{oc} (V)	5.55	5.39
Eff (%)	39.2	39.4

Concentrator JV results



47.1 ± 2.4%
@ 143 suns

44.9 ± 2.3%
@ 1115 suns

J. Geisz et al., Nat. Energy., **5**, 326 (2020)

2019: 6-junction records: 39.2% at 1-sun, 47.1% at 143 suns

→ 2022: 39.5%, 1-sun, 3-junction IMM with quantum wells

→ 2022: 47.6%, 665 suns, 4-junction wafer bonded

III-V applications

CONCENTRATORS

$$J(V) \approx J_{sc} - J_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

J(V) = 0 at V_{oc}

Assumption of linearity:

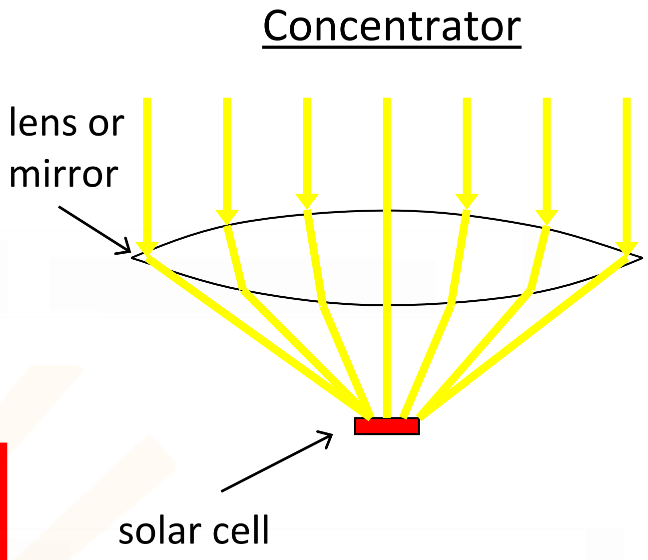
$$\text{concentration } X = \frac{J_{sc}(X)}{J_{sc}(1\text{sun})}$$

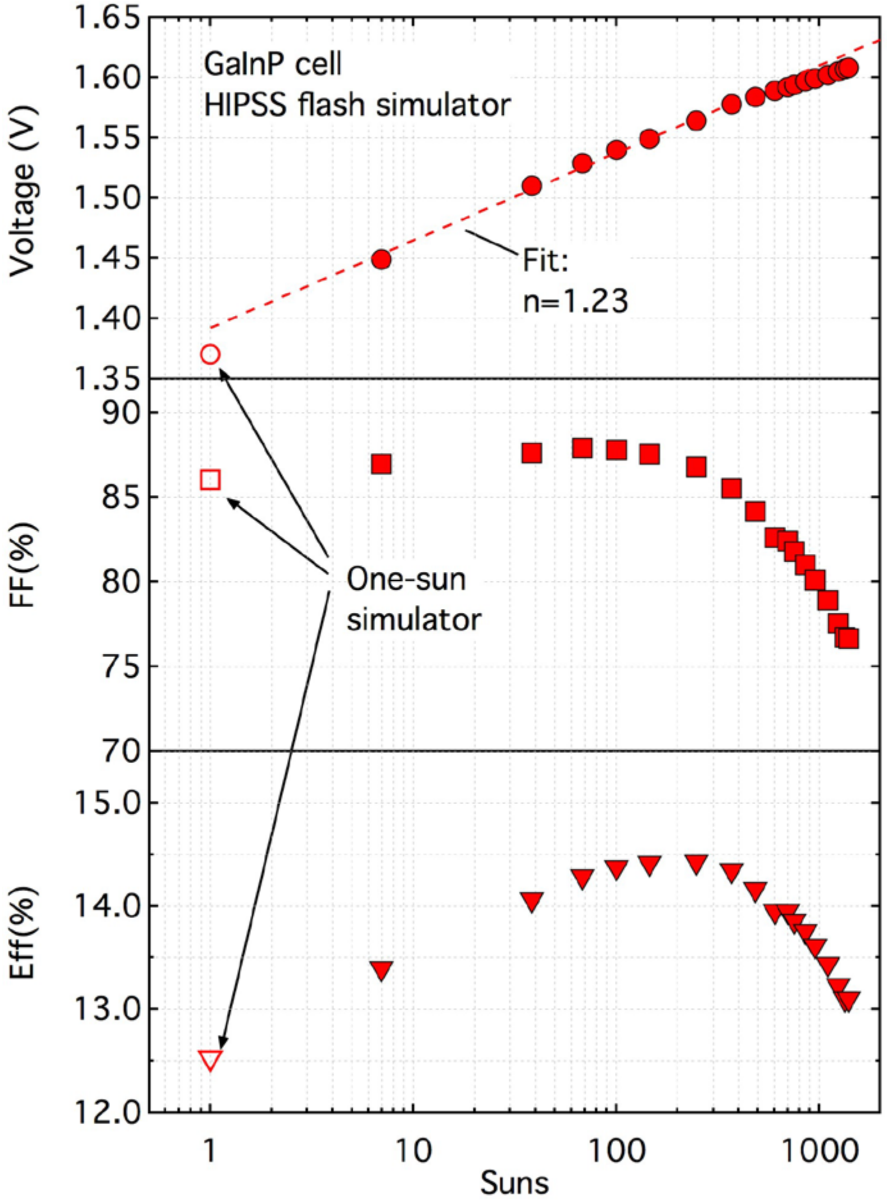
$$V_{oc} \approx \frac{nkT}{q}\ln\left(\frac{J_{sc}}{J_0}\right)$$

$$= \frac{nkT}{q}\ln\left(\frac{X \cdot J_{sc}^{1sun}}{J_0}\right)$$

$$= V_{oc}^{1sun} + \underbrace{\frac{nkT}{q}\ln(X)}$$

60 mV/decade at 300K (n=1)



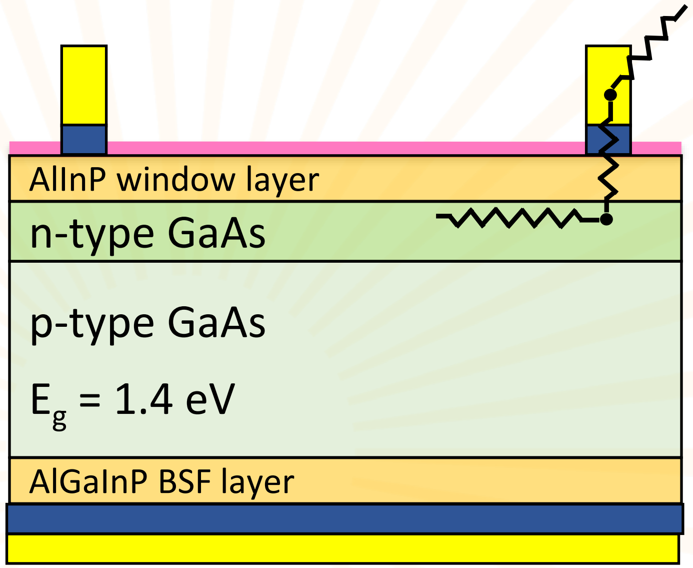


III-V application requirements

CONCENTRATORS, HIGH CURRENT APPLICATIONS

$P = I^2R$

4-junction cell current:
1 sun = 12 mA/cm^2
500 suns = 6 A/cm^2

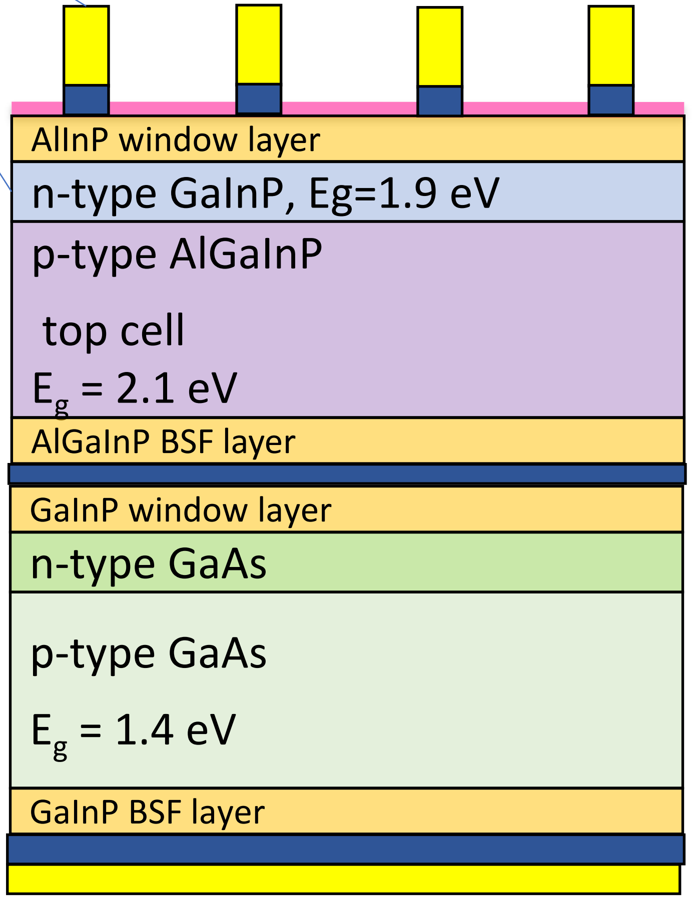


Metal resistance

Metal-Semiconductor resistance

Semiconductor sheet resistance

Tactics:
Modify grid spacing
Heterojunctions
More junctions

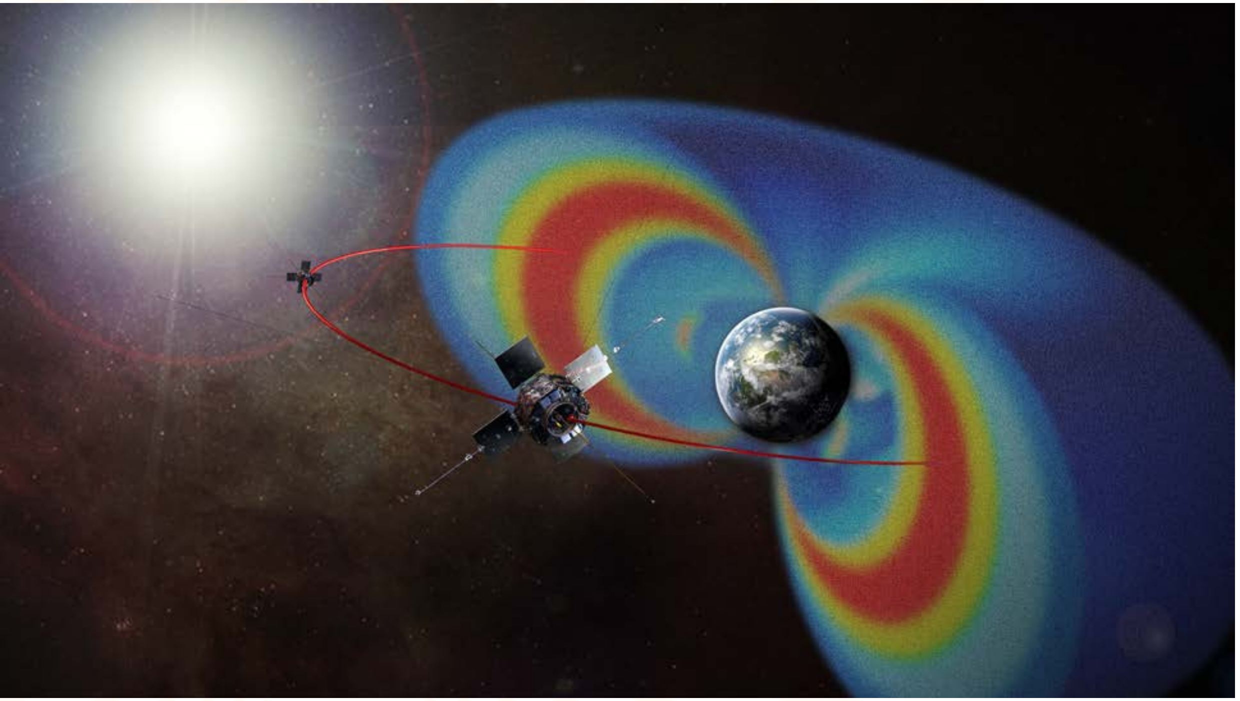


III-V application requirements

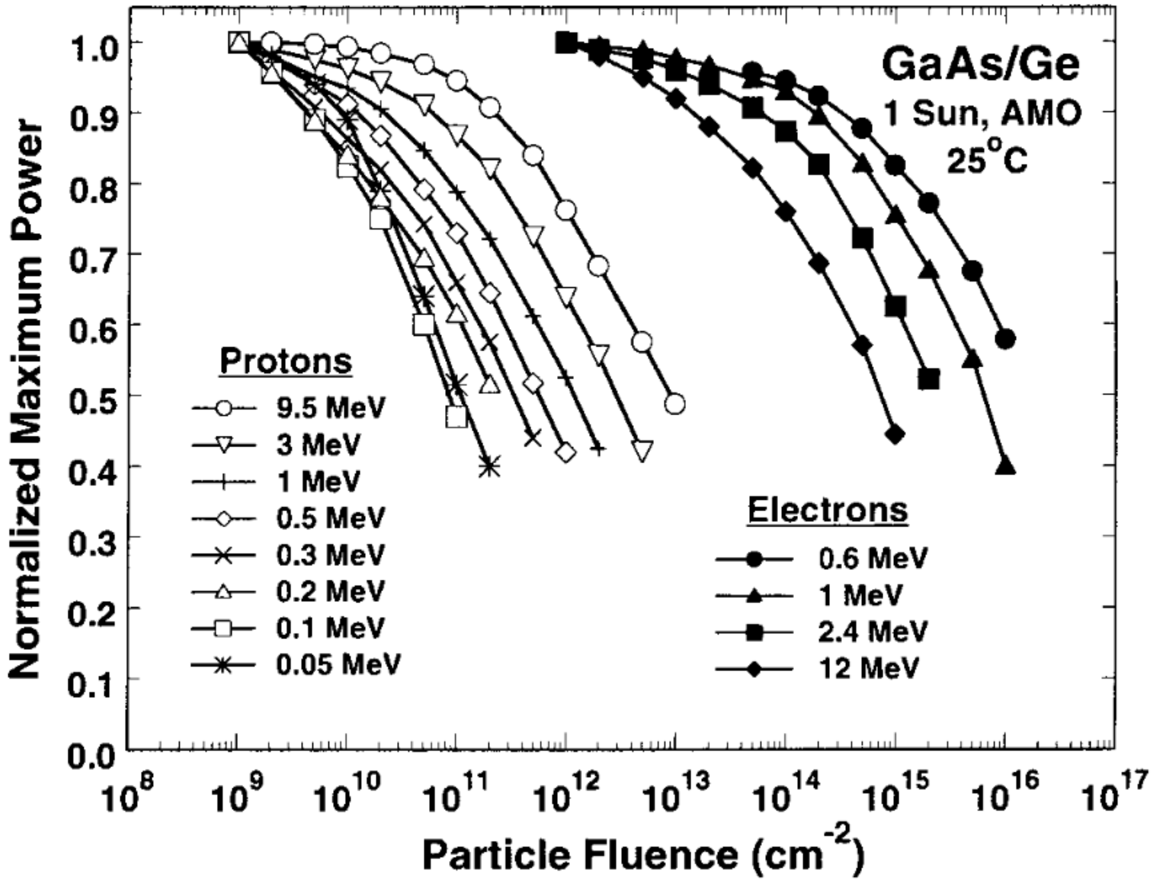
SPACE PV

- Radiation hardness
- Thermal cycling
- Lightweight

- Design for end-of-life efficiency
  - diffusion length, voltage
- Radiation shielding



https://www.nasa.gov/sites/default/files/images/725156main_rbsp-belts-orig_full.jpg
Image credit: NASA



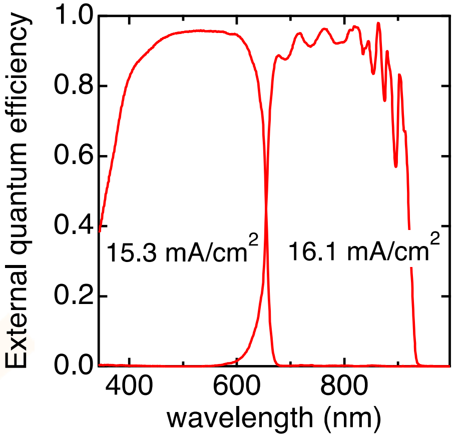
S.R. Messenger et al. Prog. Photovolt., 9, 103 (2001).

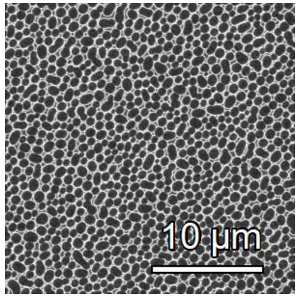
Current topics

LOW COST III-VS

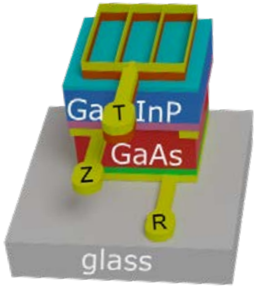
High efficiency architectures

- Absorb as many photons as possible
- Minimize voltage losses
- Spectral insensitivity?





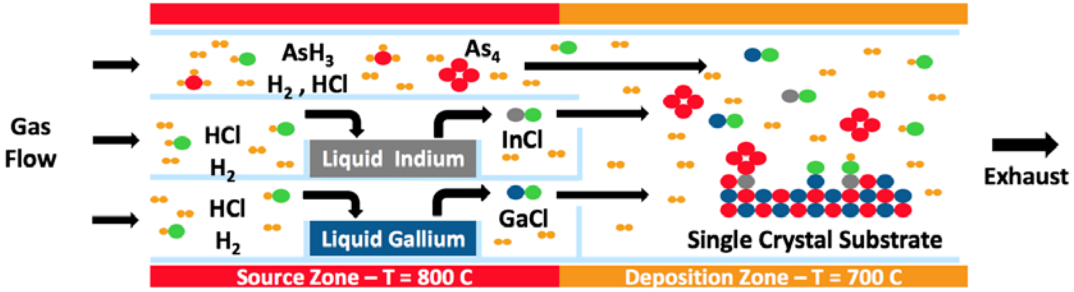
Light-trapping for thin cells



3T tandems

Low-cost growth and fabrication

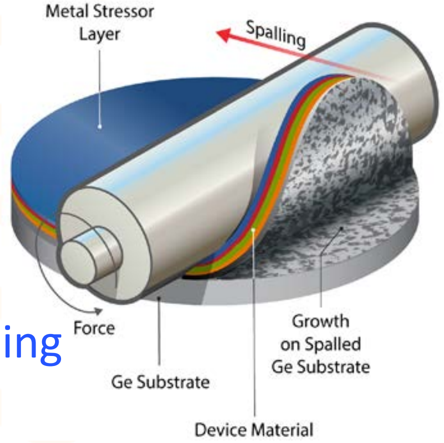
- Inexpensive source material
- High throughput
- Good source utilization
- Low-cost metallization & processing



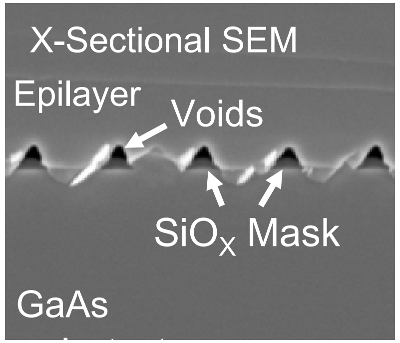
Hydride Vapor Phase Epitaxy

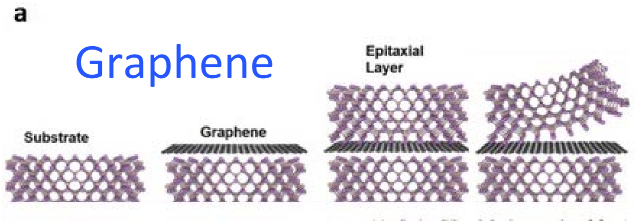
Low-cost substrates

- Remove and reuse the substrate
- Grow on something very inexpensive



Spalling





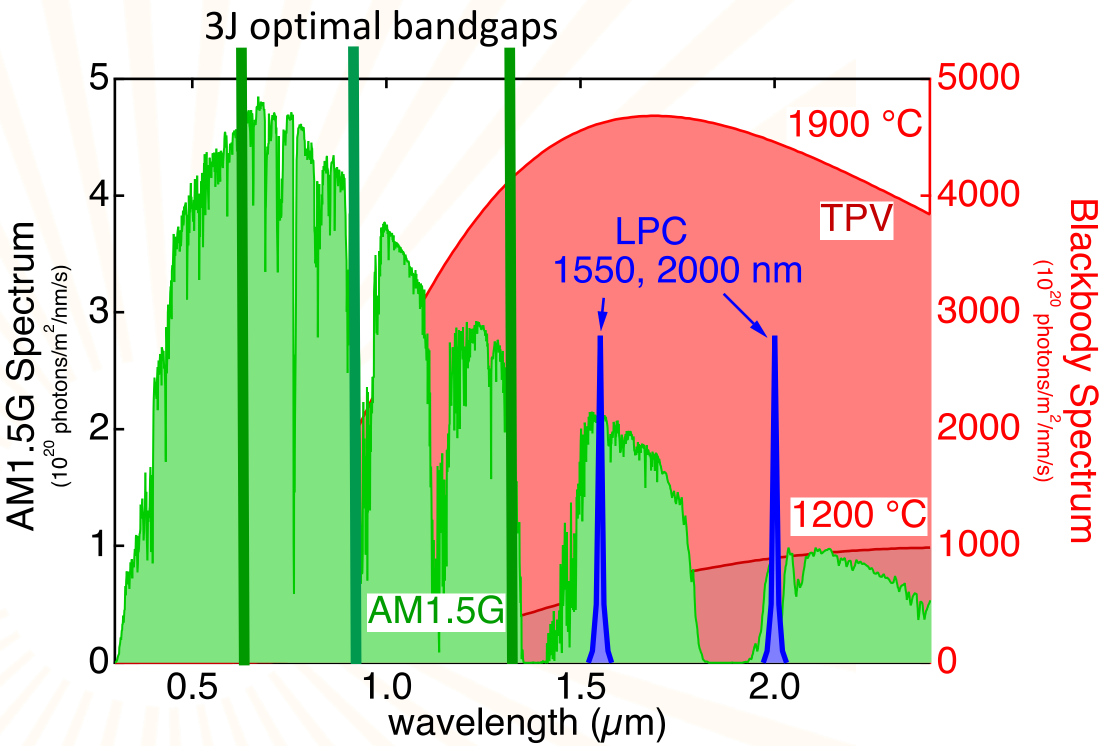
Graphene

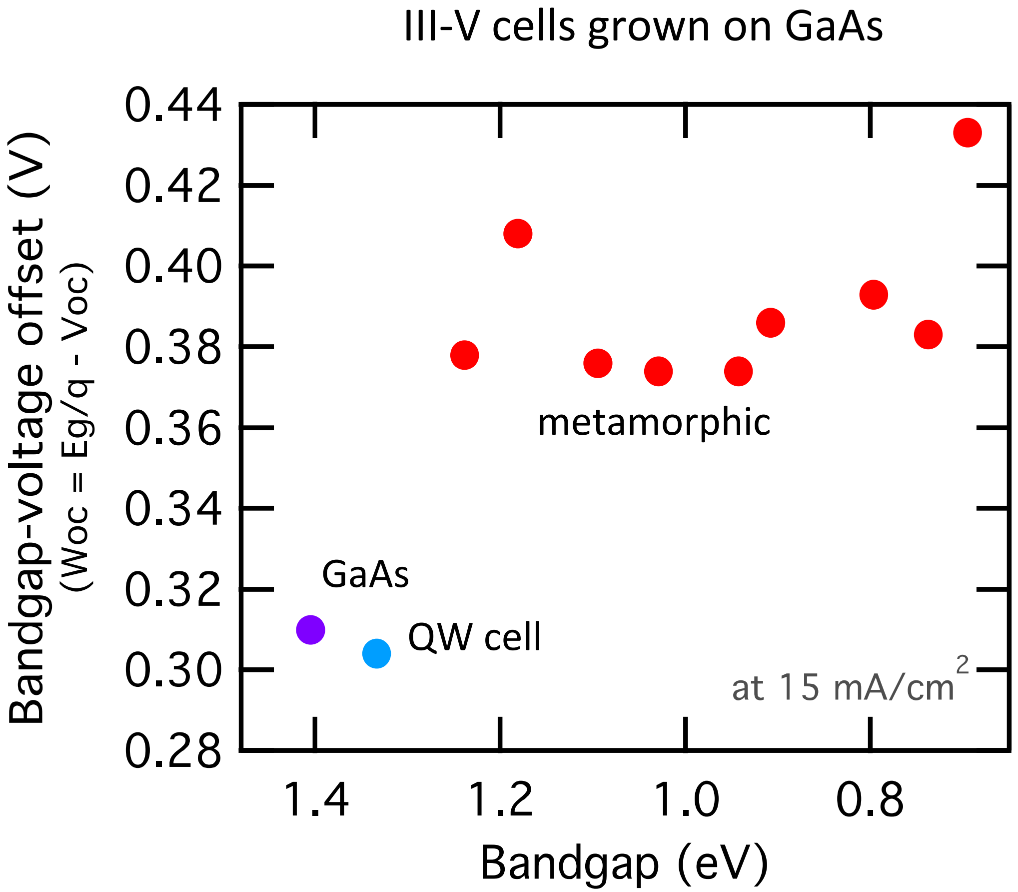
Patterned weak layers

Current topics

NEW APPLICATIONS

- Other uses of high quality III-Vs with tunable bandgaps
  - Hydrogen Production
  - Laser power converters (LPC)
  - Thermophotovoltaics (TPV)





Current topics

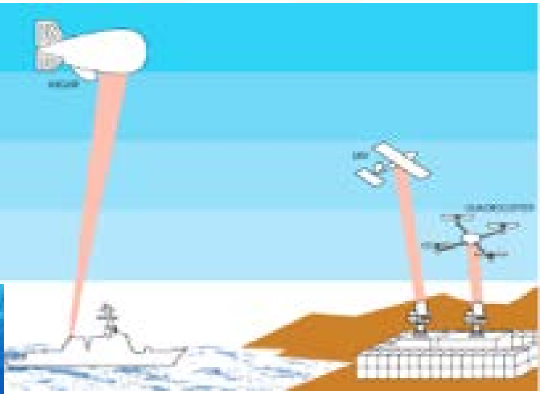
LASER POWER CONVERSION

LPCs used for power transmission to difficult to reach areas

- Multijunction reduces I, increases V
- Eg can be tuned to laser wavelength

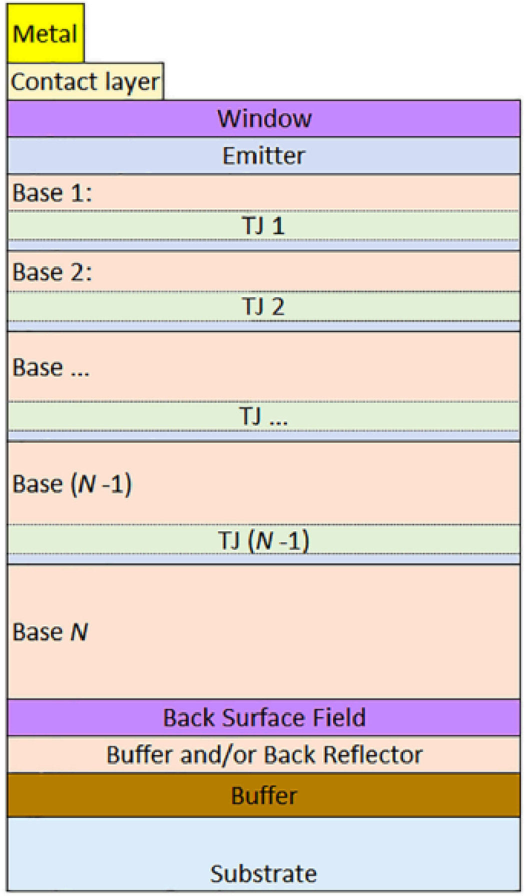
Remote sensors

UAVs



Galvanic isolation, other difficult environments

S. Fafard et al., J. Appl. Phys., 160901 (2021)

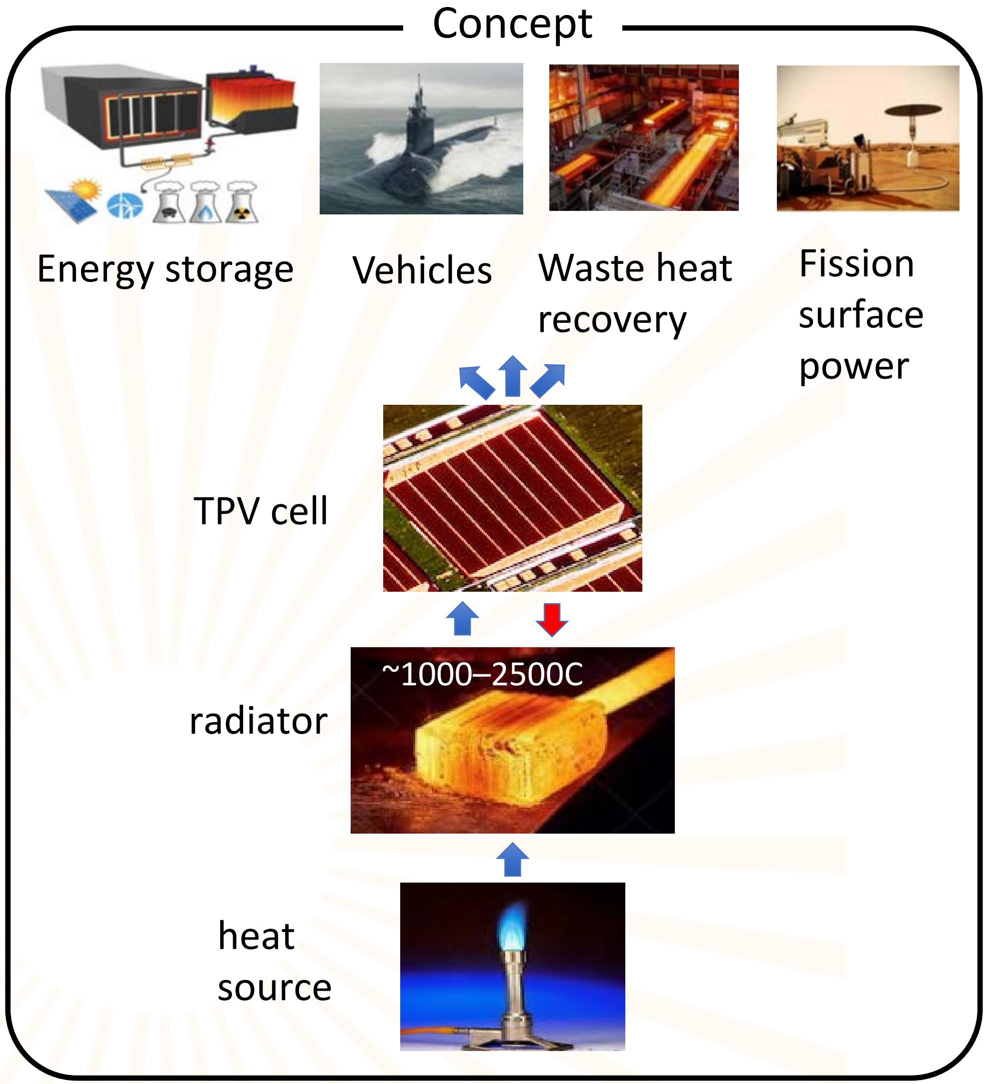


> 70% efficiency demonstrated!

S. Farad et al., Photonics, 9, 59 (2022).
H. Helmers et al., phys. Stat. sol., 15, 2100113 (2021).

Current topics

THERMOPHOTOVOLTAICS

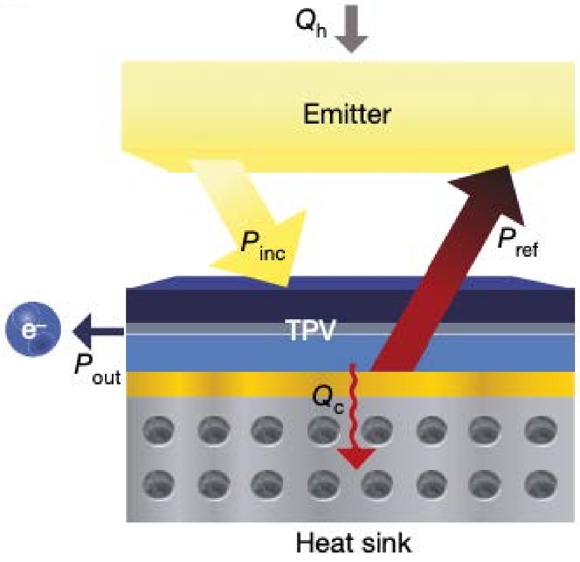


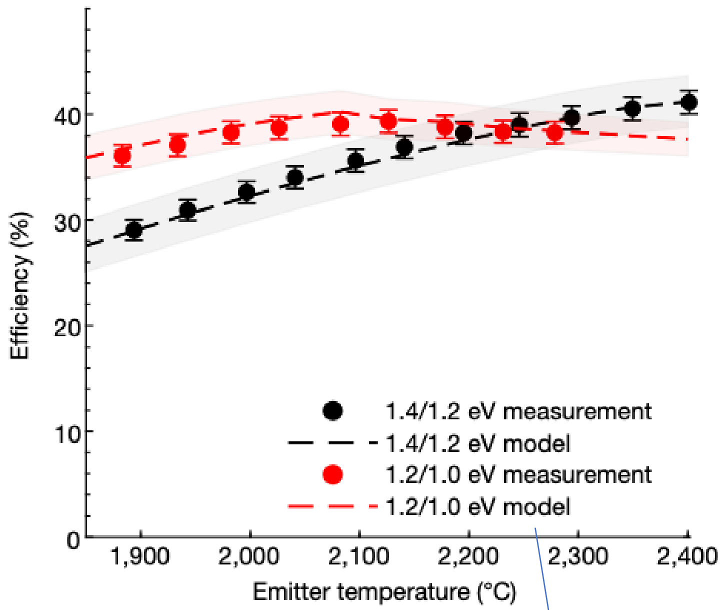

Article

Thermophotovoltaic efficiency of 40%

nature

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]✉





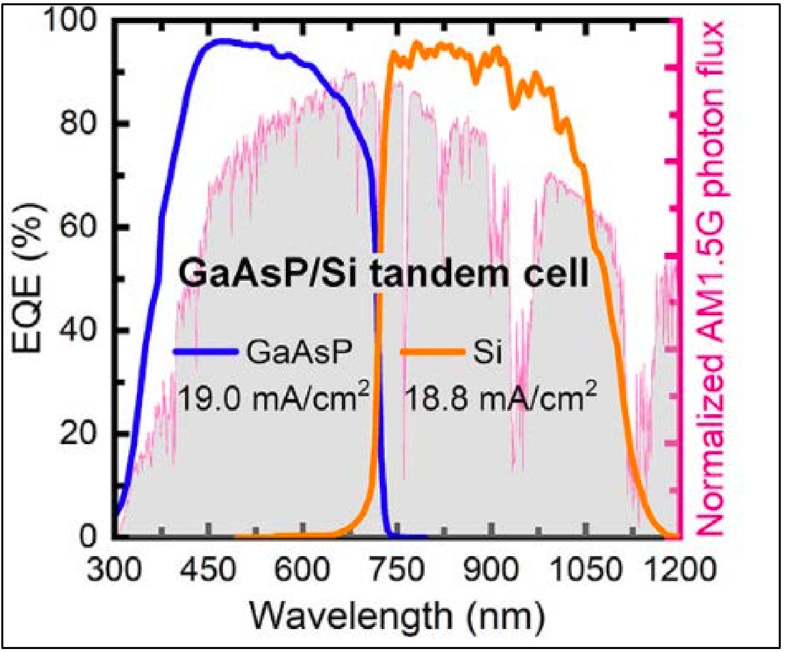
Metamorphic 2-junction cells

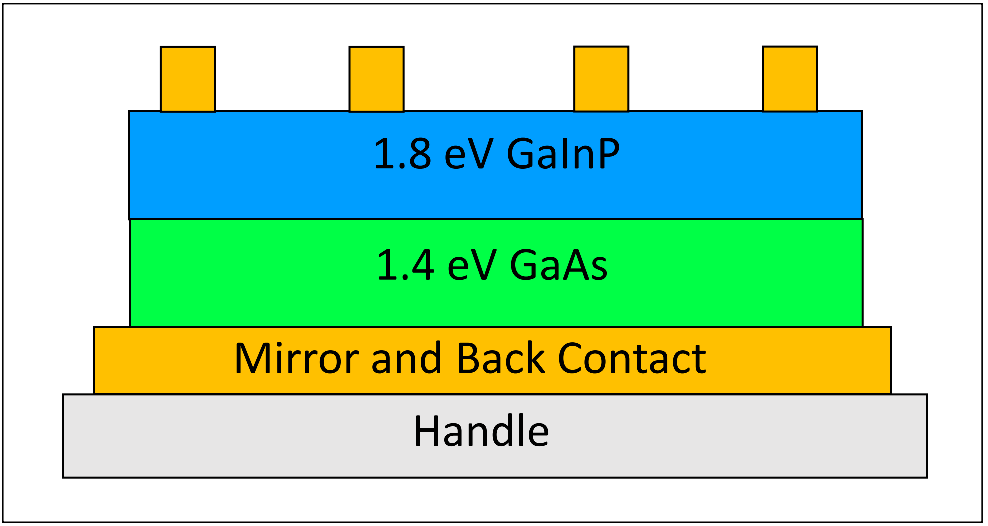
Break

Q&A

- Combining 1.7 eV III-V cell with a 1.1 eV Si cell would target the optimal 2J bandgap combination. What materials integration challenges exist?
- Consider a reflective rear contact. How can the reflector benefit a photovoltaic device? What about a thermophotovoltaic device?

Fan, S.; et al. *Cell Reports Physical Science* **2020**, *1* (9), 100208.



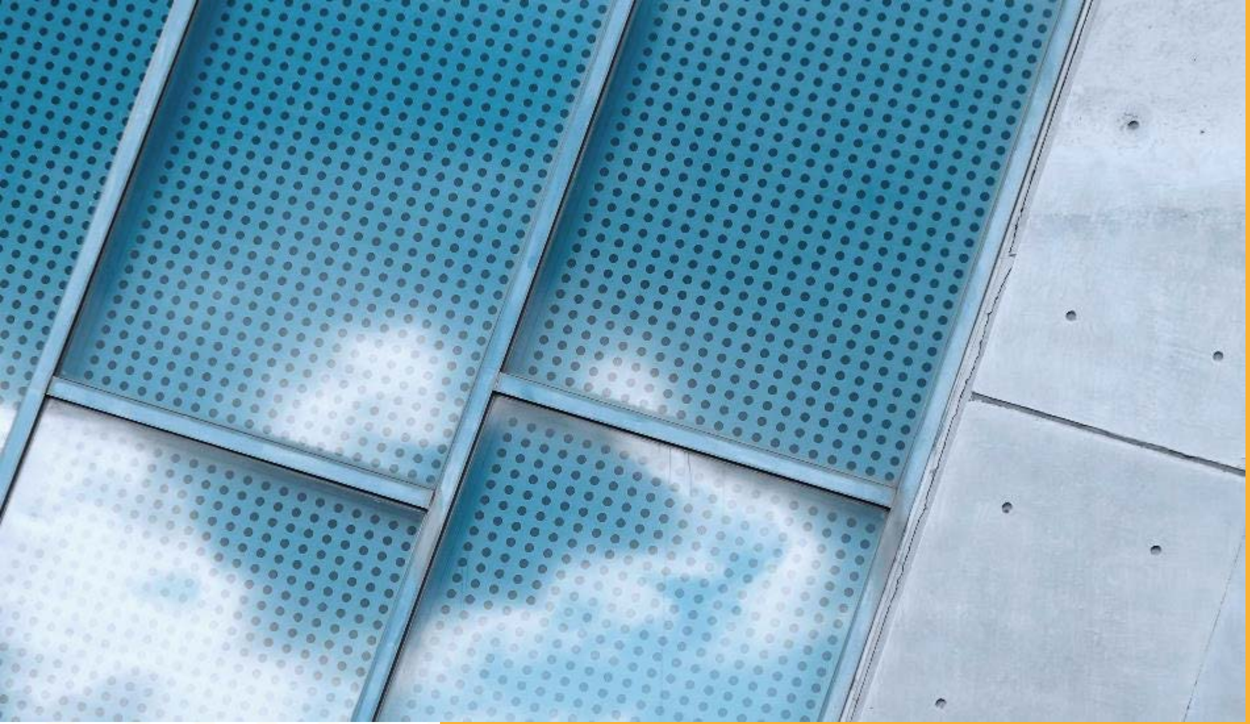


1.8 eV GaInP

1.4 eV GaAs

Mirror and Back Contact

Handle



Thank you!

NREL/PR-5900-83985

Ryan France

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