NREL
Transforming ENERGY

Record efficiency multijunction solar cells with strain-balanced quantum well superlattices

Myles A. Steiner, Ryan M. France

Spring MRS – May 10, 2022

Analysis: John Geisz
Growth: Waldo Olavarria, Alan Kibbler
Processing and characterization: Michelle Young
Top cell development: Manuel Hinojosa (IES-UPM)
TEM: Jenny Selvidge (UCSB)
Official Measurements: Tao Song

Outline:

- Overview of quantum wells
- Fabrication and characterization
- GaInP top cells
- Triple junction results

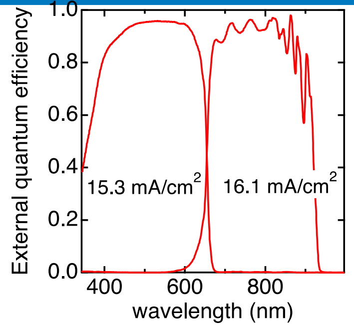
2022 MRS SPRING MEETING & EXHIBIT
May 8-13, 2022 | Honolulu, Hawai'i
May 23-25, 2022 | Virtual

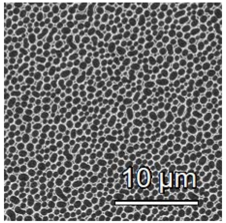
SunShot
U.S. Department of Energy

What is needed for cost-effective, high efficiency solar cells?

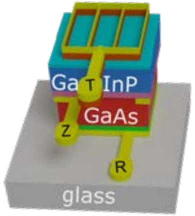
High efficiency architectures

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





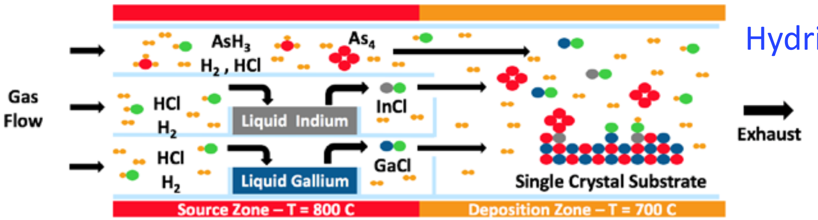
Light-trapping for thin cells



3T tandems

Low-cost growth and fabrication

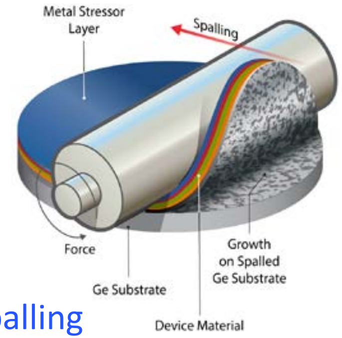
- Inexpensive source material
- High throughput
- Good source utilization



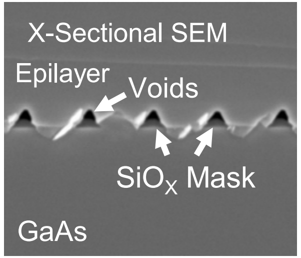
Hydride Vapor Phase Epitaxy

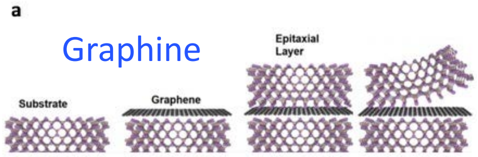
Low-cost substrates

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



Spalling

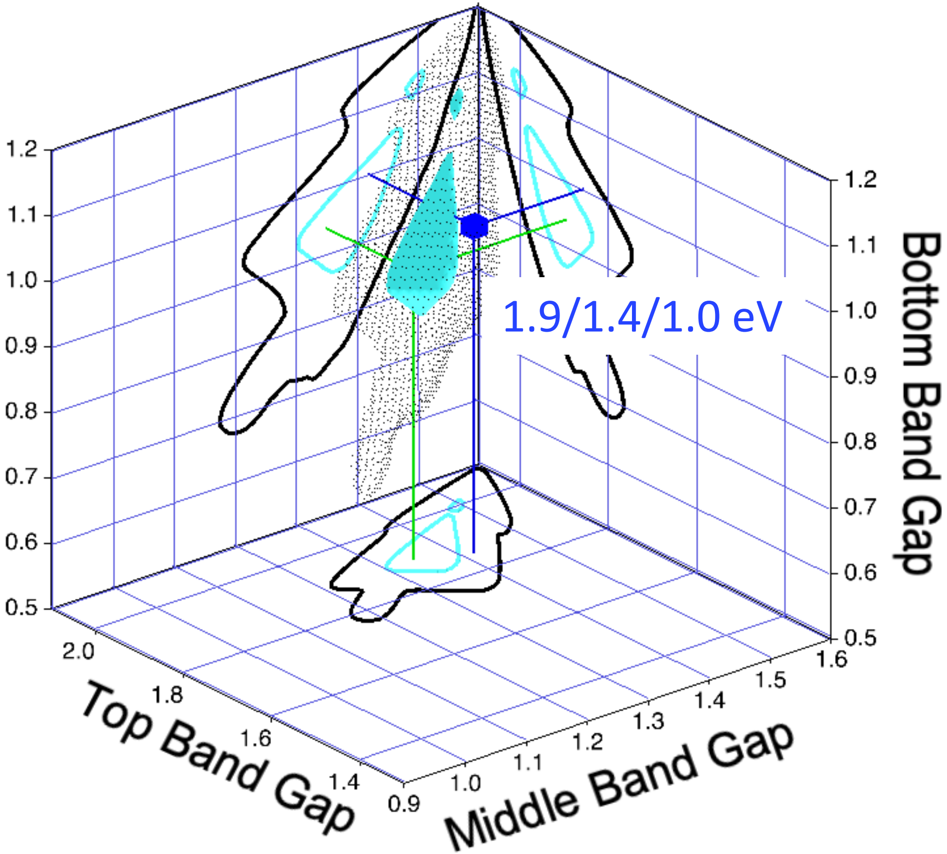


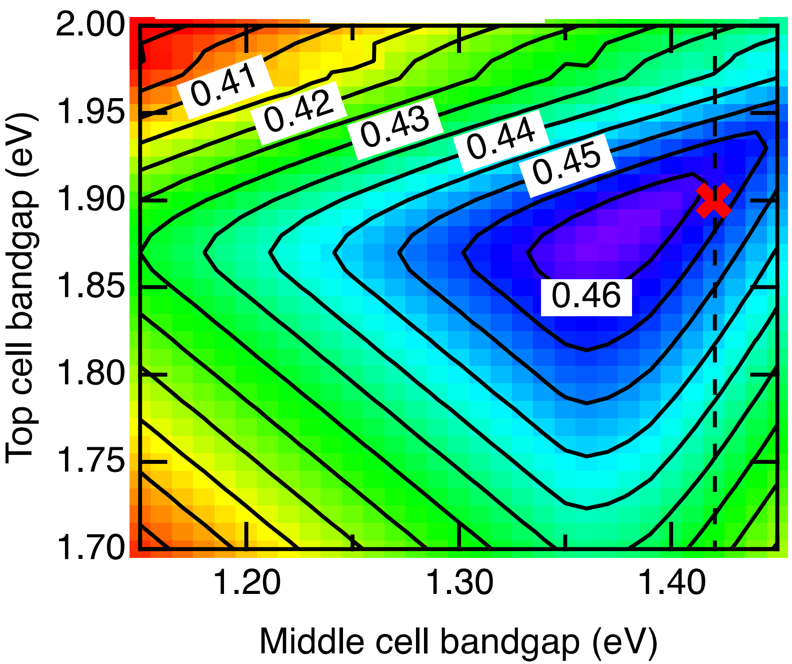


Patterned weak layers

Bandgaps for a three-junction cell

GaAs is slightly too high a bandgap for AM1.5g (and AM0)



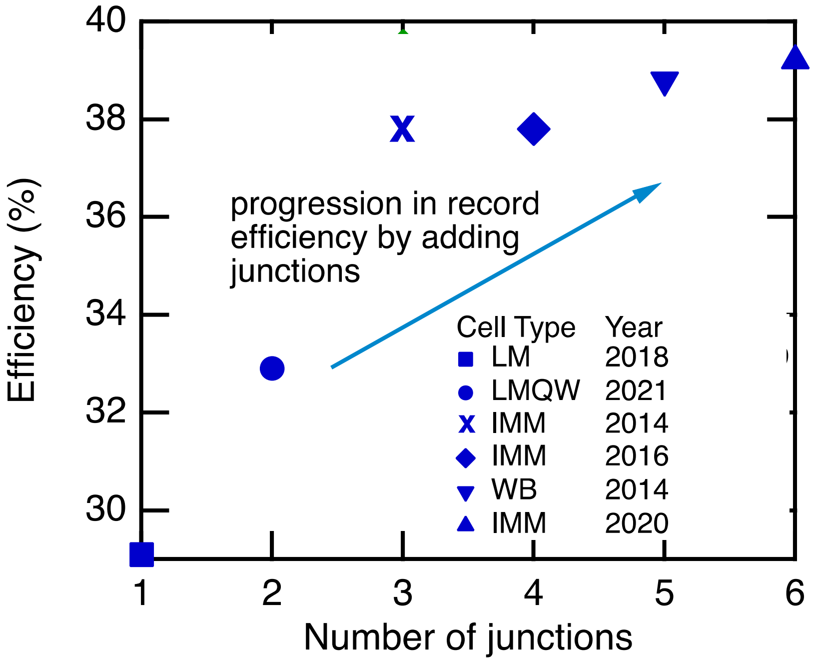


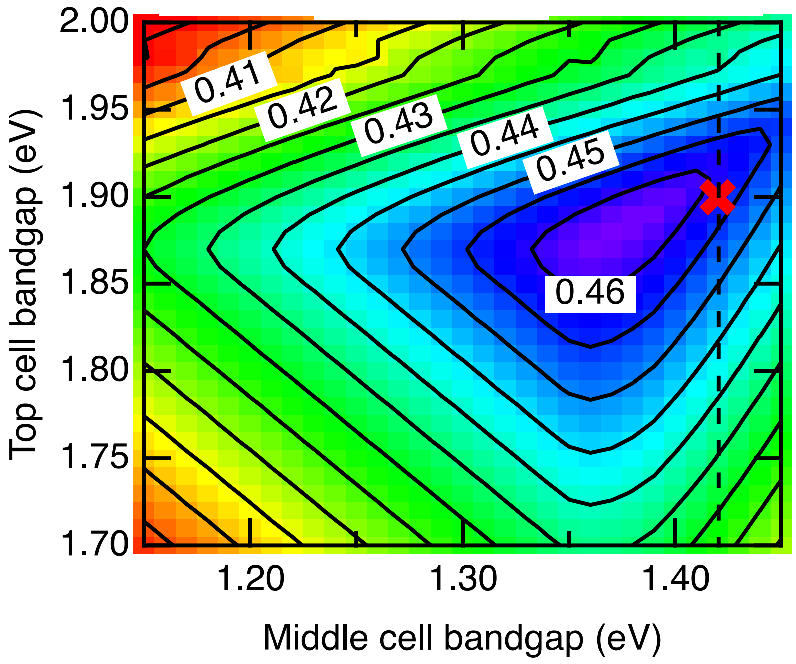
(Bottom cell optimized for each point)

Bandgaps for a three-junction cell

GaAs is slightly too high a bandgap for AM1.5g (and AM0)

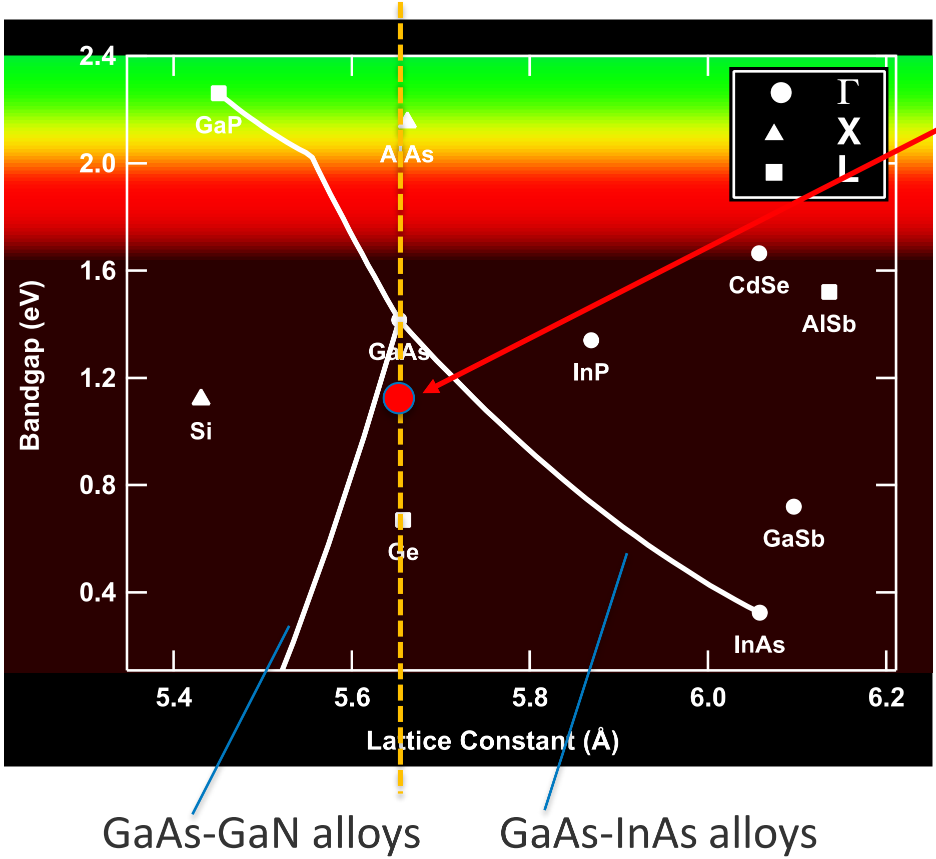
Can we get the same material quality as GaAs, but with a lower bandgap alloy?





(Bottom cell optimized for each point)

How to extend the absorption edge?

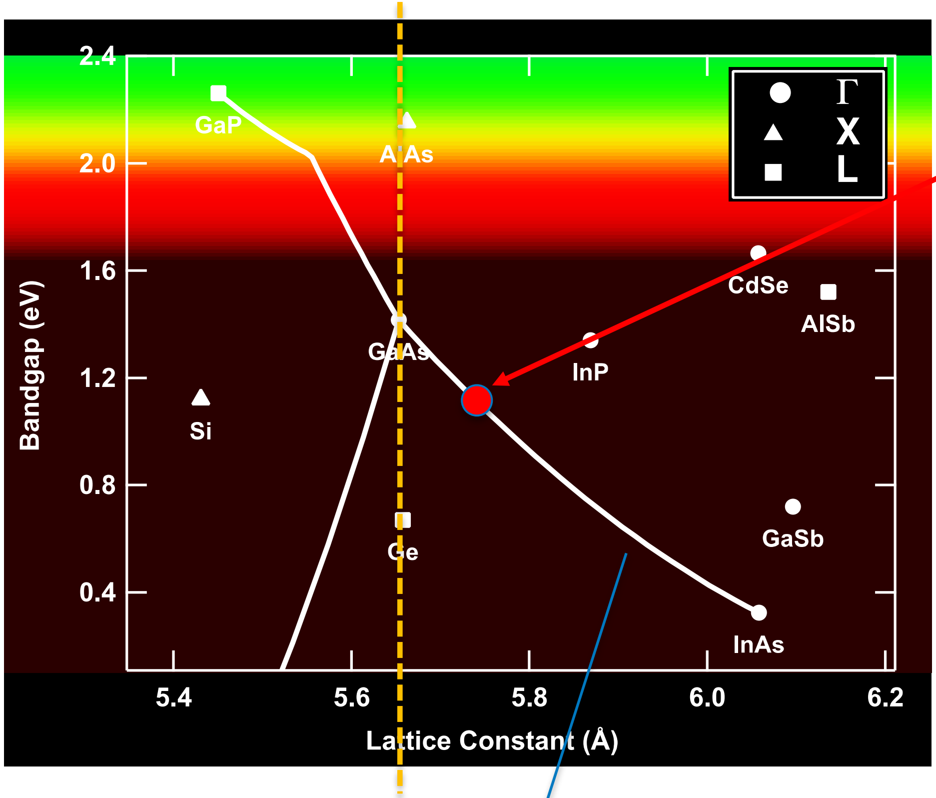


1. GaInAsN
2. Metamorphic epitaxy
3. Quantum wells

Material would be lattice-matched

GaInAsN tends to have a short diffusion length, leading to a poor quantum efficiency

How to extend the absorption edge?



GaAs-InAs alloys

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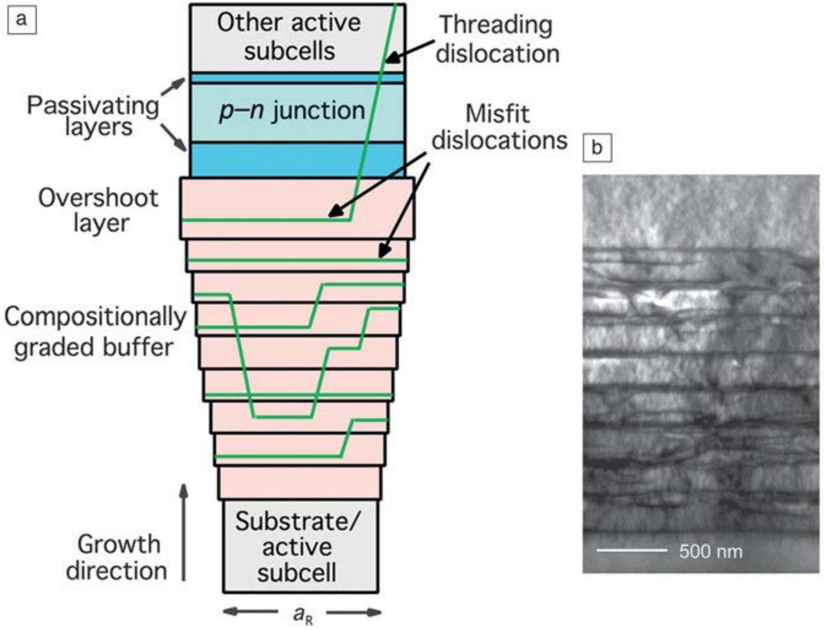

France *et al.*, MRS bulletin 41, 202 (2016)

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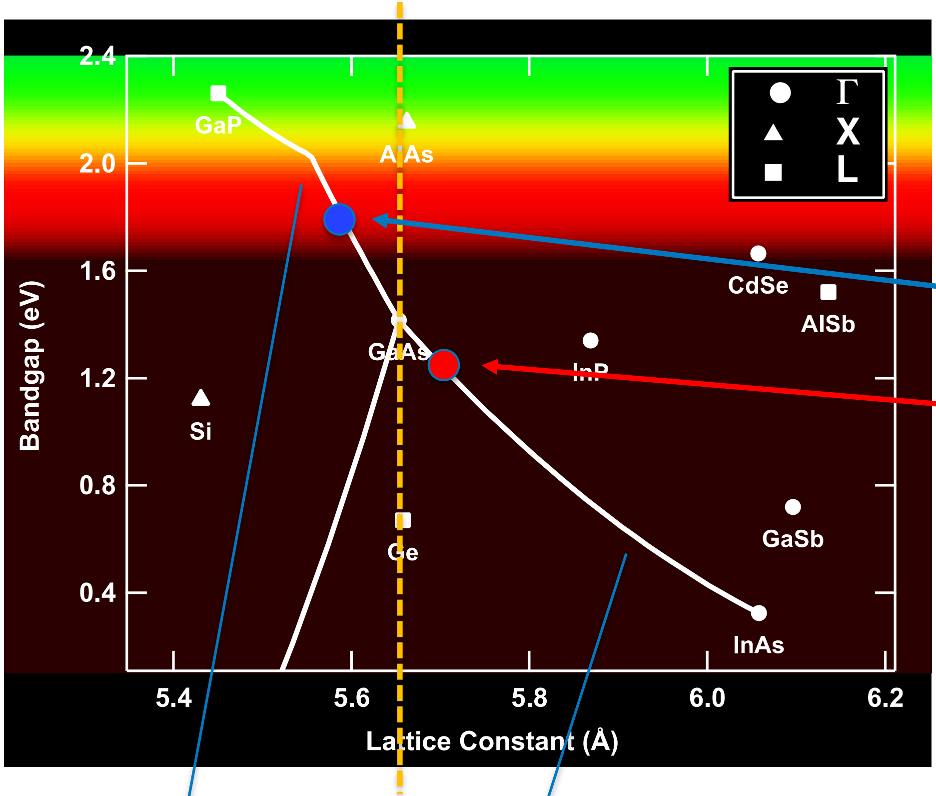

GaAs-GaP alloys

GaAs-InAs alloys

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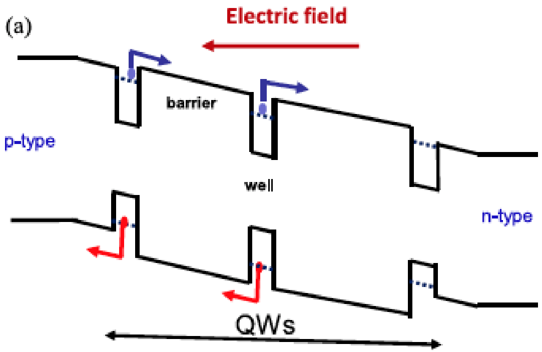
Barrier: $GaAs_{0.68}P_{0.32}$, ~1.81 eV, 50 Å

Well: $Ga_{0.89}In_{0.11}As$, ~1.27 eV, 85 Å



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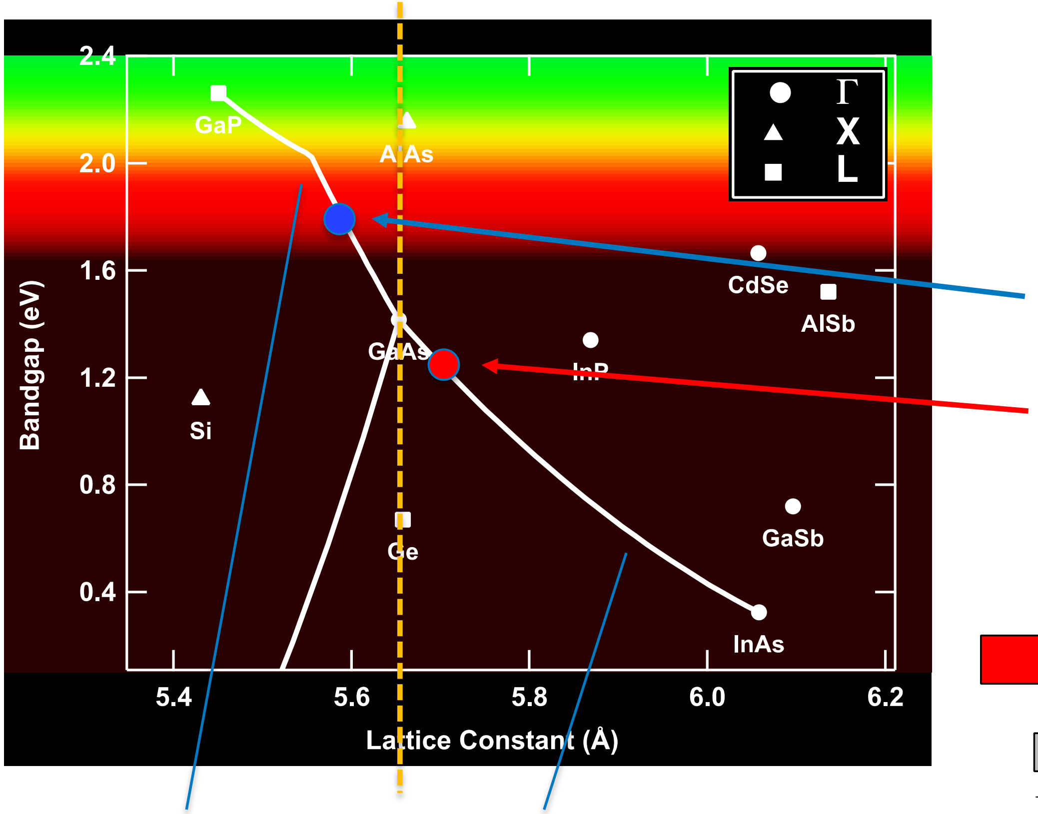

GaAs-GaP alloys   GaAs-InAs alloys

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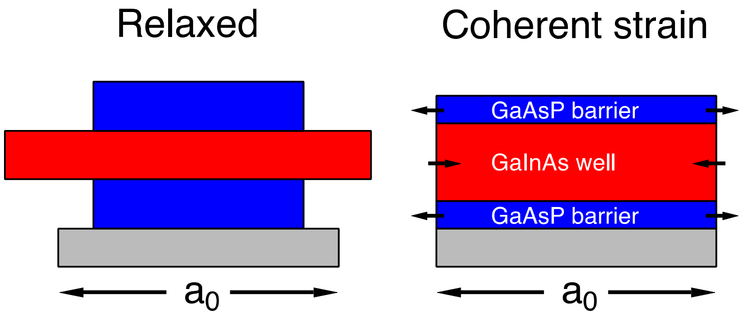
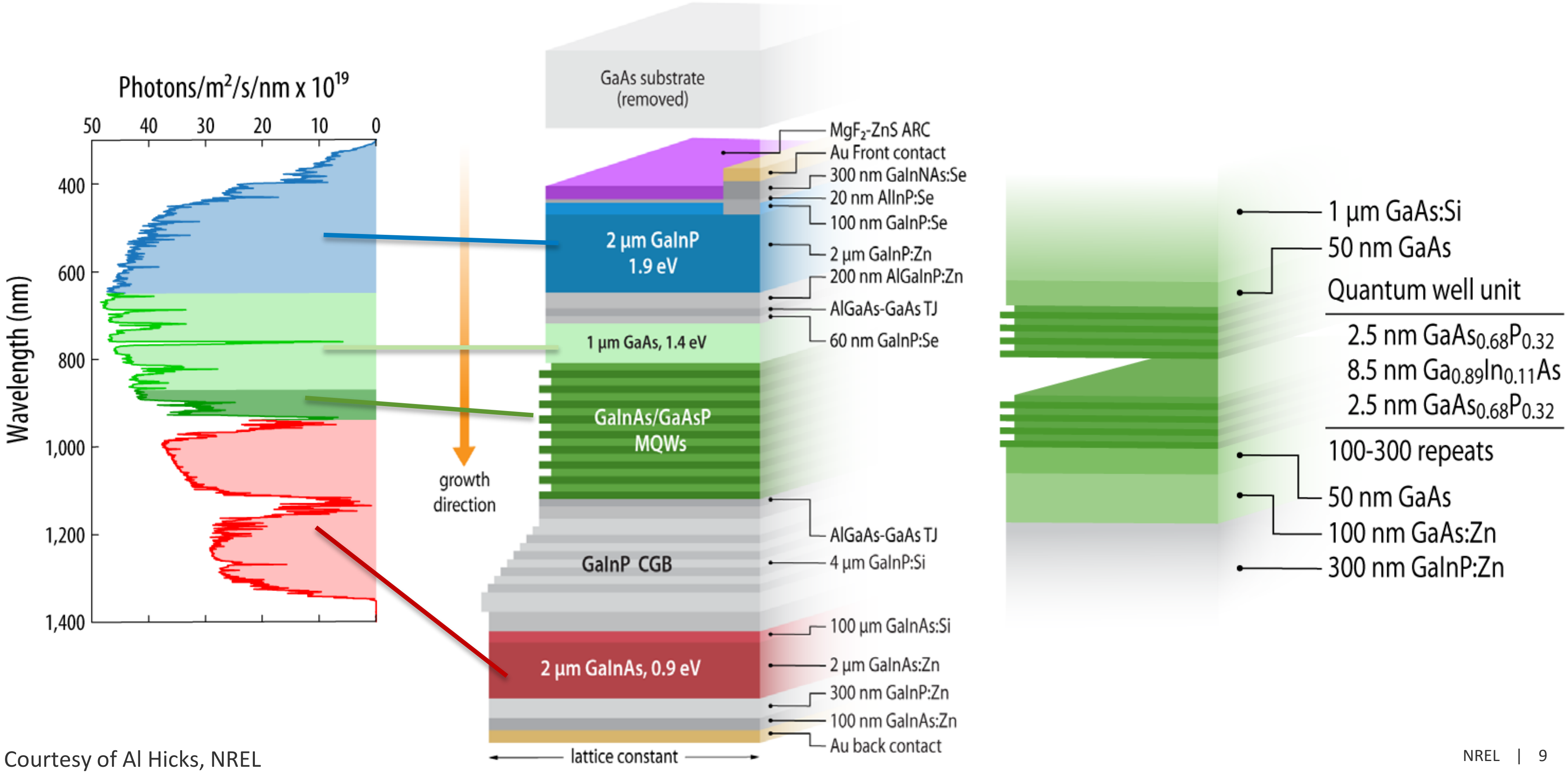


Triple junction cell architecture



Courtesy of Al Hicks, NREL

Energy levels in a quantum well

"Band edge"

=

Raw bandgap in the well

(1.27 eV for $Ga_{0.894}In_{0.106}As$)

+

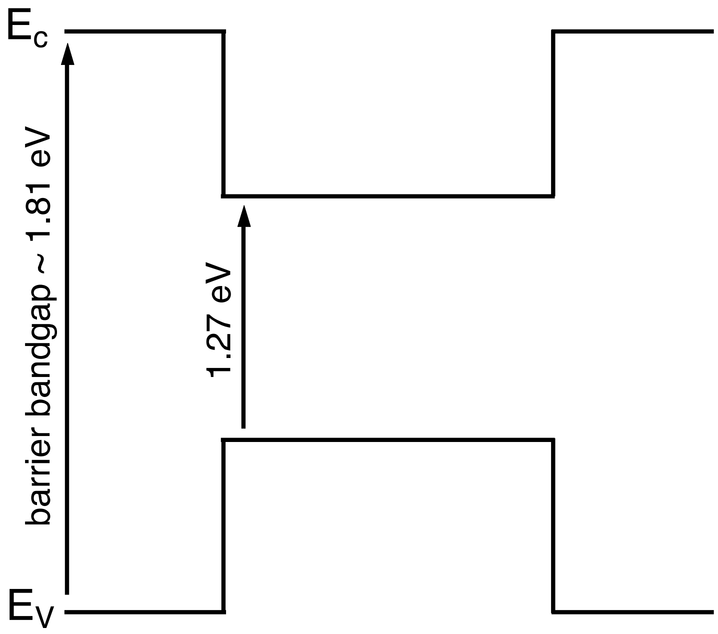
Effects of strain (→ 1.31 eV)

+

Effects of 2D quantum confinement (→ 1.35 eV)

+

Effects of well asymmetry due to voltage bias (quantum confined Stark effect → very small effect)



(schematic, not drawn to scale)

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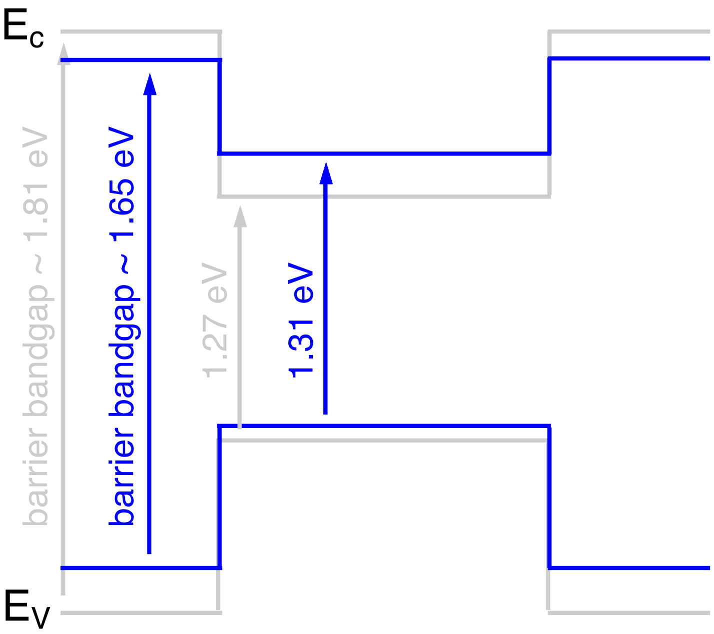

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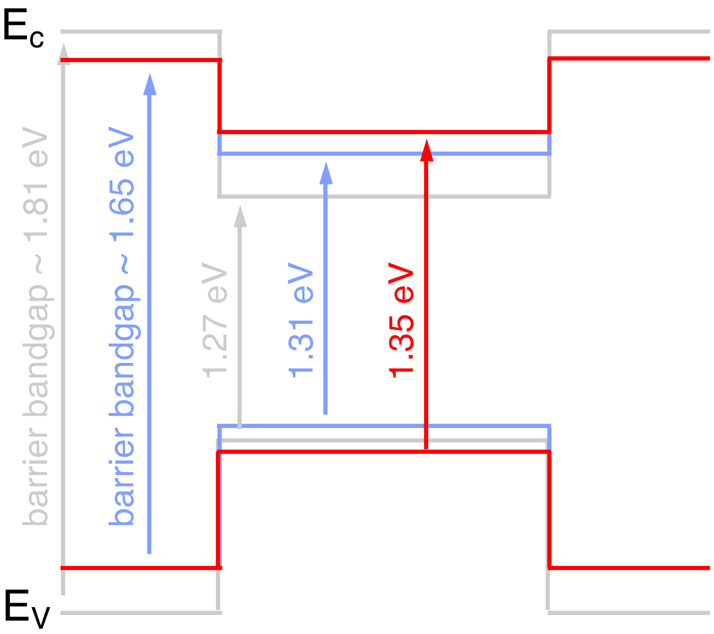
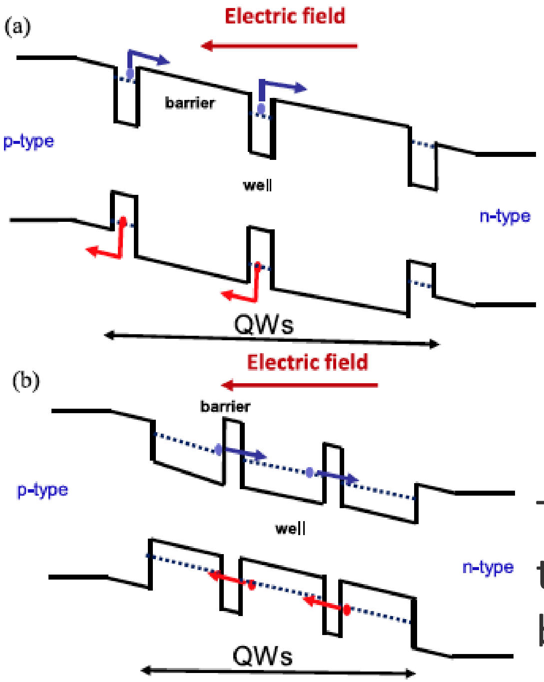


(schematic, not drawn to scale)

Transport in quantum wells

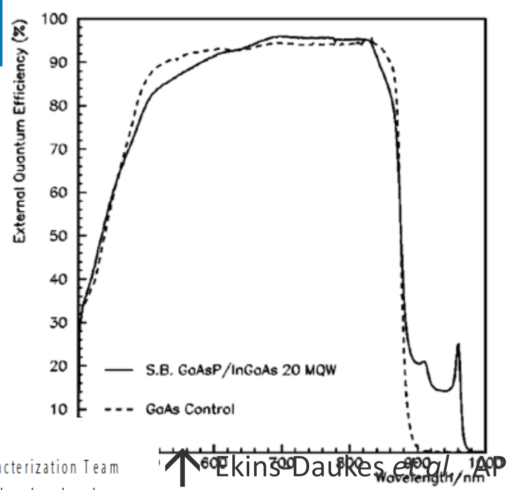
Transport is dominated by drift in the electric field, rather than diffusion.



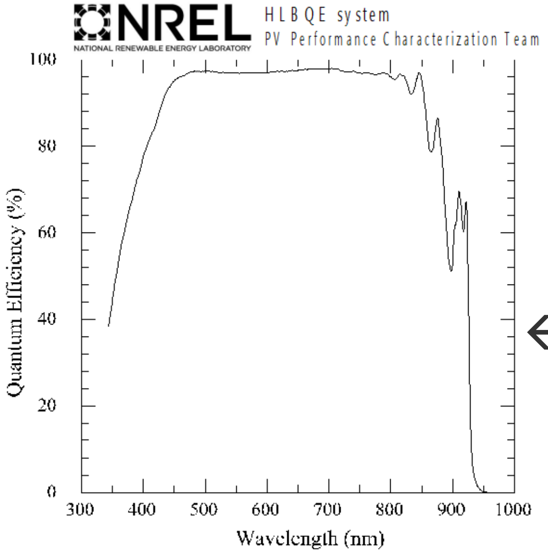
Thermionic emission out of wells

Tunneling through the barriers

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



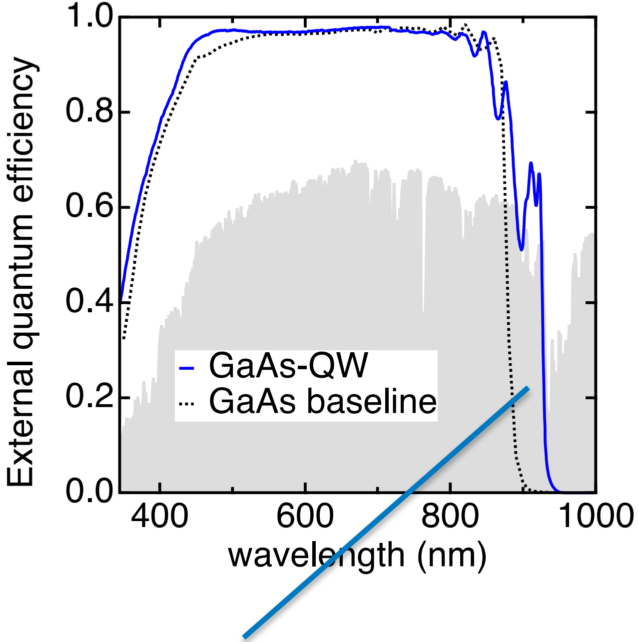
Ekins-Daukes *et al.*, APL **75**, 4195 (1999)



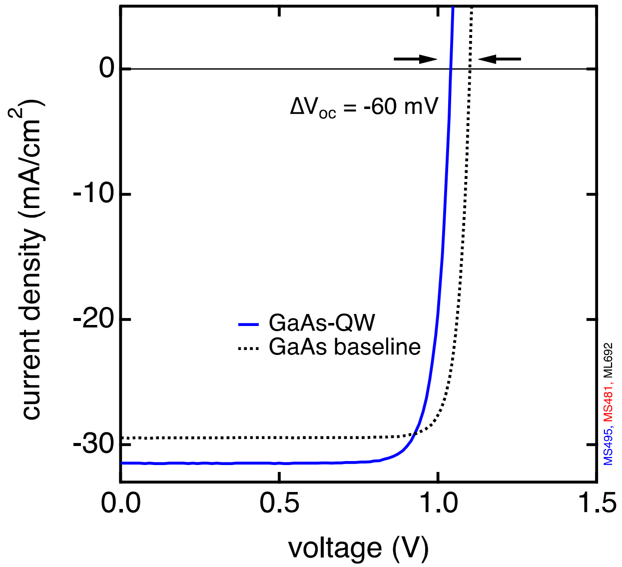
Steiner *et al.*, Adv. Energy Materials 2002874 (2020)

GaAs-QW state of the art (c. 2020)

Quantum efficiency



Current-voltage



NREL
GaAs Cell

Device ID: MS495A_6
Jan 3, 2020 13:28
Spectrum: ASTM G173 global

Device Temperature: 25.0 ± 0.5 °C
Device Area: 0.2496 cm^2 ± 0.3 %
Irradiance: 1000.0 W/m^2

NREL NATIONAL RENEWABLE ENERGY LABORATORY
X25 IV System
PV Performance Characterization Team

V_{oc} = 1.0402 ± 0.0027 V
I_{sc} = 7.858 ± 0.048 mA
J_{sc} = 31.48 ± 0.22 mA/cm^2
Fill Factor = (82.98 ± 0.52) %
Efficiency = (27.18 ± 0.20) %

Woc ~ 0.31 V

Absorption edge at ~1.34 eV

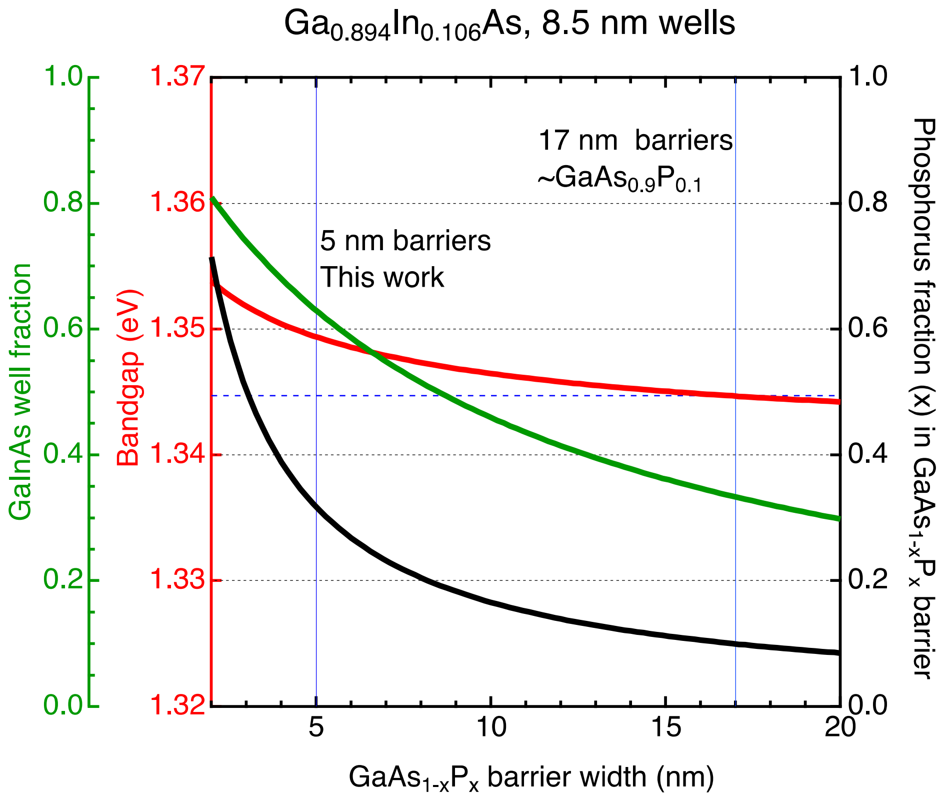
ΔE_g ~ 70 meV

ΔJ_{sc} ~ 2 mA/cm^2

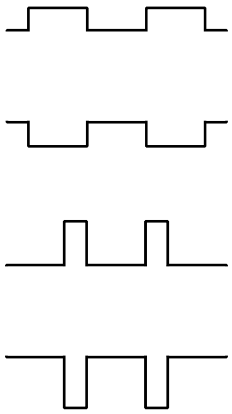
The loss in voltage corresponds mostly to the shift in band edge

How can we maximize the absorption in the quantum wells ?

→ Thin the barriers, so that a larger fraction of each QW is made of absorbing well material.



Thermionic + Tunnelling ← Thermionic



Thick barrier
17/8.5/17 nm
33%

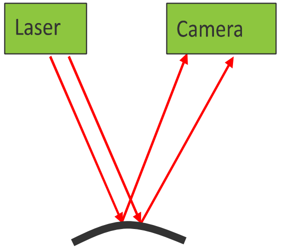
Thin barrier
5/8.5/5 nm
63%

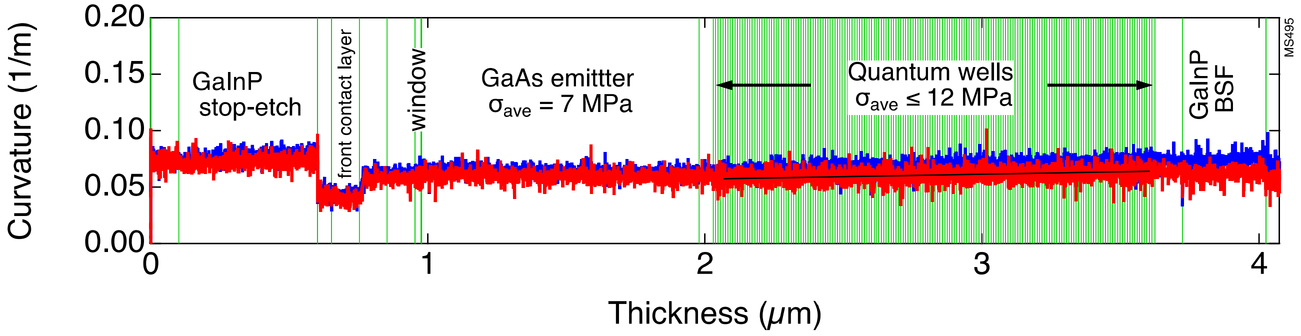
$$a_0 = \frac{A_w t_w a_w a_b^2 + A_b t_b a_b a_w^2}{A_w t_w a_b^2 + A_b t_b a_w^2} = 5.653\ \text{Å}$$

4 variables, 3 degrees of freedom

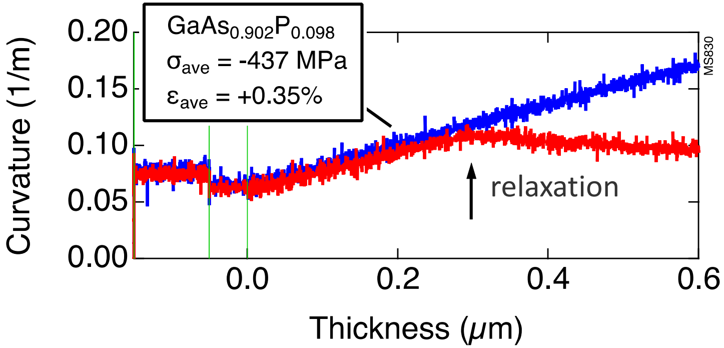
- $a_{w,b}$ = lattice constant (well, barrier)
- $t_{w,b}$ = thickness
- $A_{w,b}$ = elastic constants

in situ stress – thick barriers

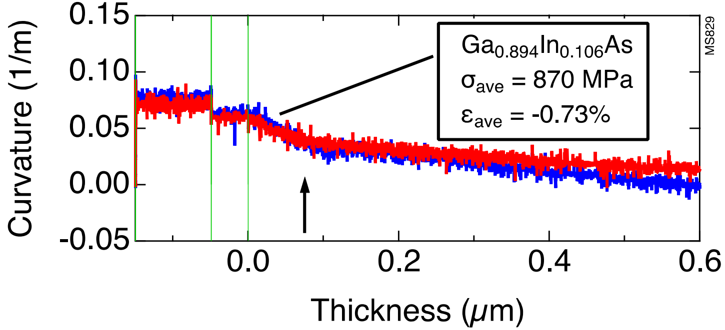




Single layer GaAsP

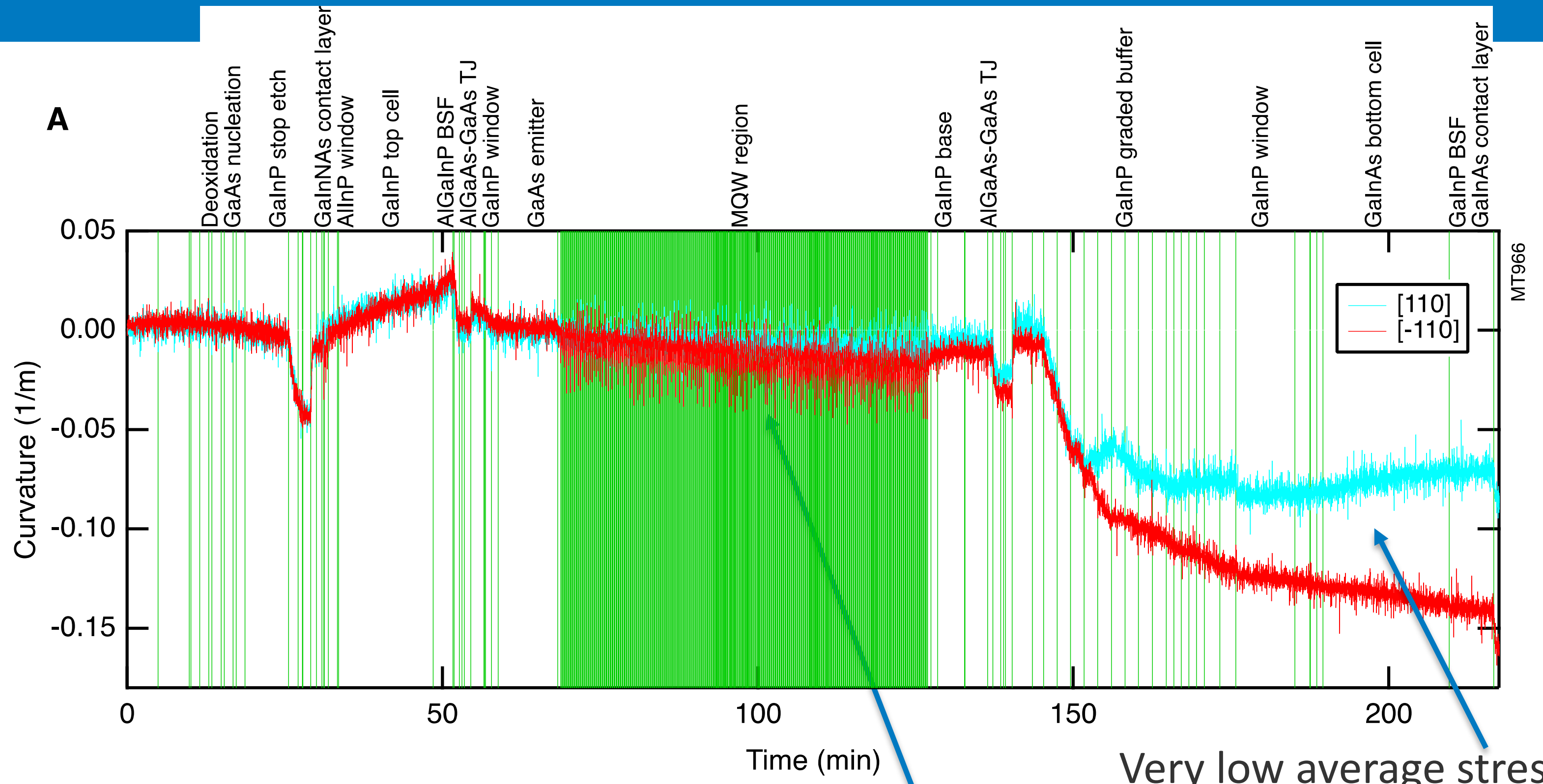


Single layer GaInAs



Red and blue data show orthogonal [110] directions

in situ stress – thin barriers

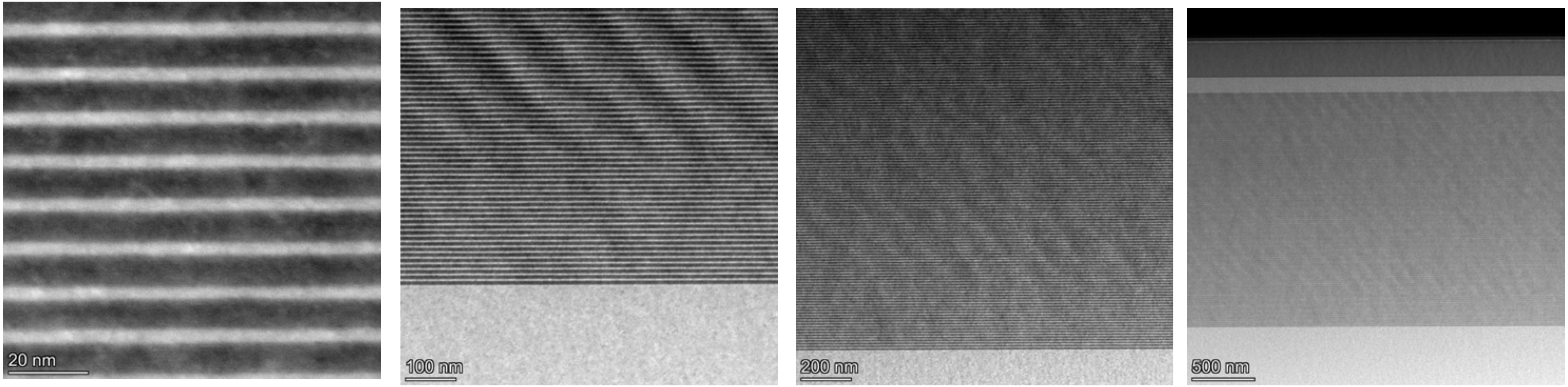


Very low average stress in LMM GaInAs bottom cell

- Careful calibration of GaAsP reactant flows
- Constant flow of AsH_3 and TMGa
- Simple switching of PH_3 and TMIn

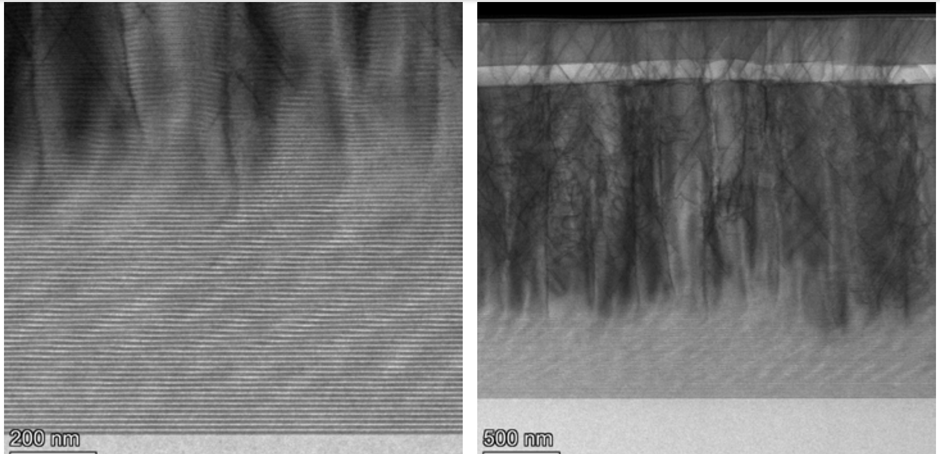
Stress ≤ 0.11 GPa in QW layers

Effect of AsH_3 flow in the GaInAs well material



High AsH_3 (MS766)

Low AsH_3 (MS722)



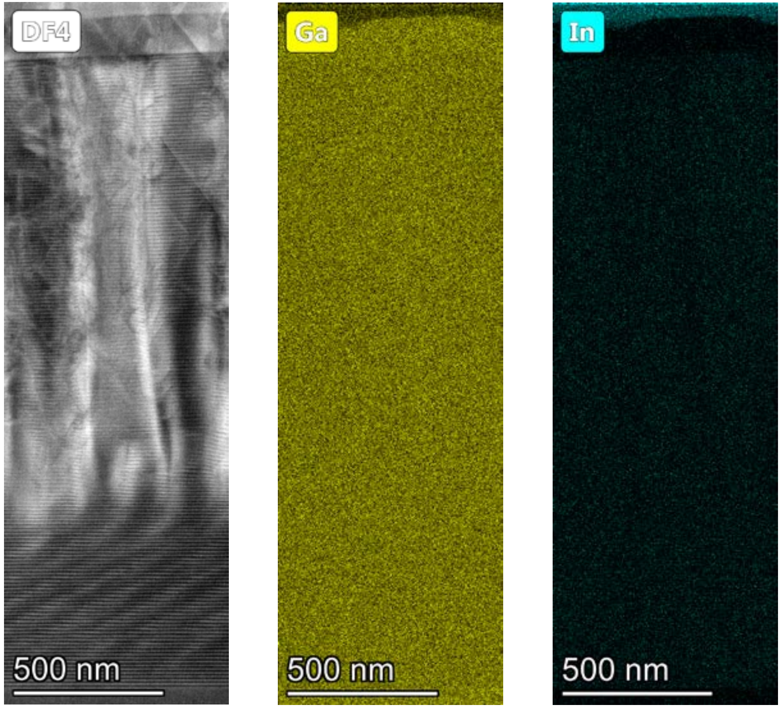
High mag: interfaces

Med mag: lateral composition modulation

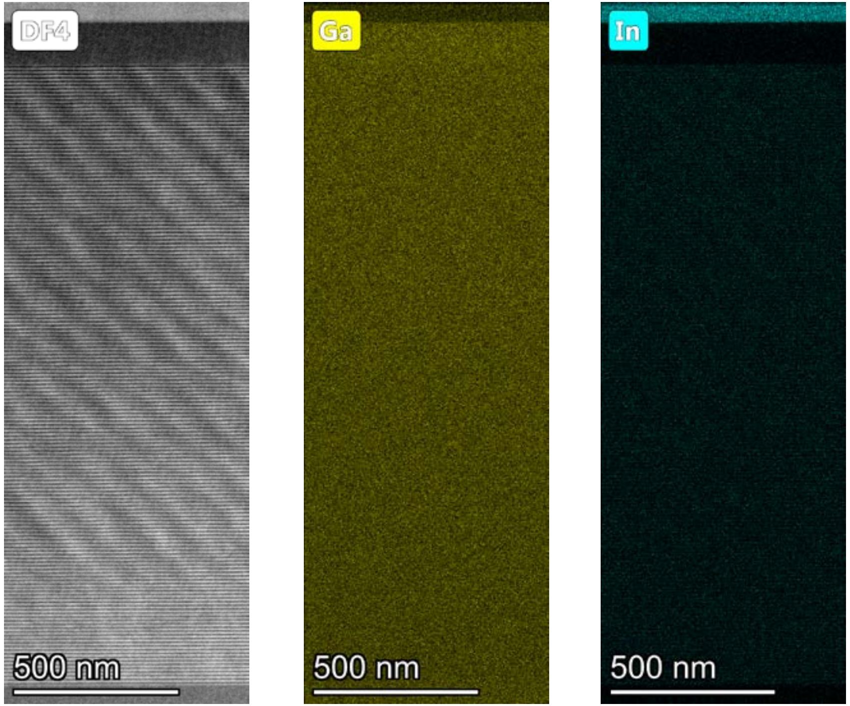
Low mag: phase separation with low AsH_3

EDS Comparison Group III

Low AsH_3



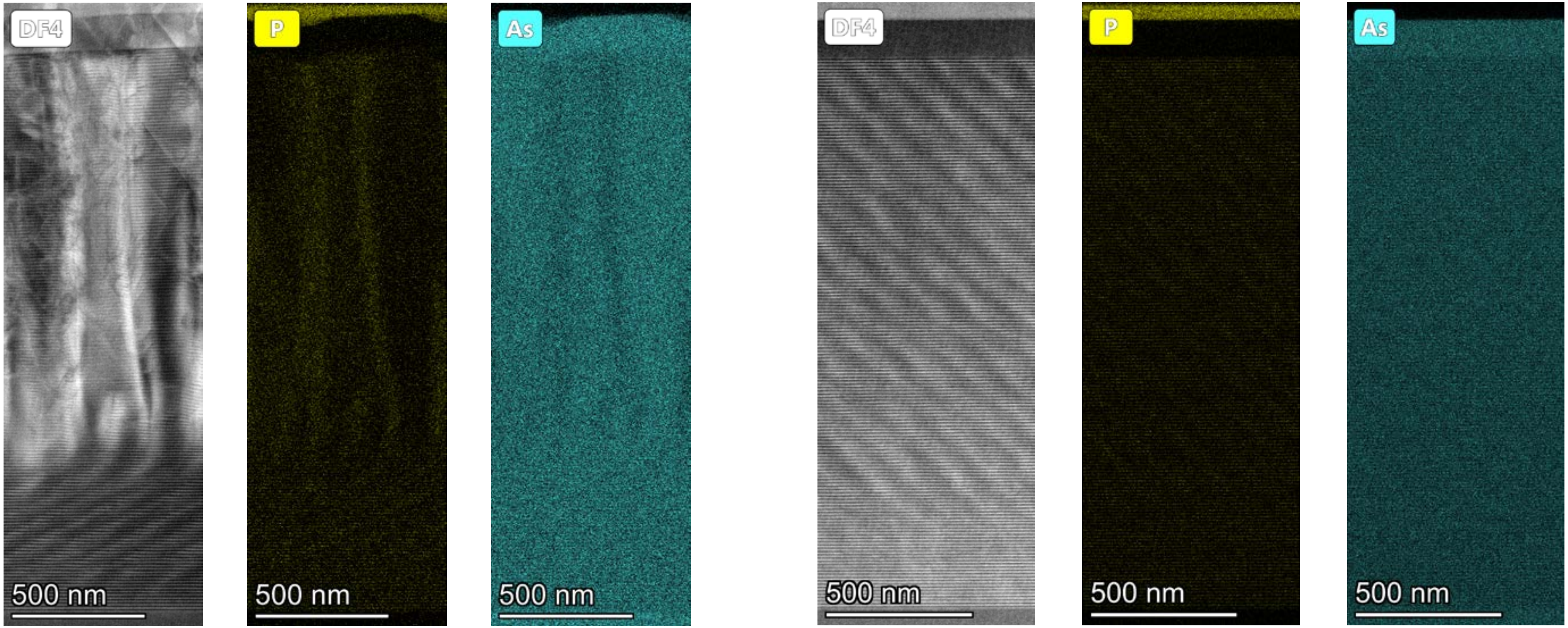
High AsH_3



TEM images from Jenny Selvidge, UCSB

EDS Comparison Group V

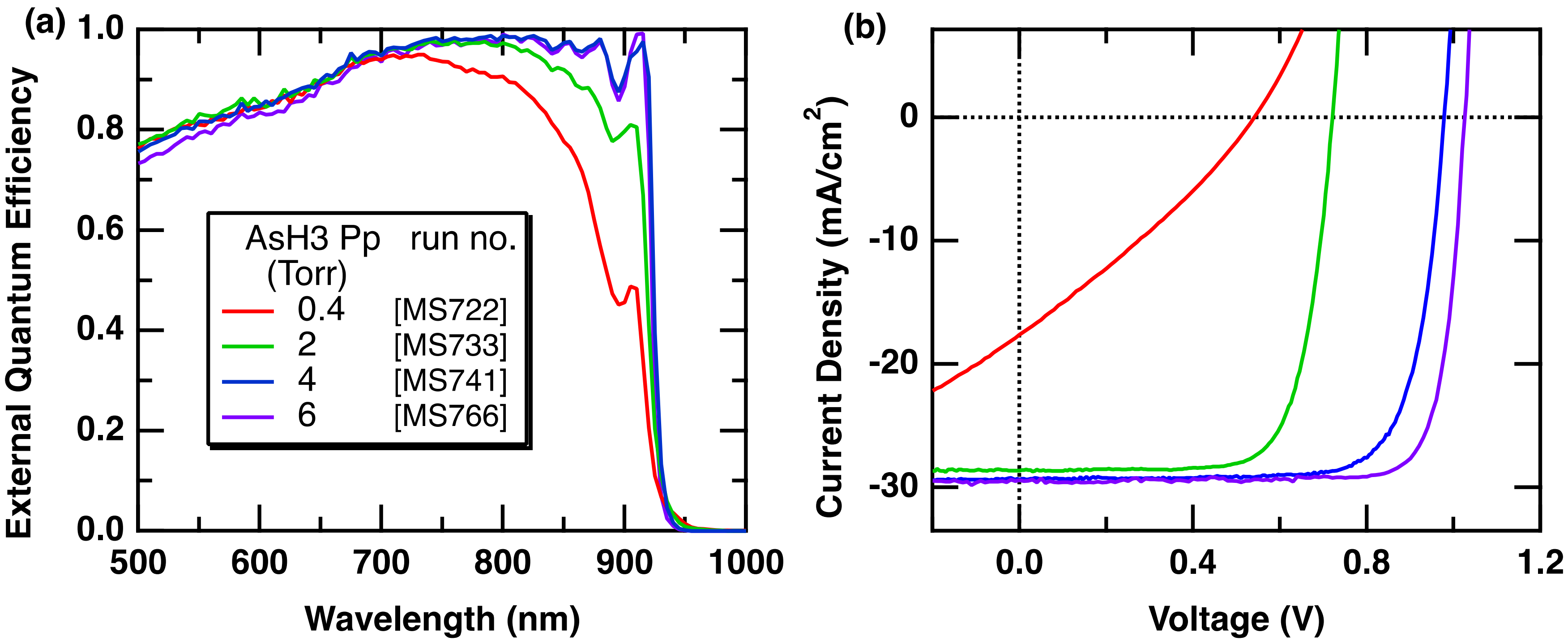
Low AsH_3 | High AsH_3



TEM images from Jenny Selvidge, UCSB

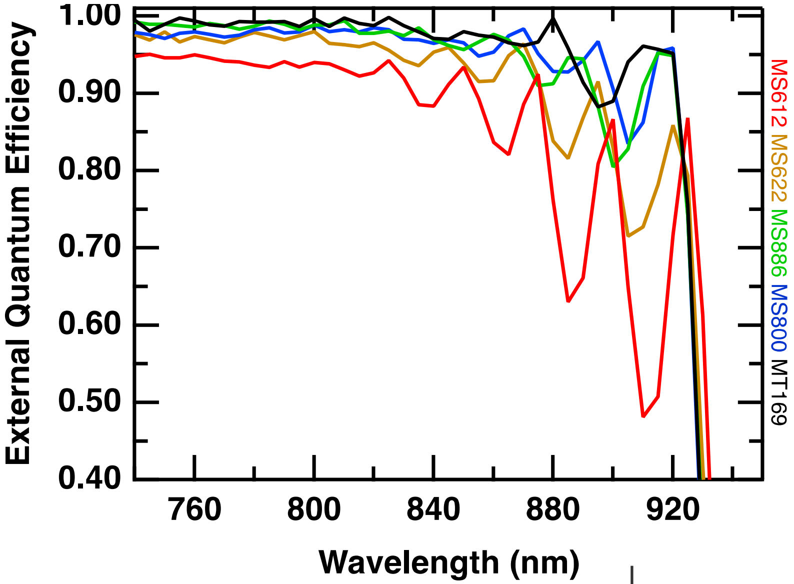
Limit elastic relaxation by increasing AsH_3 flow

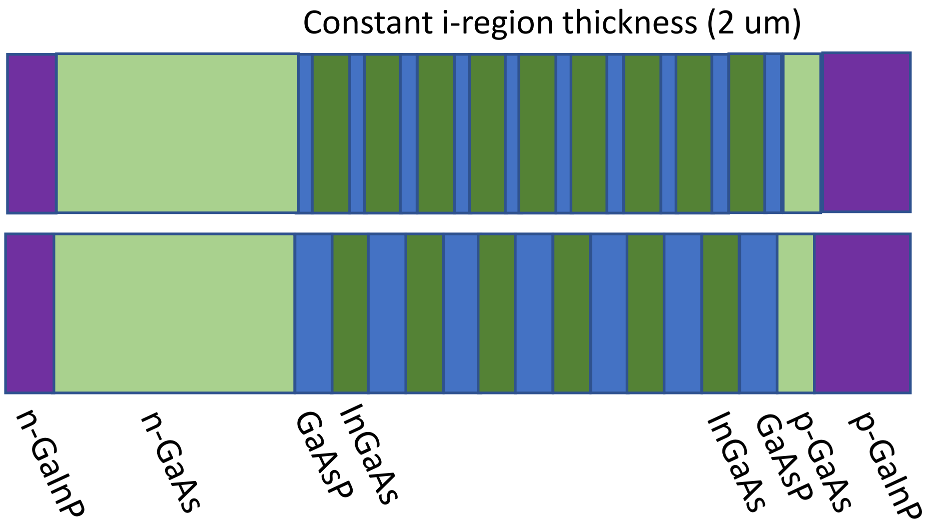
Increased AsH_3 flow during InGaAs QWs limits indium surface mobility



Barriers: 36 Å, $GaAs_{0.4}P_{0.6}$ Number of wells = 168

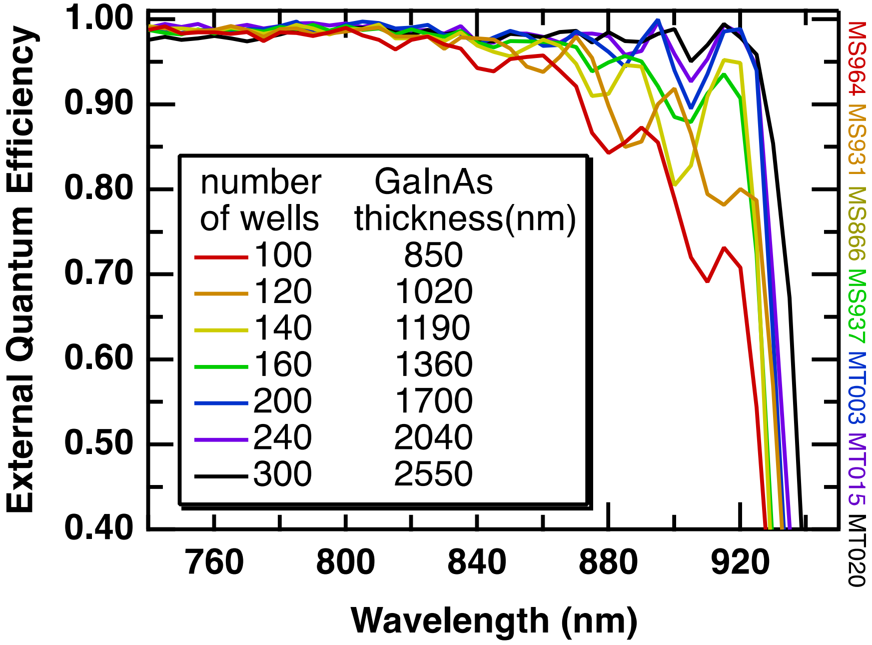
Vary the barrier thickness and the number of wells

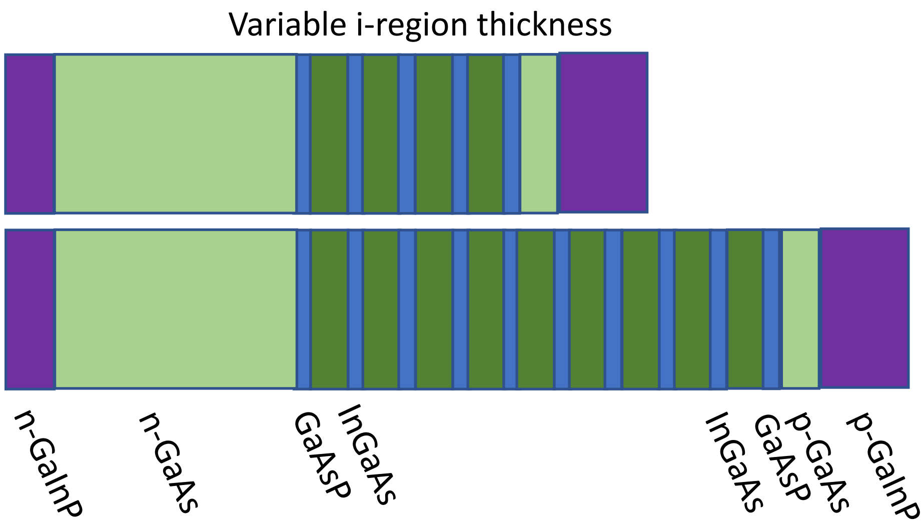




	Barrier thickness	P_x	# wells	Well Fraction	Total Well
MS612	170 Å	0.1	80	33%	680 nm
MS622	100	0.2	110	46%	935
MS886	60	0.35	140	59%	1190
MS800	36	0.6	168	70%	1428
MT169	20	1.0	184	84%	1564

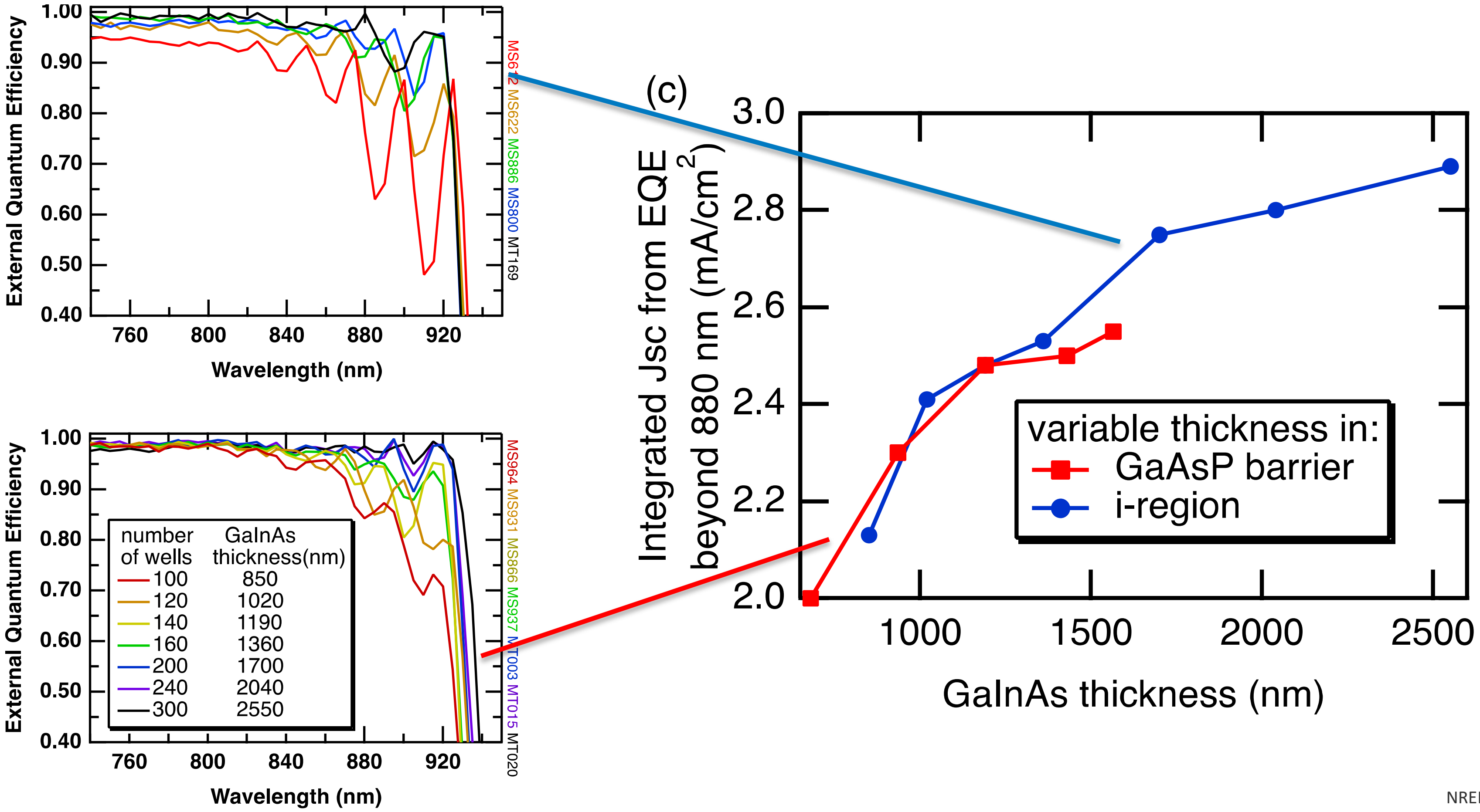
Vary the number of wells and the depletion layer thickness





Barriers: 60 Å, $GaAs_{0.65}P_{0.35}$

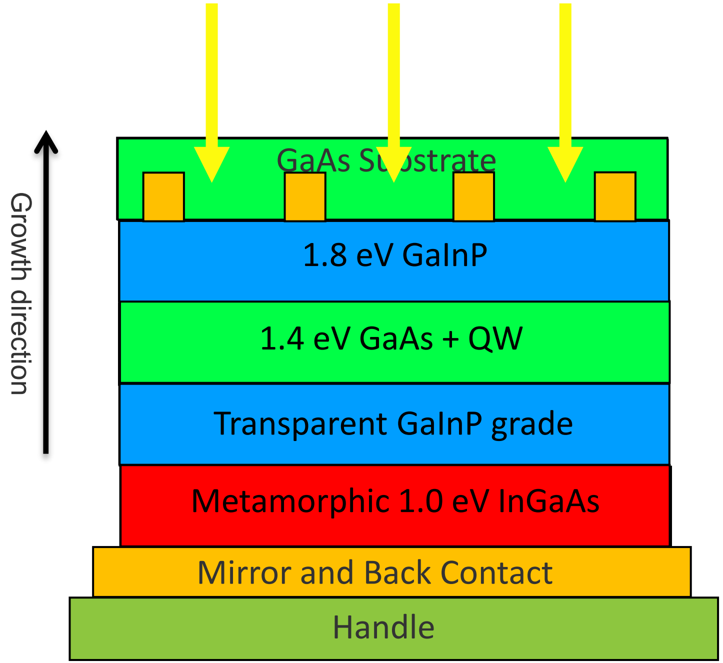
Clear increase in sub-bandgap absorption and collection



Fabrication of inverted PV devices

Gives easy access to the device backside for applying advanced contacts
Enables a range of device designs

Substrate can be etched away, or removed and reused

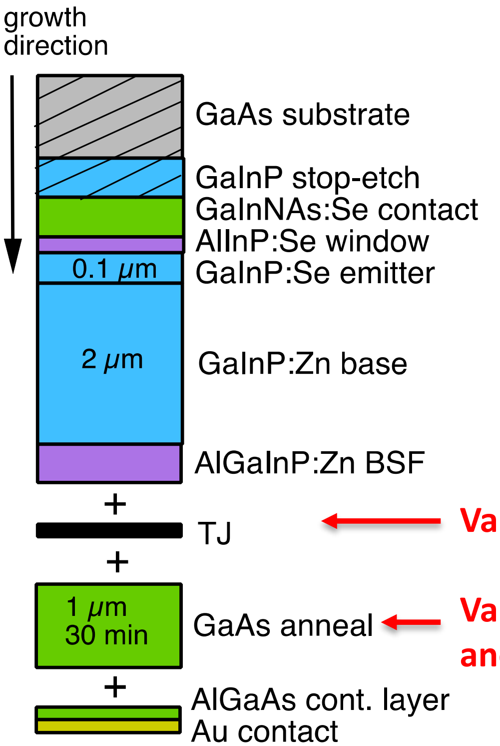


Handle can be:

- silicon or glass
- something flexible
- another solar cell

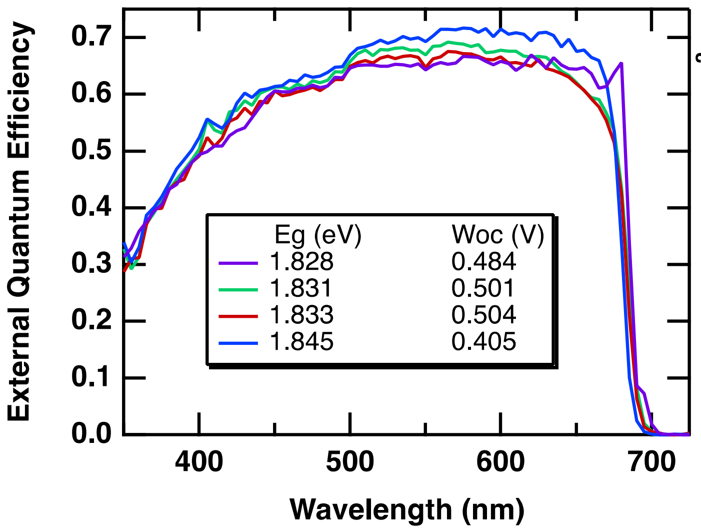
Annealing of front-junction GaInP

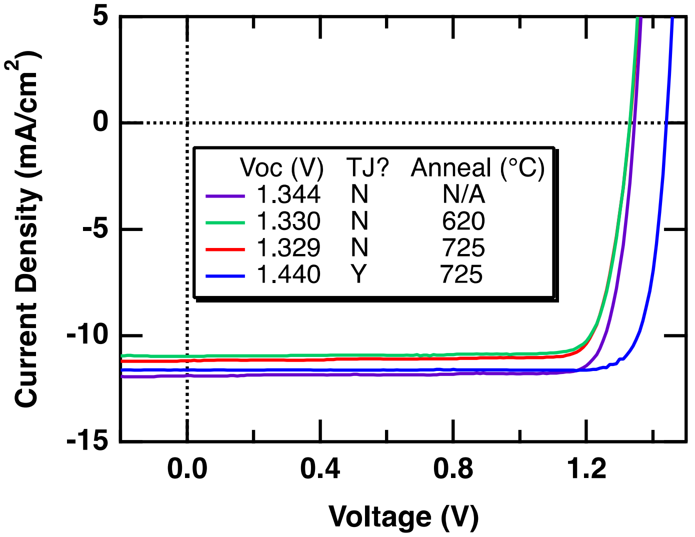
Inverted GaInP cells



Vary presence of TJ

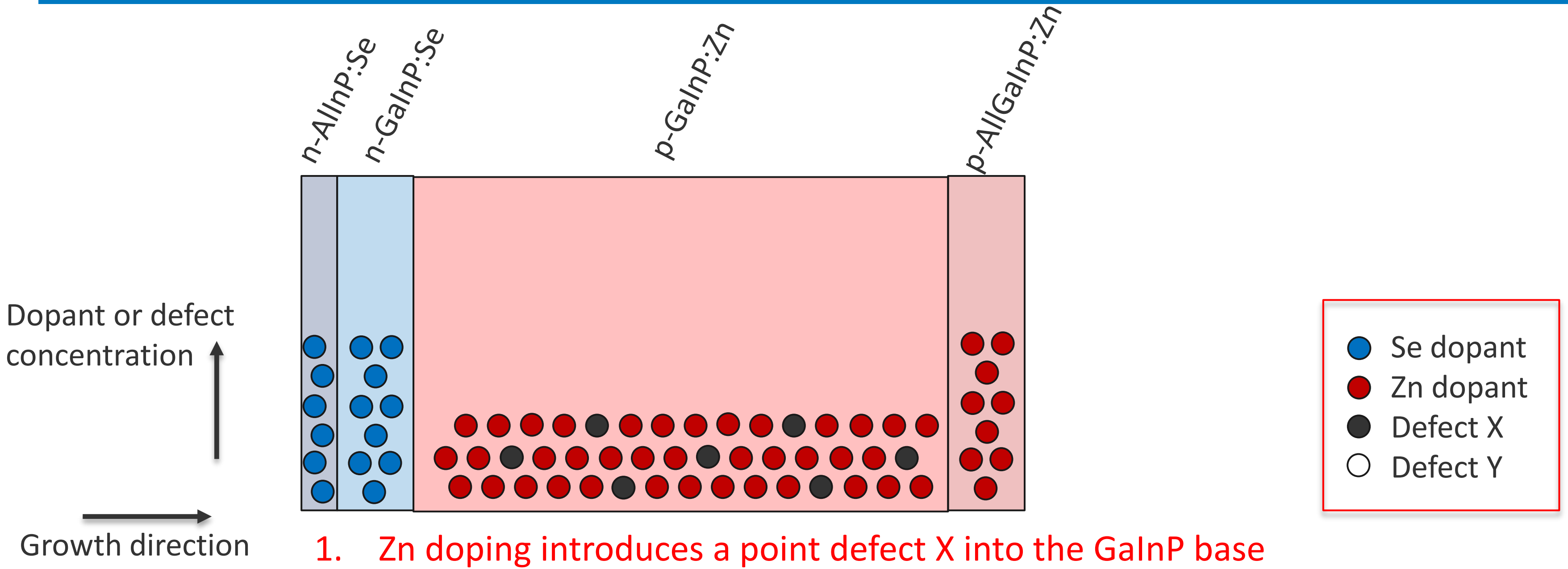
Vary anneal temp. and time





- P-type absorber is important for optical thickness
- Voltage gets slightly worse under standard anneal
- Voltage improves by ~100 mV under anneal after point-defect injection

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 = Ga vacancy, Y = Ga interstitial
X = Zn interstitial, Y = Ga vacancy

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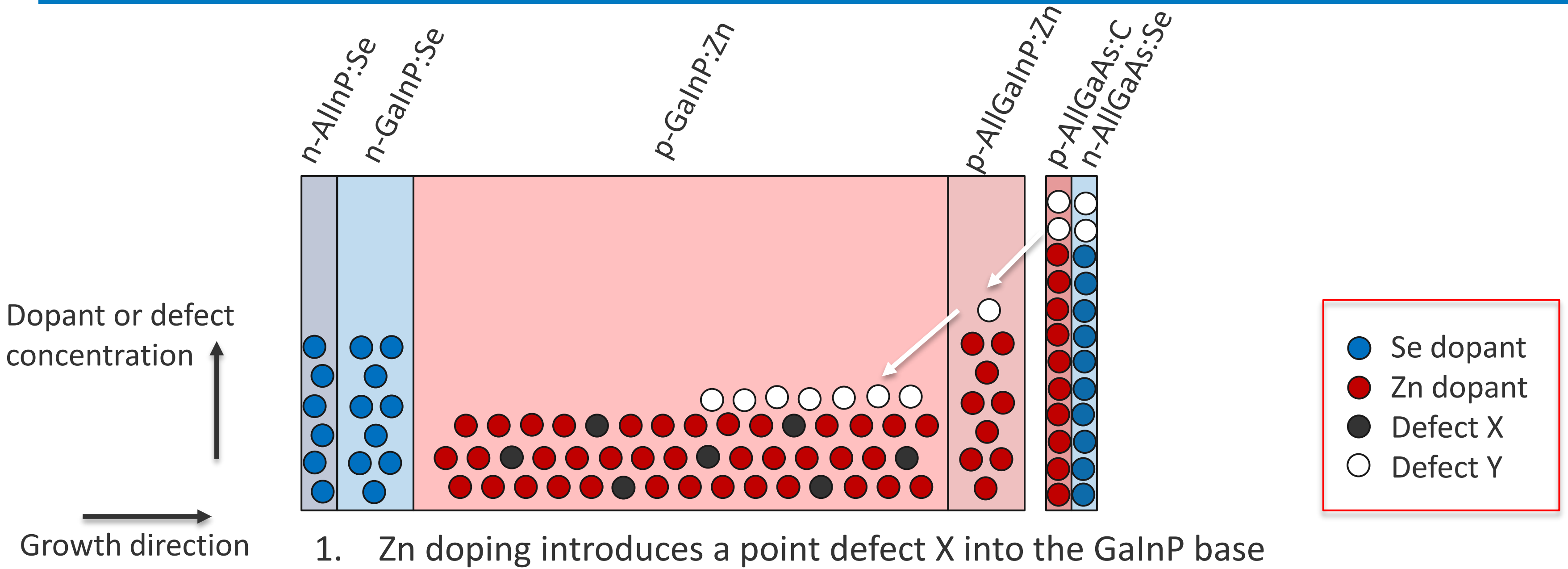

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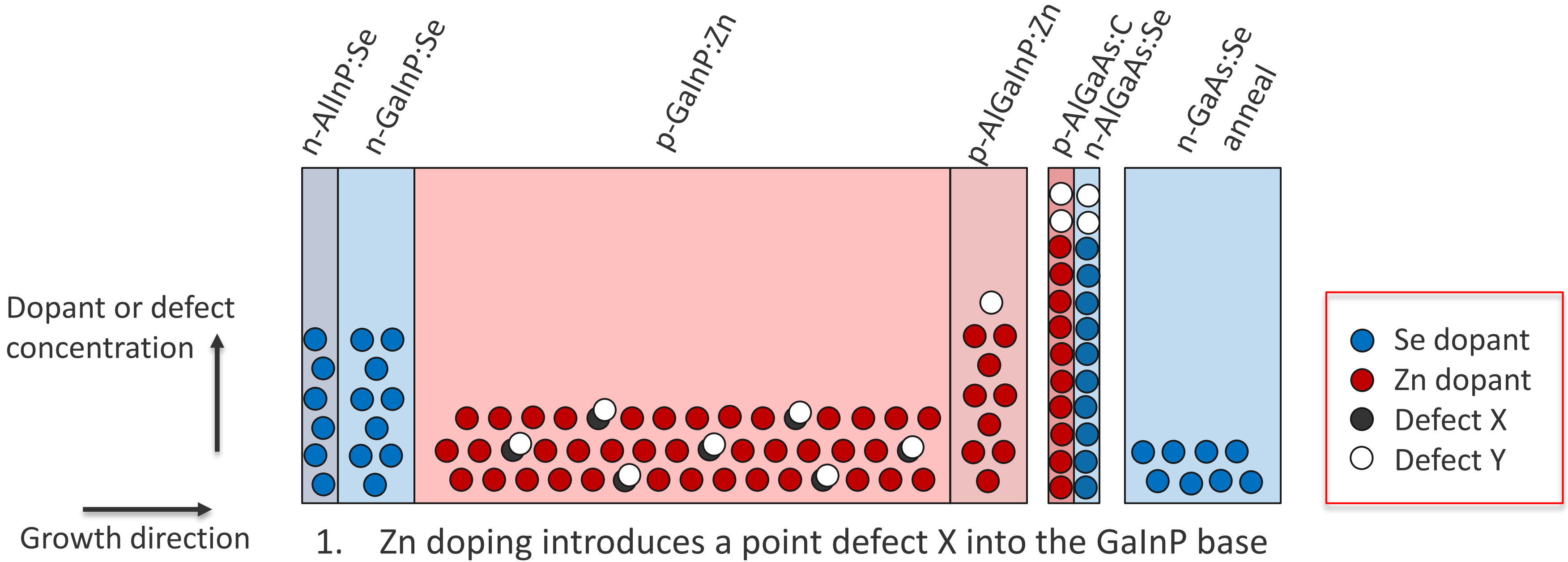

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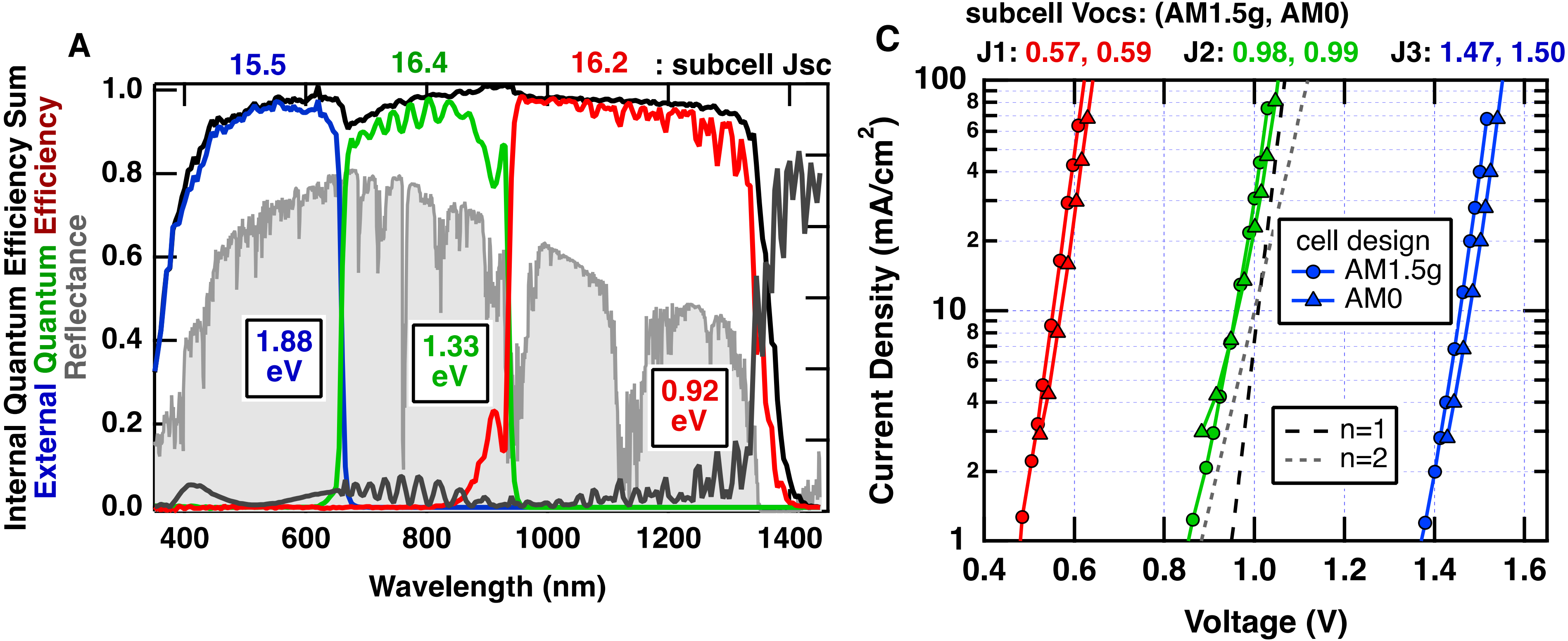
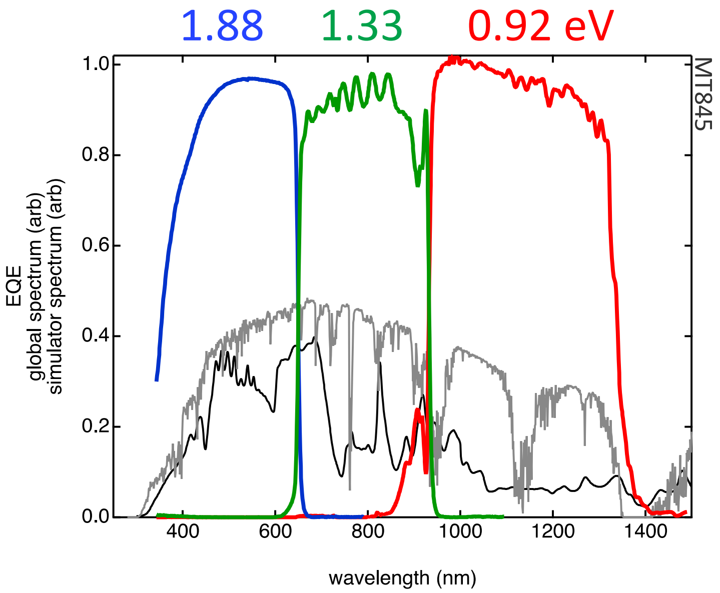
Subcell analysis: AM1.5G and AM0



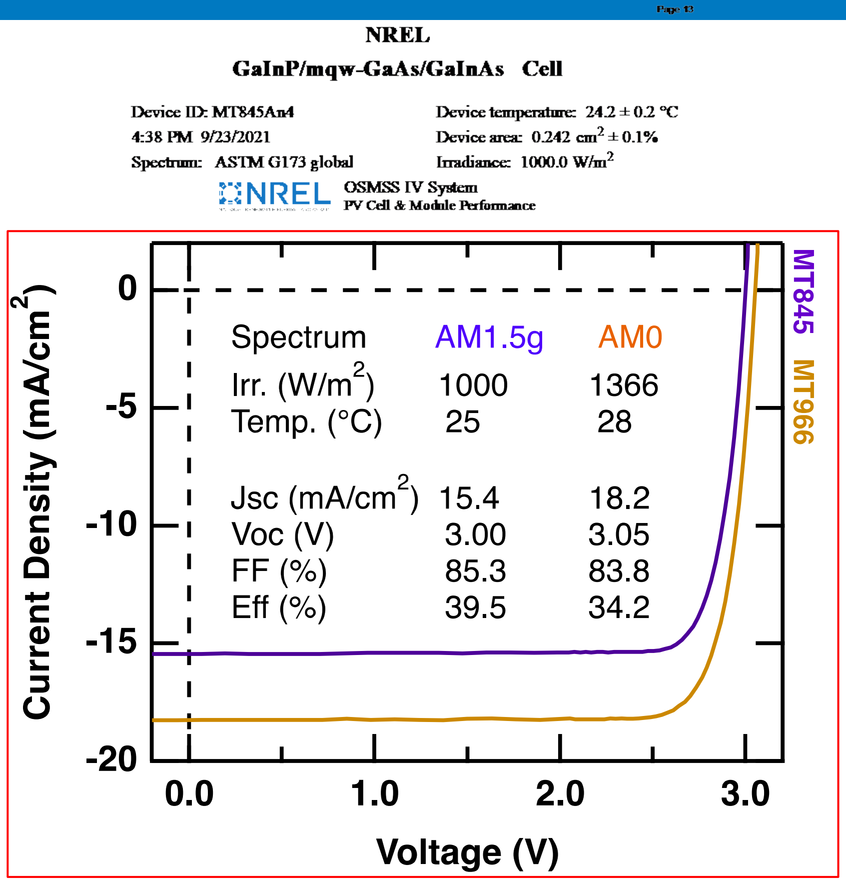
$W_{oc} = E_g/q - V_{oc}$: GaInP = 0.41 V / GaAs-QW = 0.35 V / LMM GaInAs = 0.35 V

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



184 QWs, ~1560 nm of GaInAs

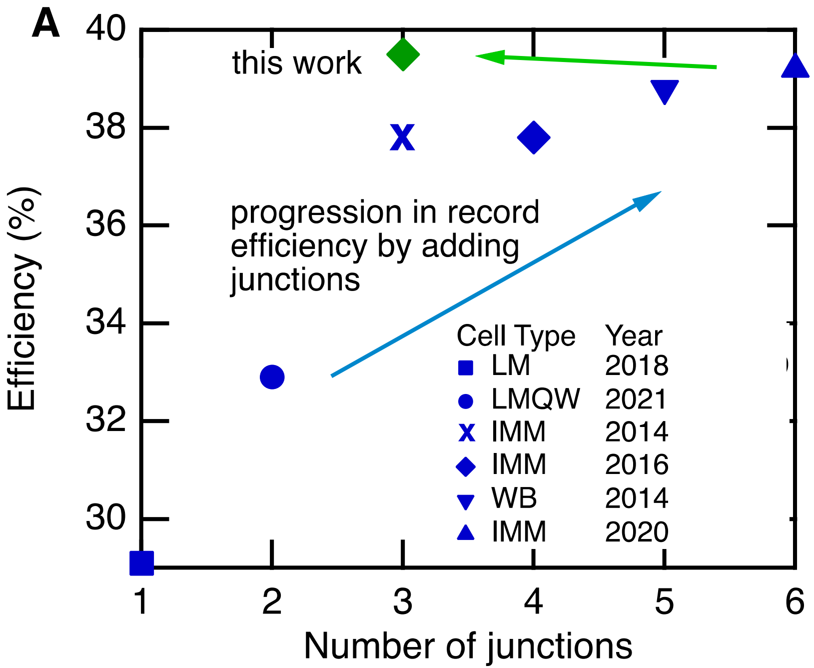
No DBR behind the QWs

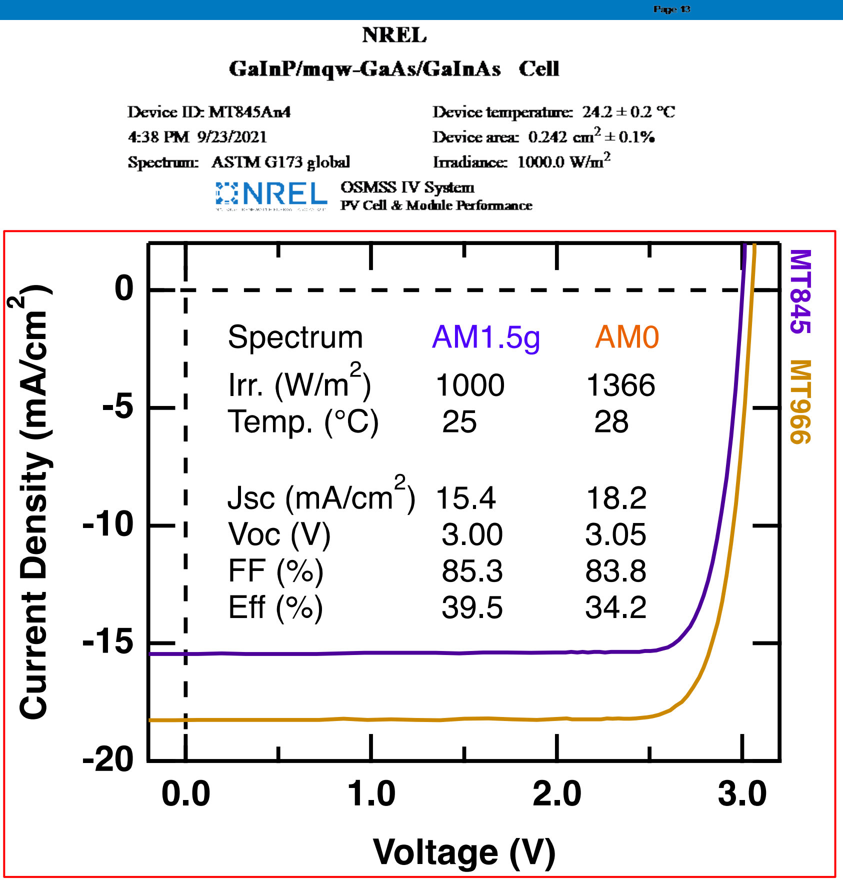


France *et al.*, Joule, to appear May 18

New world record!

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





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Thank you

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