High polarization InAlGaAs/AlGaAs photocathodes grown using MBE

PSTP 2024

20th International Workshop on Polarized Sources, Targets and Polarimetry

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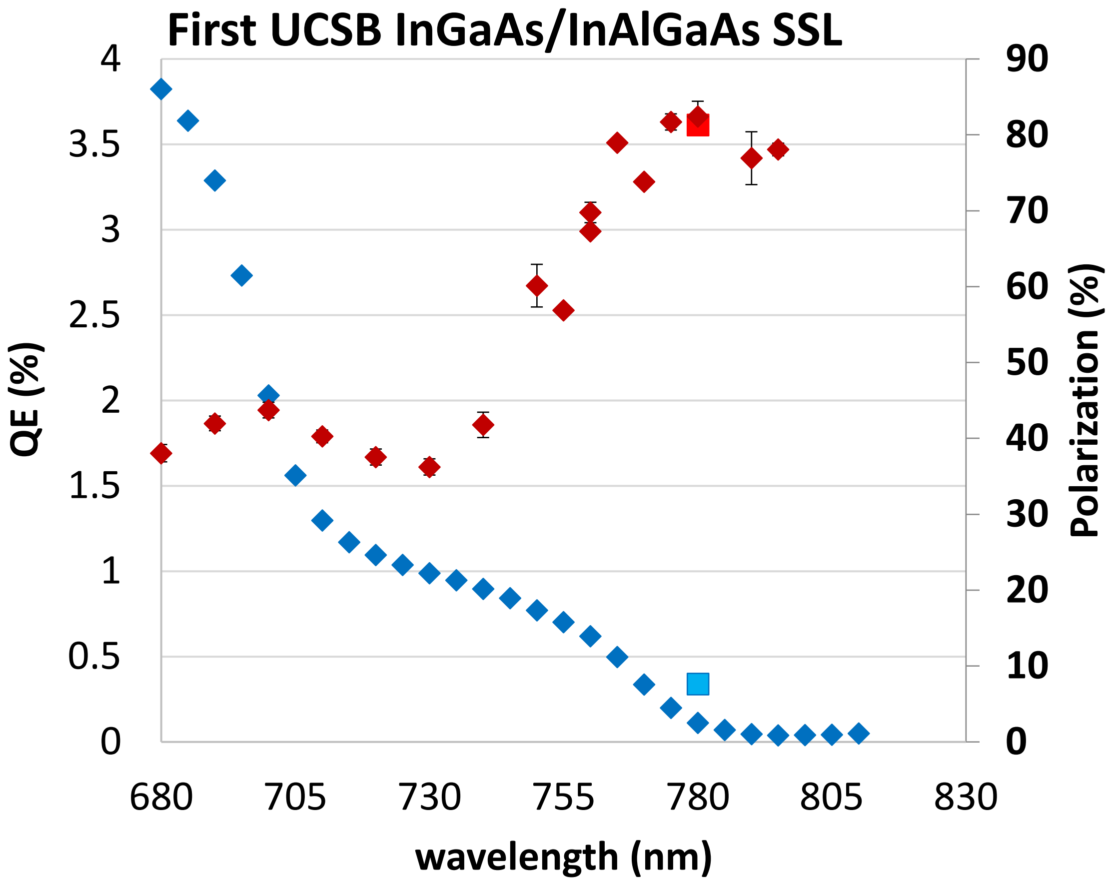

Jefferson Lab

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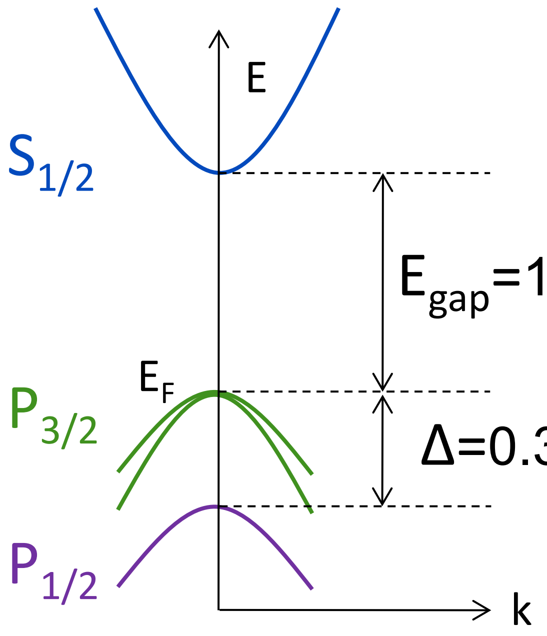
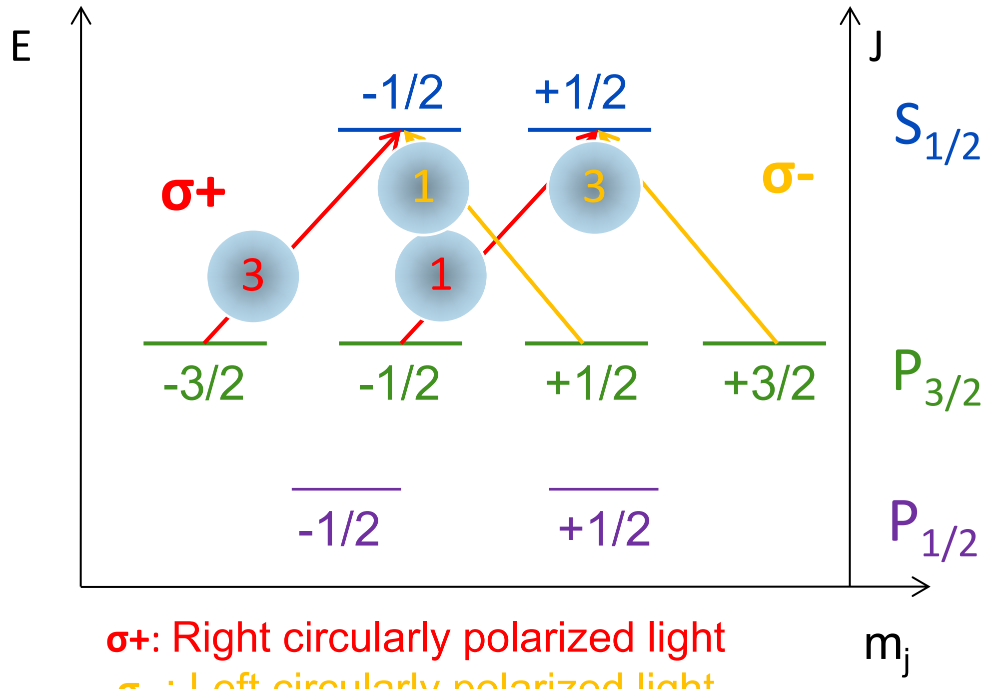
JSA

Spin Polarized Photoemission from Bulk GaAs

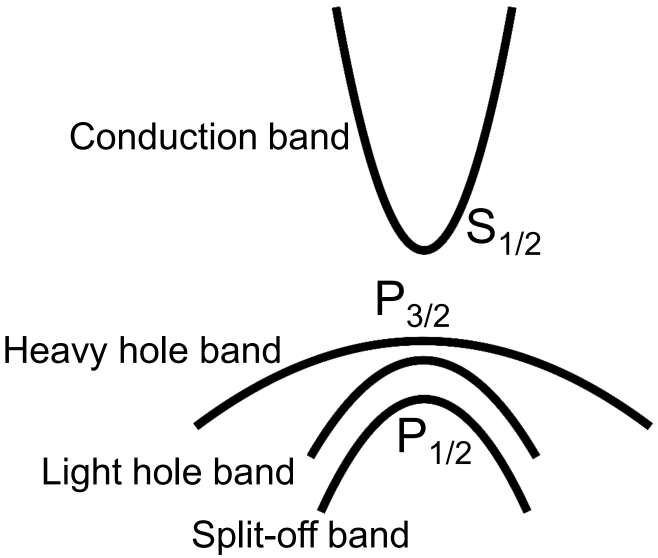


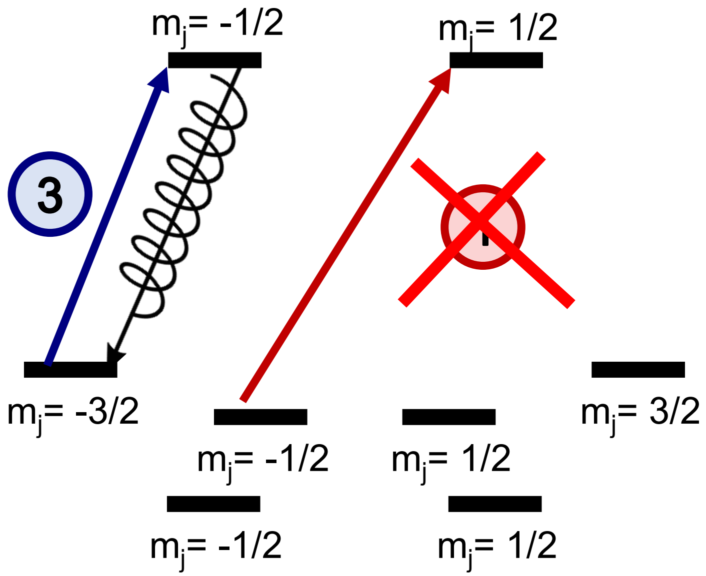


- Laser excitation from $P_{3/2}$ to $S_{1/2}$: $E_{gap} < E_\gamma < E_{gap}+\Delta$
- Electron Polarization: $P_e < \frac{3-1}{3+1} = 50\%$
- Reverse electron polarization by reversing light polarization

How does spin selectivity arise in III-Vs?

- Circularly polarized light couples to electron angular momentum
- Degeneracy limits the theoretical maximum spin polarization
- **<u>Confinement and strain</u> break heavy hole/light hole degeneracy**





$$\eta_{Electron\ Spin\ Polarization} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$

$$\eta_{ESP} = \frac{3 - 0}{3 + 0} = 100\%\ !$$

Spin Crisis: Efforts to restore high polarization restore supply

- DOE Funding Opportunity 20-2310
  - MOCVD (*metal organic chemical vapor deposition*)
    - ODU/BNL/JLab
  - CBE (Chemical Beam Epitaxy)
    - JLab/UCSB

Photocathode Growth at UCSB

U California Santa Barbara

Semiconductor Deposition System

- CBE and MBE growth
- Collaborators for growing GaAs/GaAsP SSL

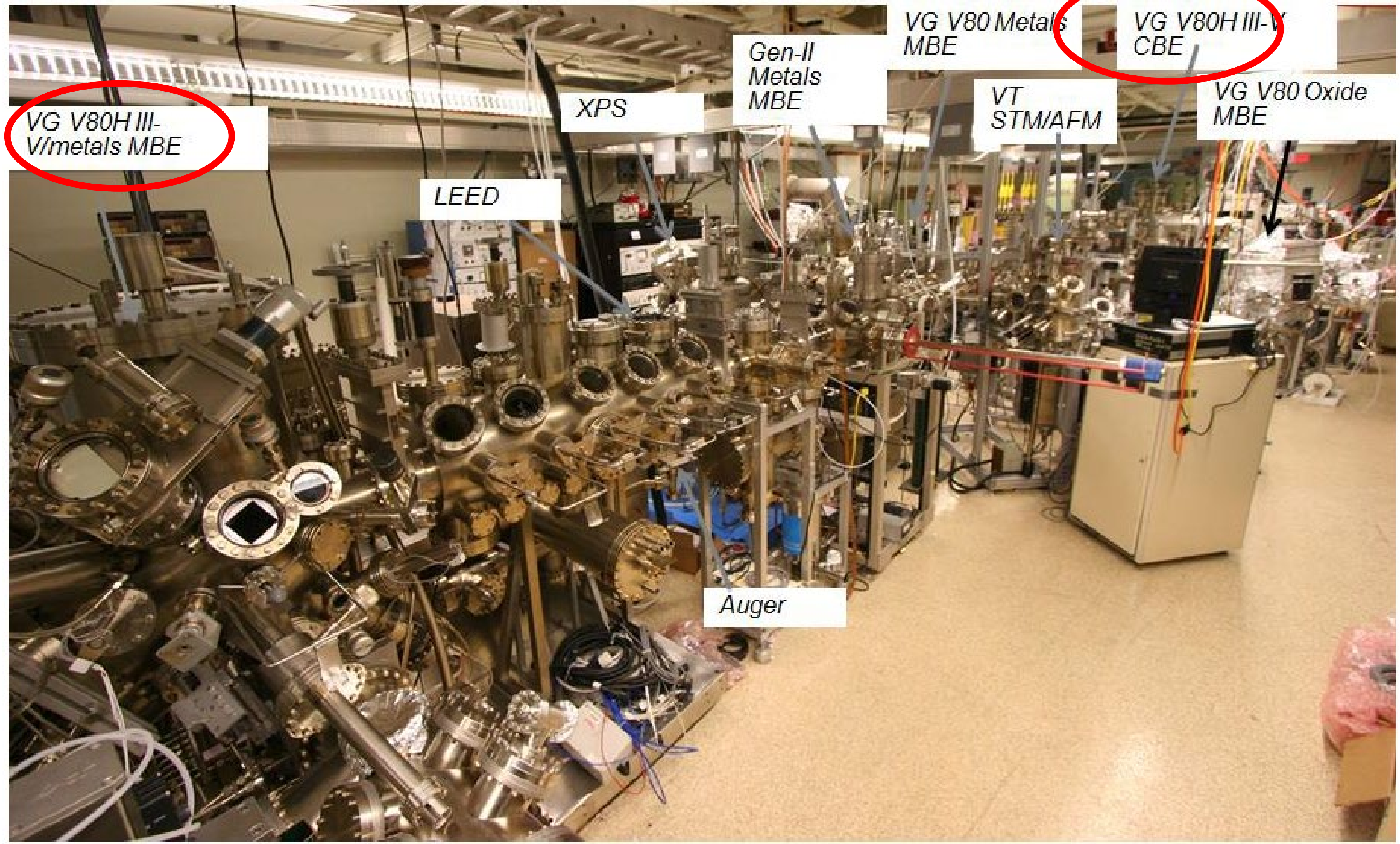
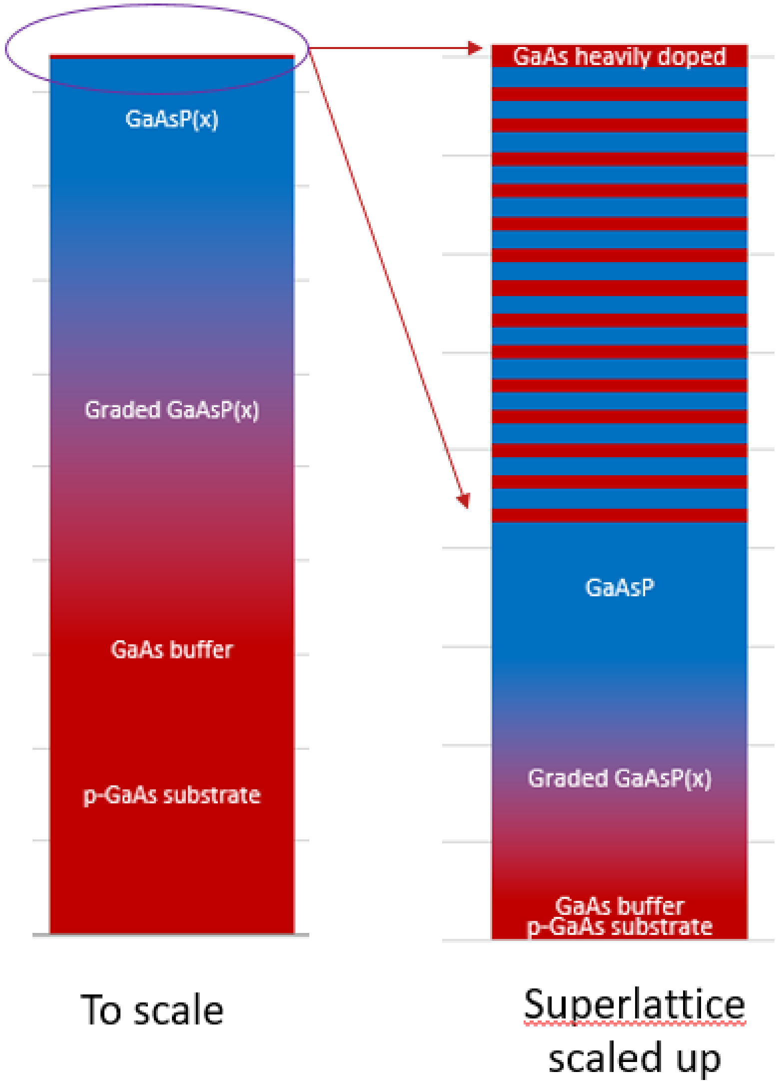


Figure 2 Semiconductor deposition system at Chris Palmstrom's lab at UCSB. The CBE system for the growth of this material is shown at the back and labelled "VG V80H III-V CBE".

Original Research Plan

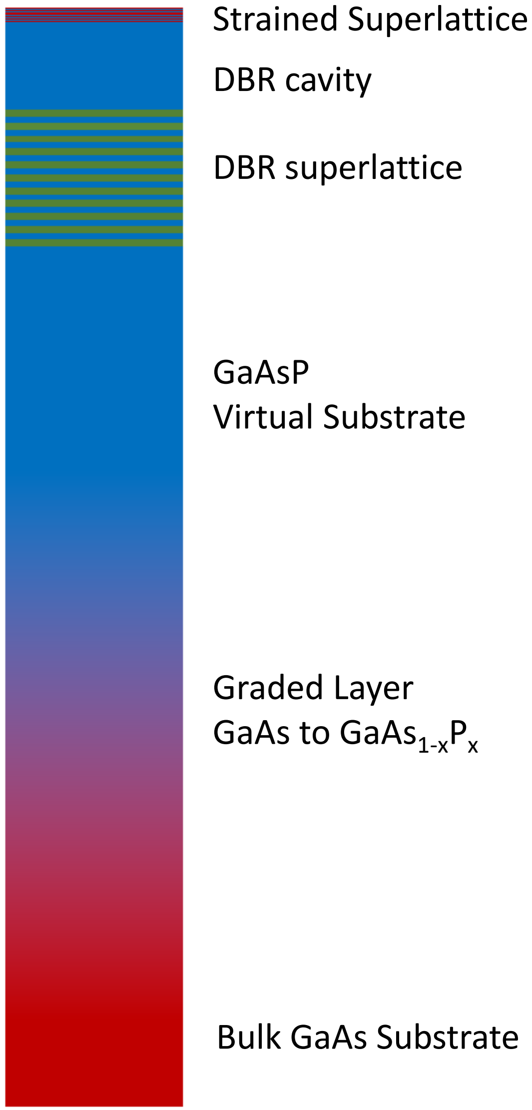


1. Grow GaAs/GaAsP: UCSB
   CBE instead of MBE
2. Measure Polarization: JLab
3. Use Photocathodes!

Obstacles -> Innovation

UCSB Highlights: Graded layer GaAs to GaAsP

GaAs/GaAsP



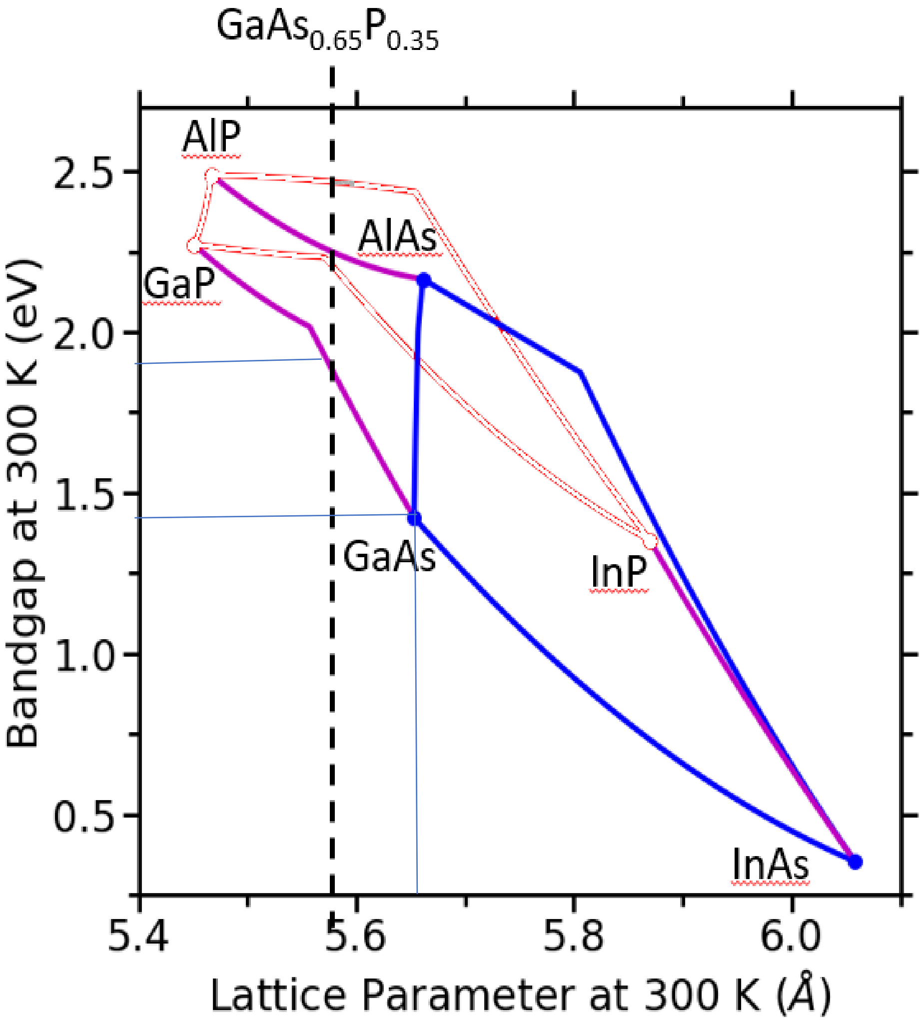
- Graded layer: slow, $$, defects
- Triethyl-gallium + P: high vapor pressure residue
  - Return to solid source Ga
    - CBE becomes MBE
- Rebuild system, recalibrate growth parameters with new heaters & sources

- Meanwhile Literature Review
  - **Try InAlGaAs/AlGaAs**
  - Lattice matched barrier – no graded layer
  - No phosphorus!
  - Literature showed high polarization
  - DBR elements subset of superlattice
  - Easy to As cap

[1] L. G. Gerchikov, *et al. Semiconductors* **40**, 1326–1332 (2006)

GaAs/GaAsP

- Strain and valence band offset coupled: both fixed by virtual substrate
- Phosphorus & MBE: Technical challenges
- Growth temperatures: Dissimilar
- *DBR adds additional elements*



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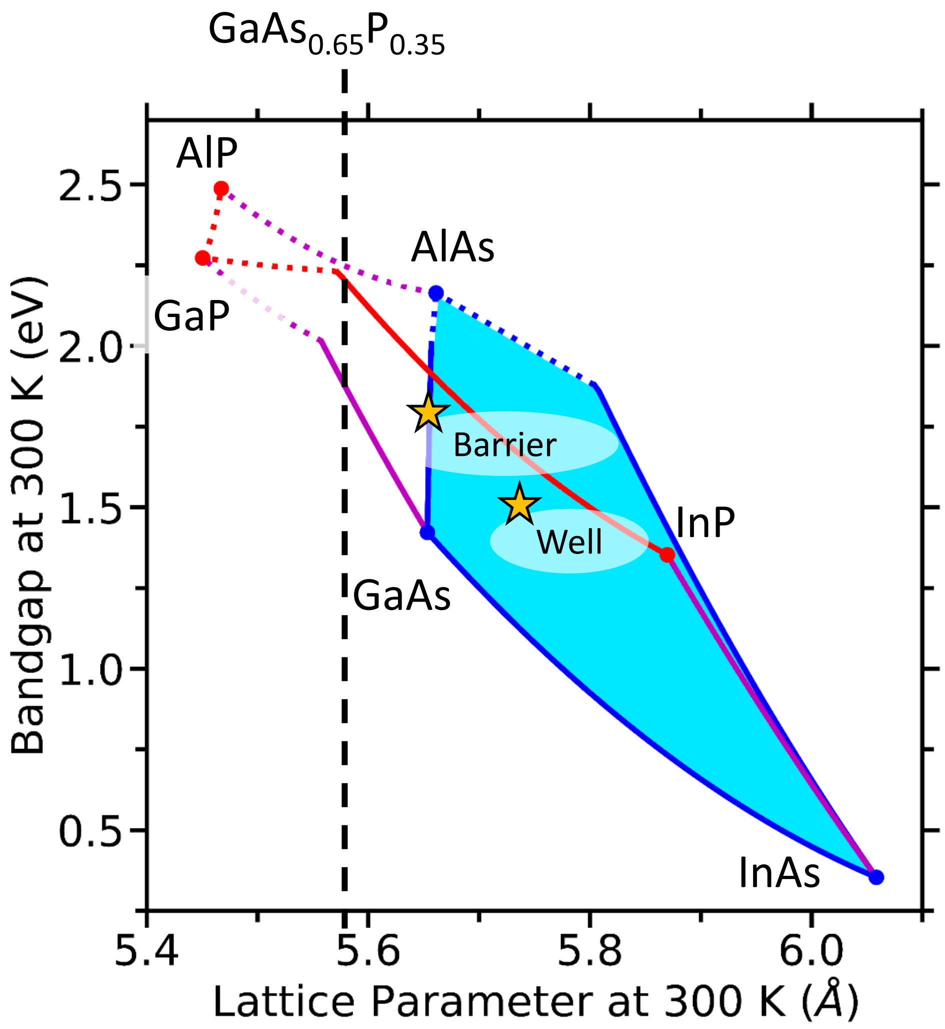
InAlGaAs/AlGaAs

- Strain and valence band offset independent

- InAlGaAs & MBE: Common
- Growth temperatures: Similar
- *Easily tunable DBRs in AlAs/AlGaAs system*
- Best Polarization ≥ GaAs/GaAsP

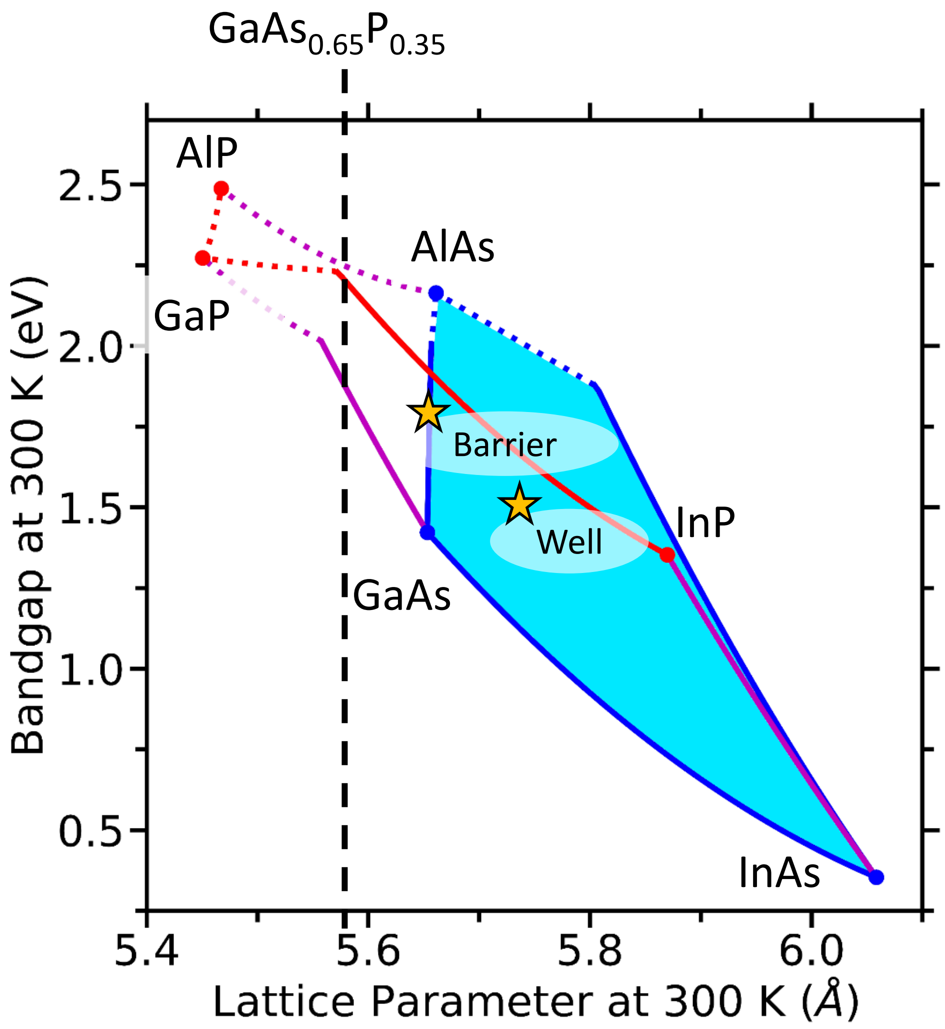
- Should be possible to get commercial vendor once optimized
- As capping straightforward



[1] L. G. Gerchikov, *et al. Semiconductors* **40**, 1326–1332 (2006)

Parametric studies

- Strain and valence band offset independent: **Higher strain**
- InAlGaAs & MBE: Common
- Growth temperatures: **Optimize**
- *Easily tunable DBRs in AlAs/AlGaAs system*
- Best Polarization ≥ GaAs/GaAsP
  - **Try Digital alloying to reduce depolarization**



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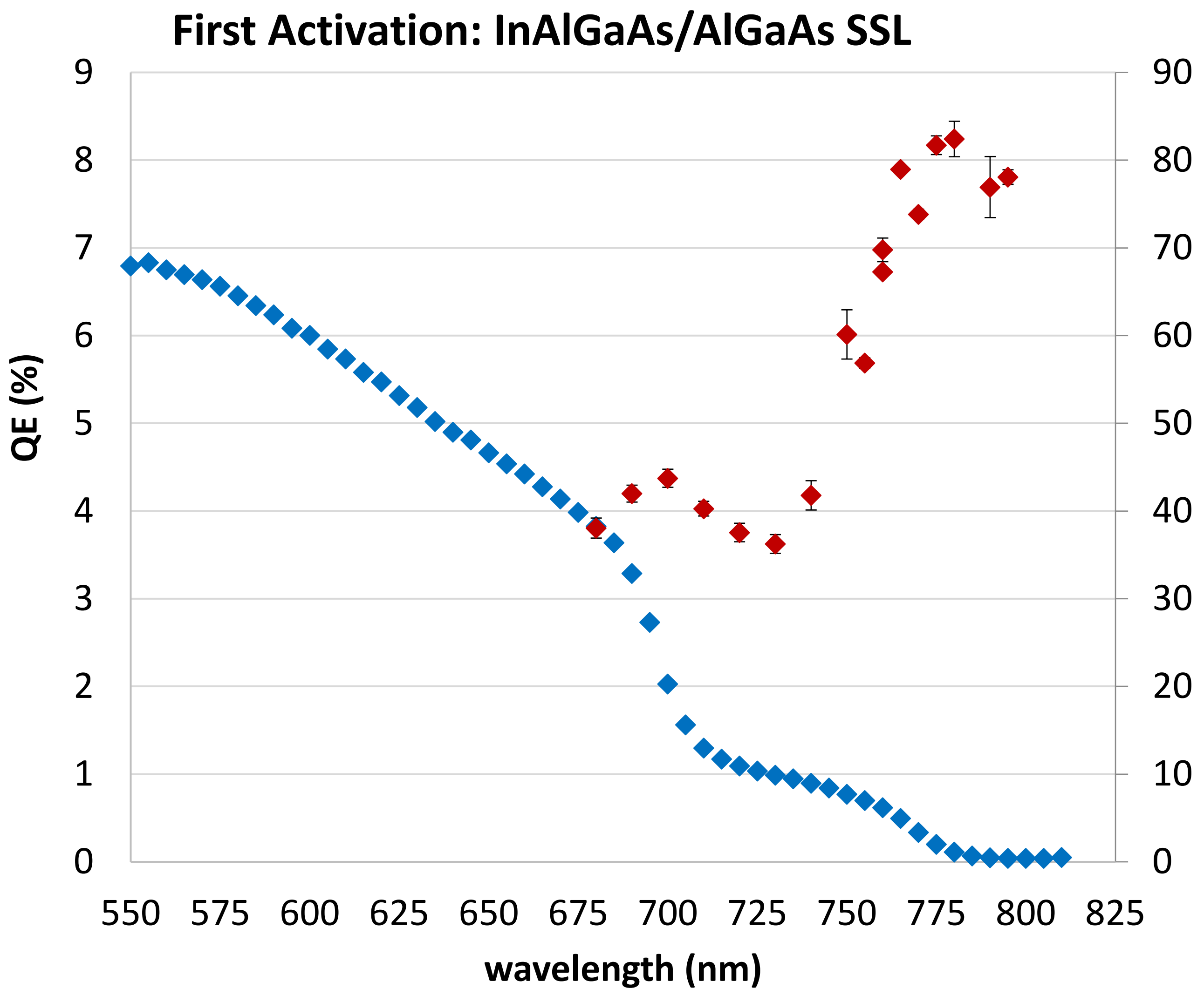
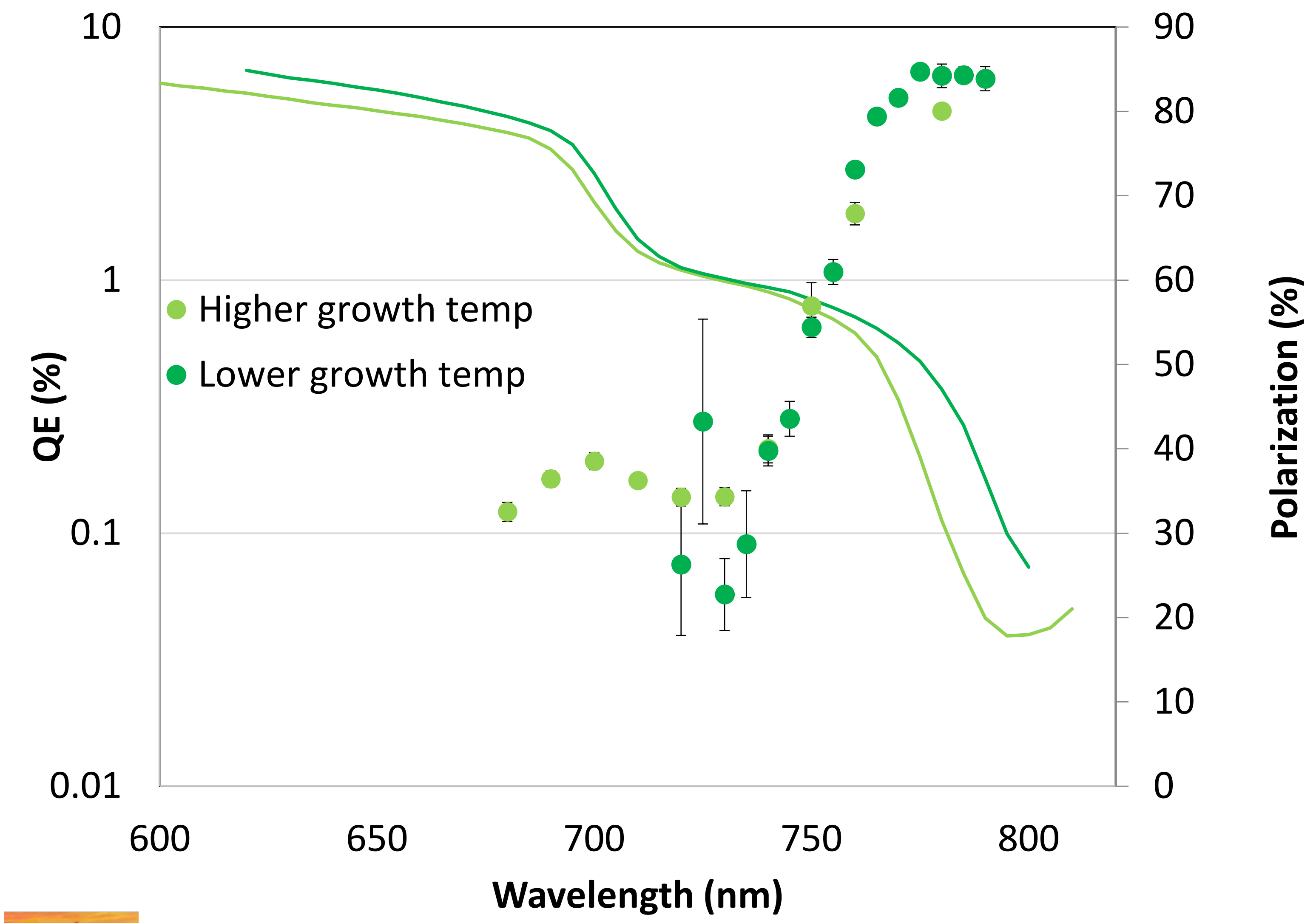
First Growth & Activation InAlGaAs/AlGaAs SSL



Max Polarization > 82.5%
Max QE at max: 0.34%

Then polarimeter problems

Parametric Studies: Growth Temperature



Lower Growth Temperature =

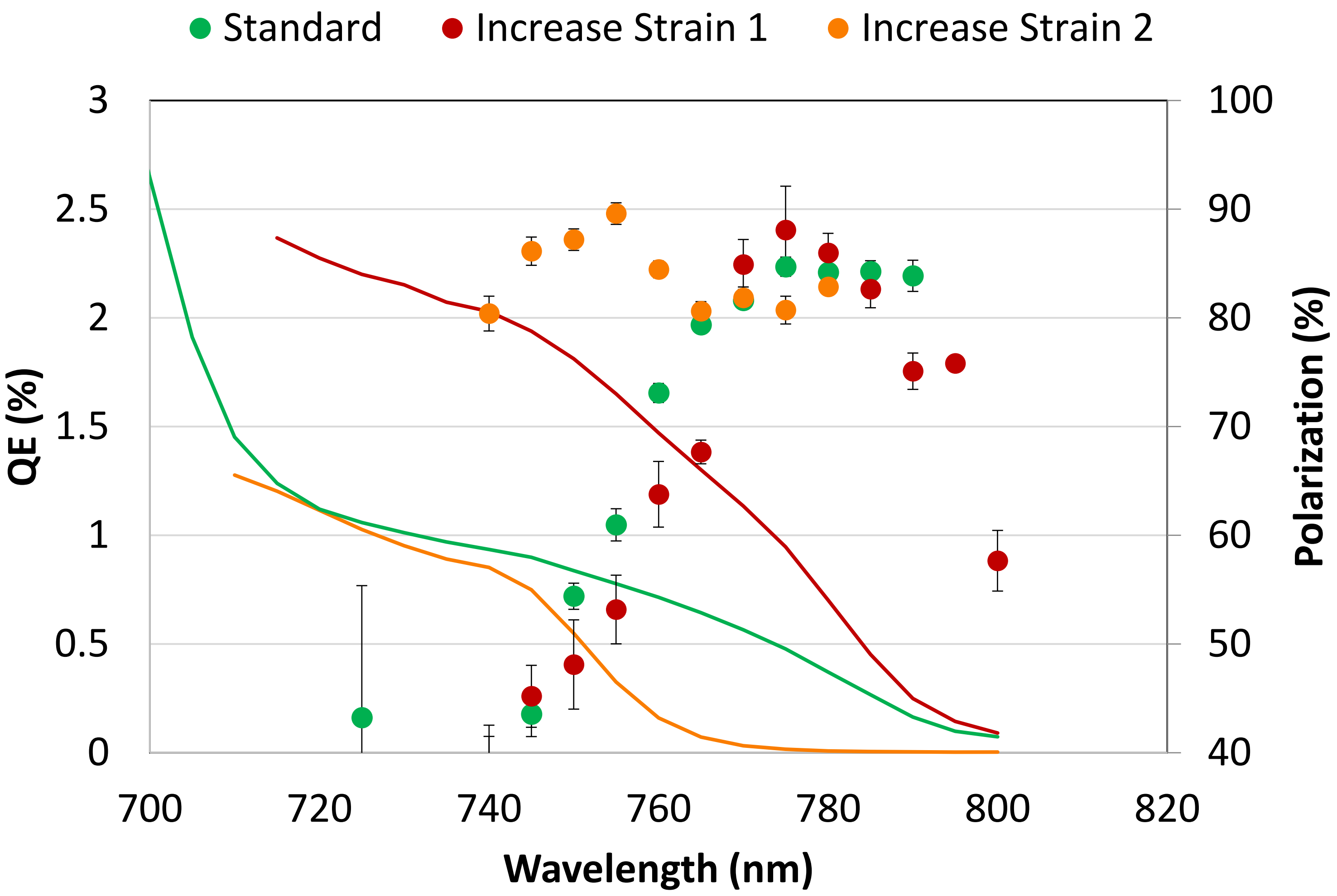
- Higher Polarization
- Higher QE

* Activations

- before and after polarimeter repair
- different heat cycle

- Heat cycles typically **370ºC** in vacuum
- First sample ~450ºC

Parametric Studies: Strain



Higher Strain =

- Higher Polarization

- Orange data
  - P = 90 ± 1%
  - 0.33% QE at 755 nm

- Red data
  - P = 88 ± 4%
  - 0.95% QE at 775 nm

Depolarization Mechanisms

Spicer 3 step model

1. Excitation
2. **Transport**
3. Emission

Transport Depolarization mechanisms

- *Spin orbit coupling (EY)*
- *Spin state splitting (DP)*
- *Electron/hole exchange (BAP)*

Scattering locations

- Impurities
- Dopants
- **Random alloy disorder**

O. Chubenko et al., Appl. Phys. 130, 063101 (2021)

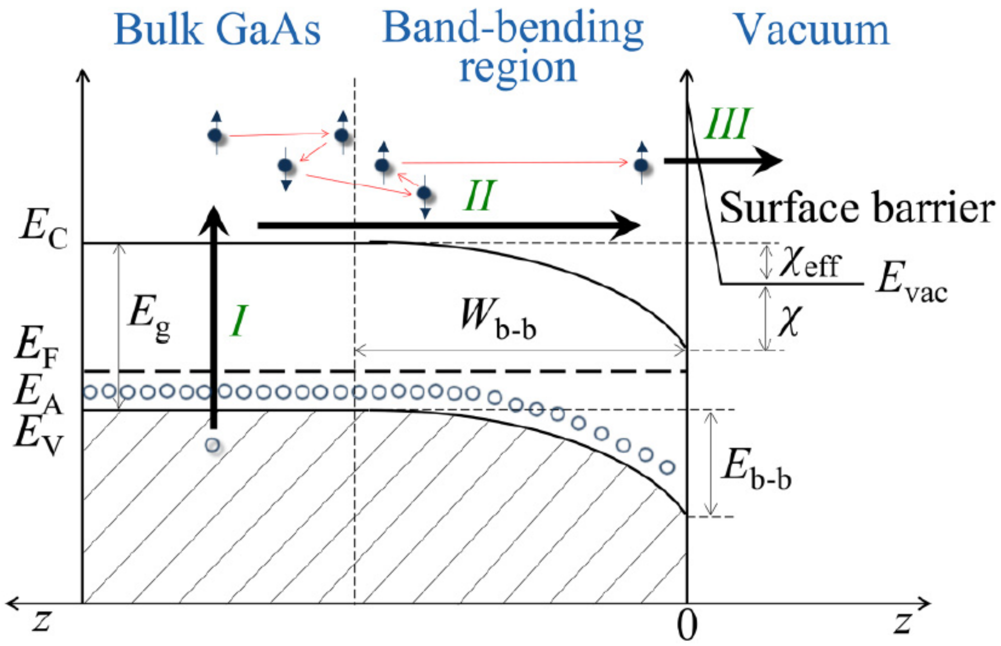
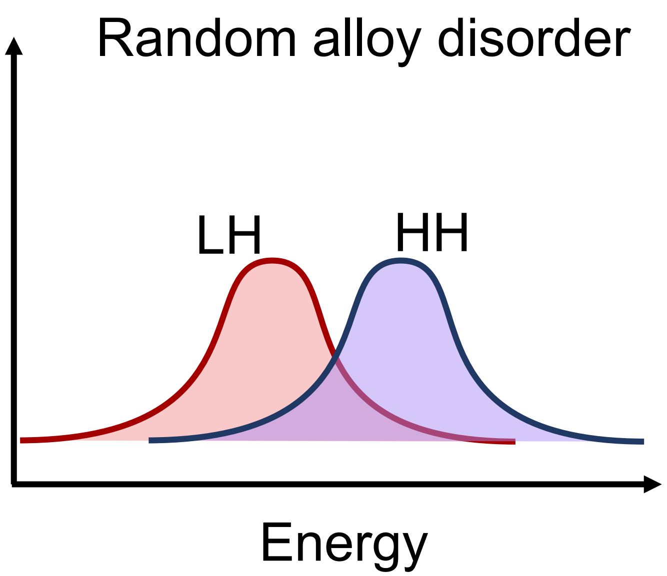
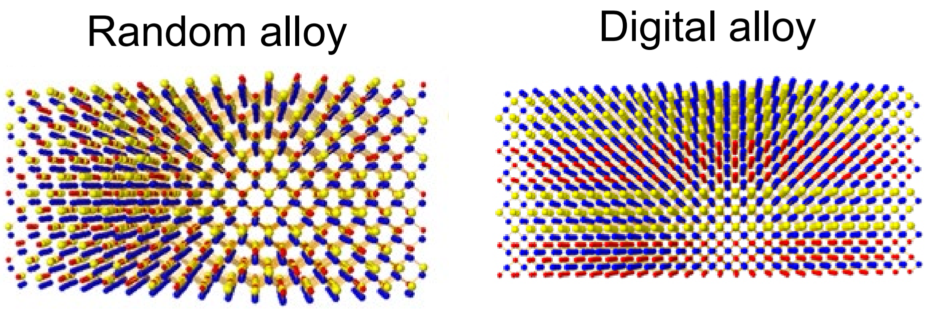


FIG. 1. Three-step model of spin-polarized photoemission from *p*-type NEA GaAs: I—photoexcitation; II—transport; III—emission into the vacuum.

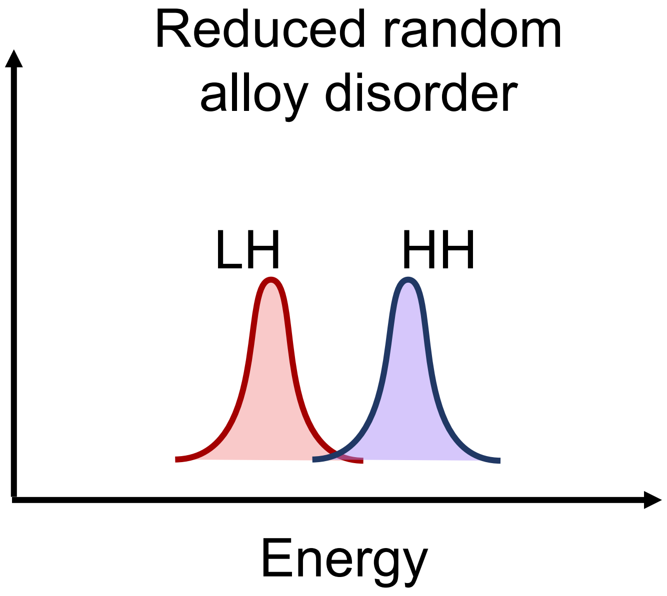
Approach to reduce alloy disorder and improve uniformity





J. Appl. Phys. **125**, 082514 (2019)

i.e.	AlGaAs	AlAs and GaAs layers



- Digital alloying minimizes random alloy disorder
  - Broader high spin-polarization window
- InAlGaAs digital alloys should have
  - Better optical emission than random alloys
  - Better uniformity than random alloys

J. Dong, A. Engel, C. Palmstrøm et al., Phys. Rev. Materials 8, 064601 (June 2024)

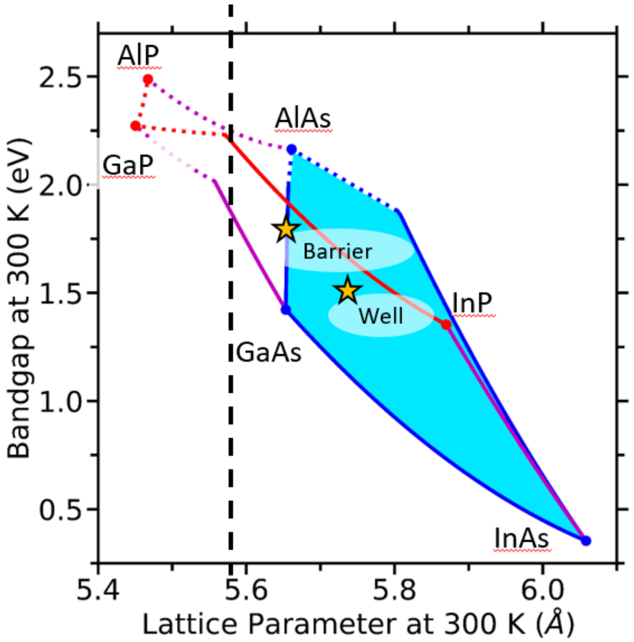
UC SANTA BARBARA MATERIALS

D. Song,…,Y.T. Lee *J. Cryst. Growth* **270**, 295 (2004)

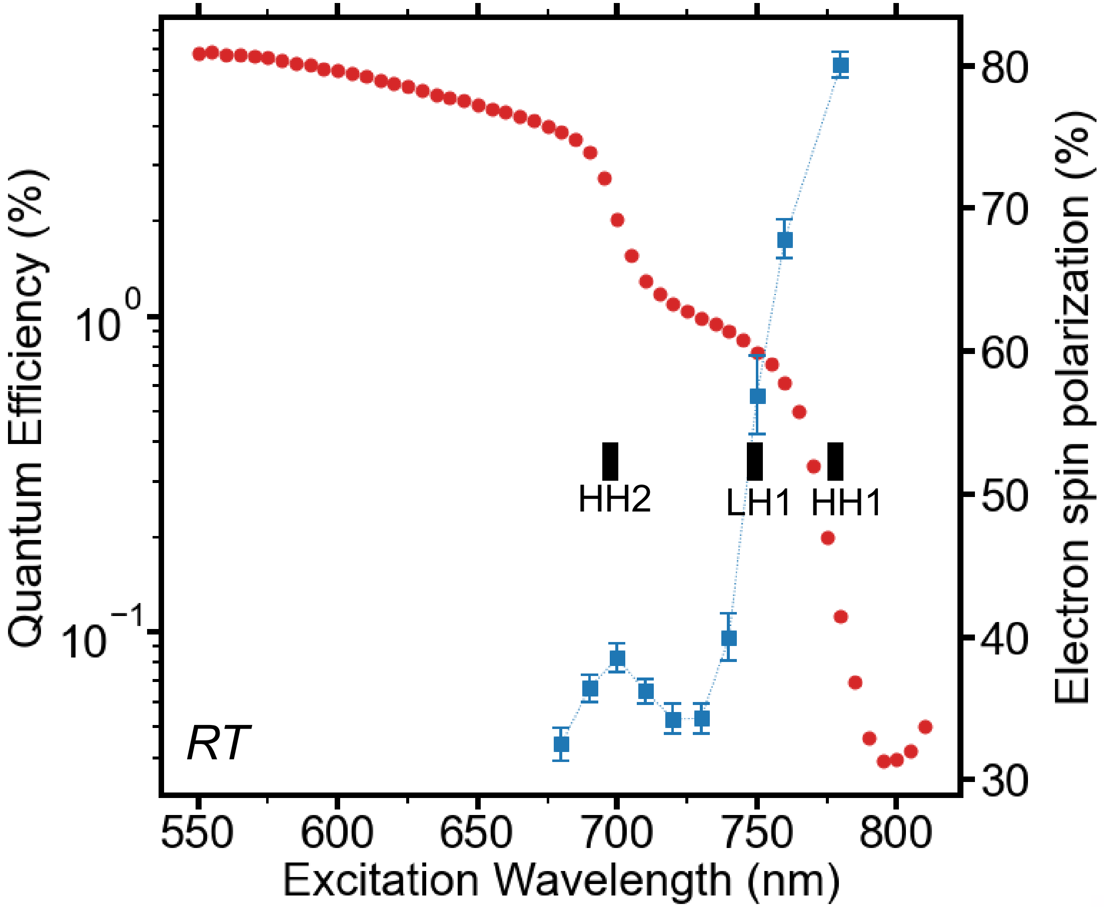
I. J. Fritz, J. F. Klem, M. J. Hafich, A. J. Howard *Appl. Phys. Lett.* **66**, 2825 (1995)

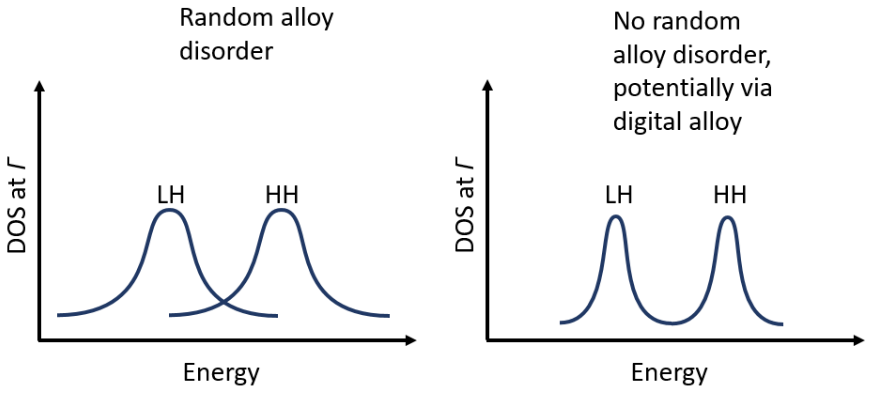
C.S. Wang,…, A.C. Gossard, L.A. Coldren *J. Cryst. Growth* **277**, 13 (2005)

Random Alloy Disorder



- Quaternary well (InAlGaAs) adds random alloy disorder
  - increased bandwidth
  - decreased spin polarization





- ~50 meV hole splitting

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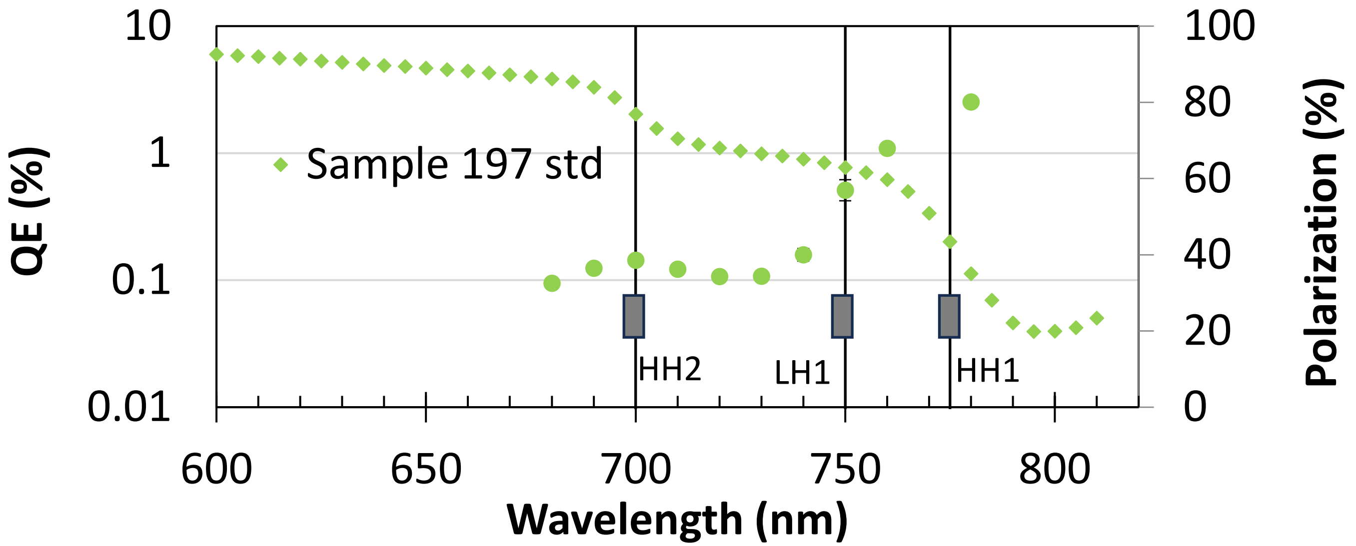
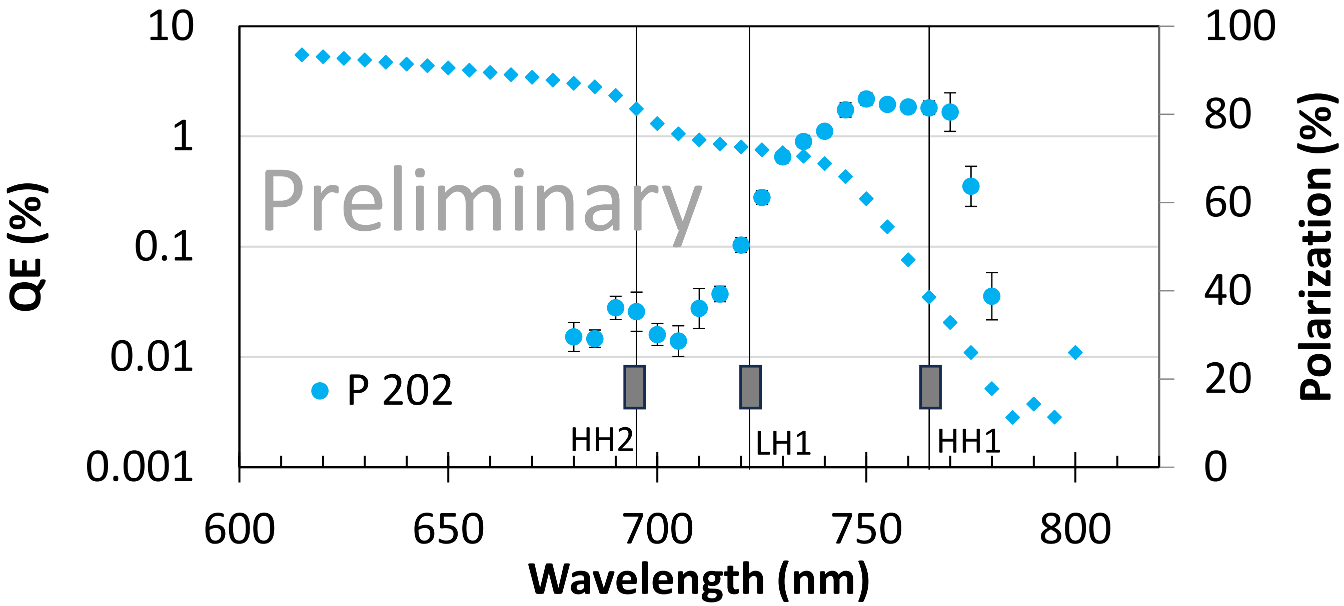
Parametric Studies: Random vs. Digital Alloy



InAlGaAs/AlGaAs

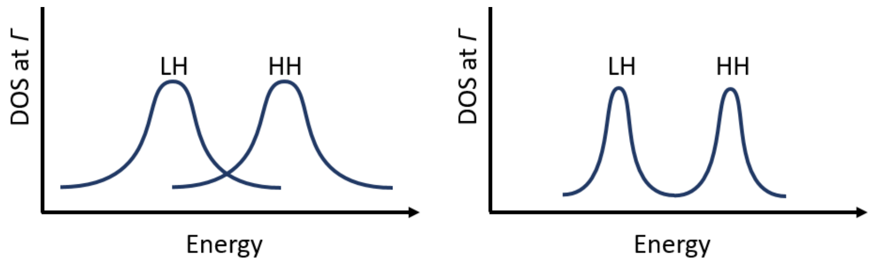
Random alloy

Δ = ~50 meV

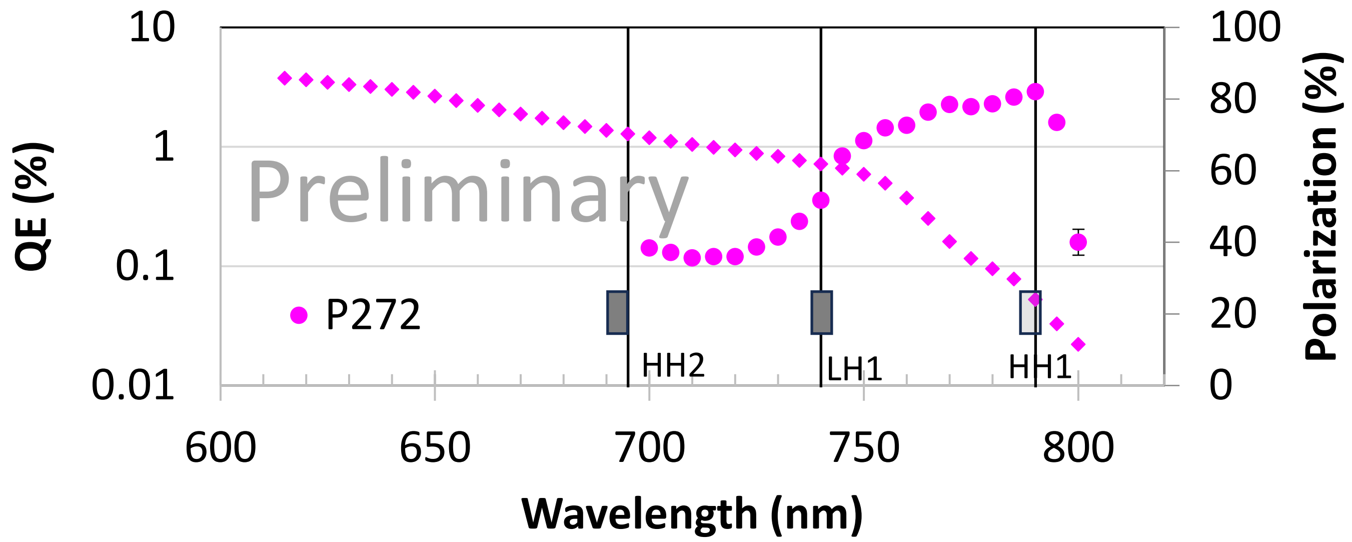


Digital alloy #202

Δ = ~97 meV



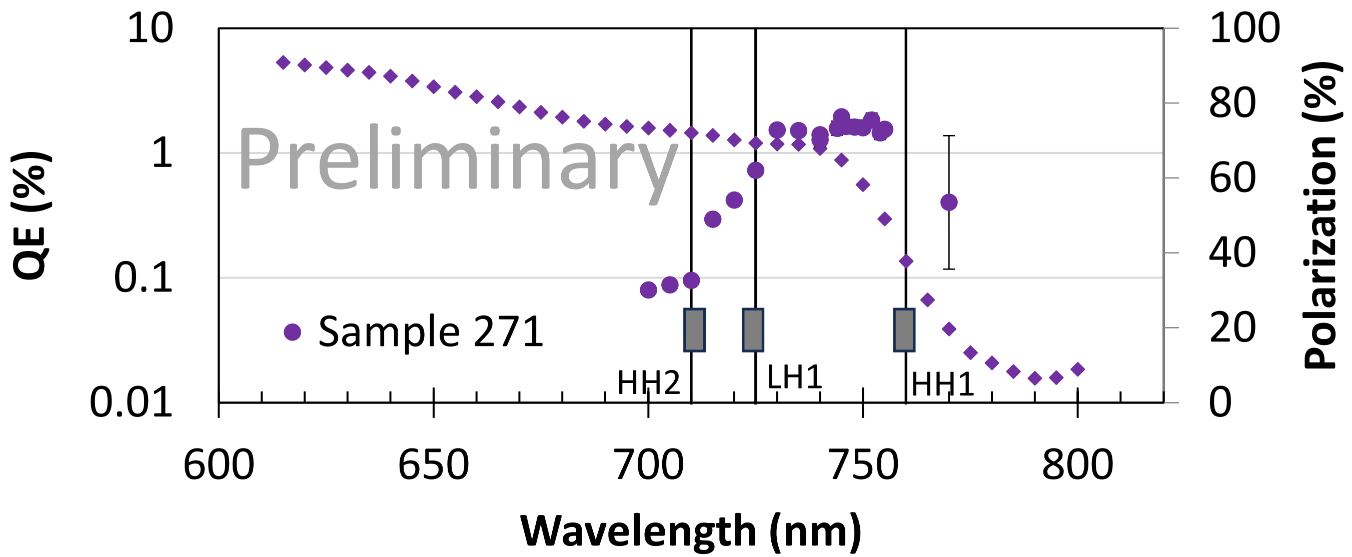
Parametric Studies: More Digital Alloy



Digital alloy #272

Δ = ~106 meV hole splitting

82% Pol, 0.09% QE

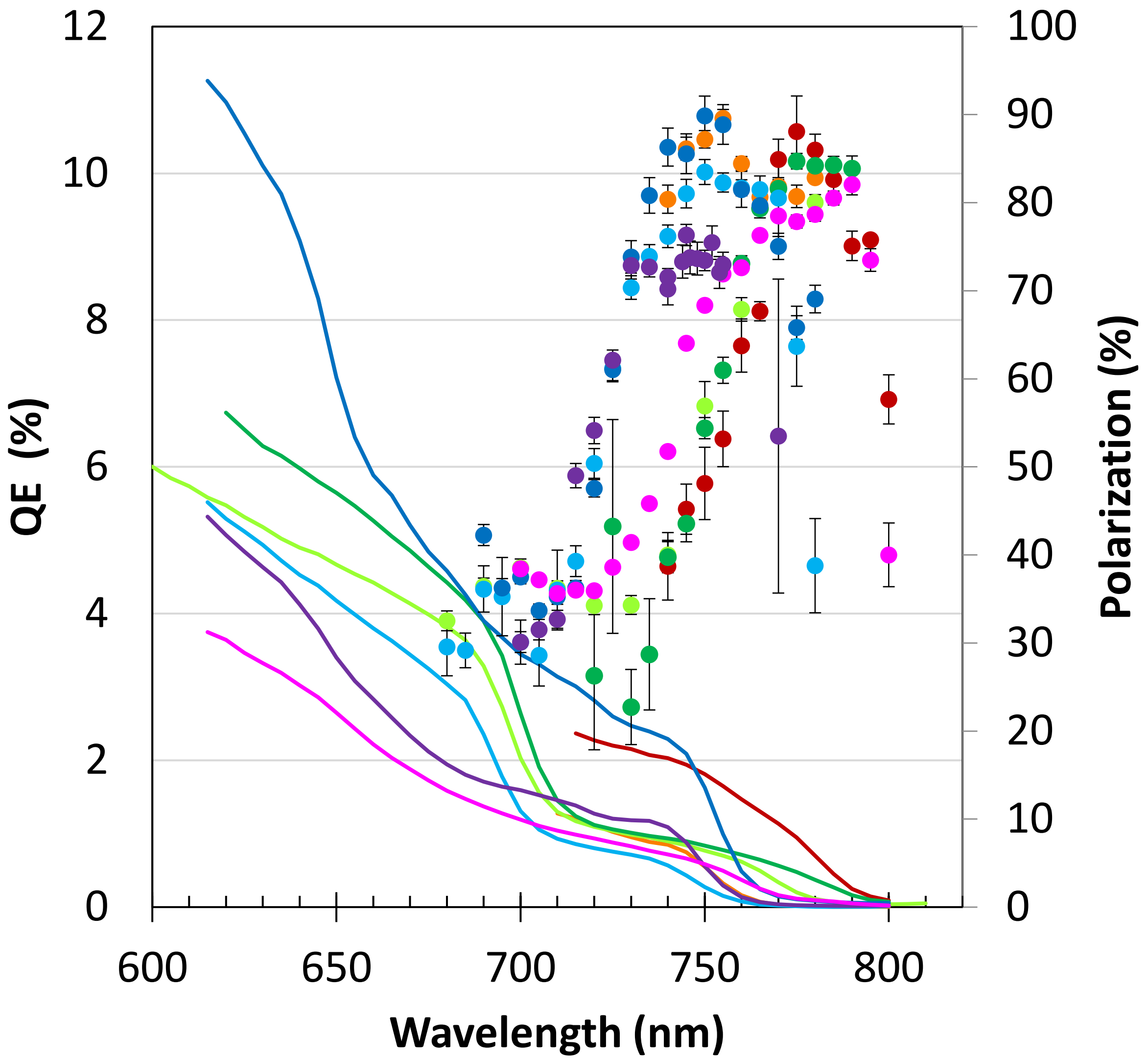


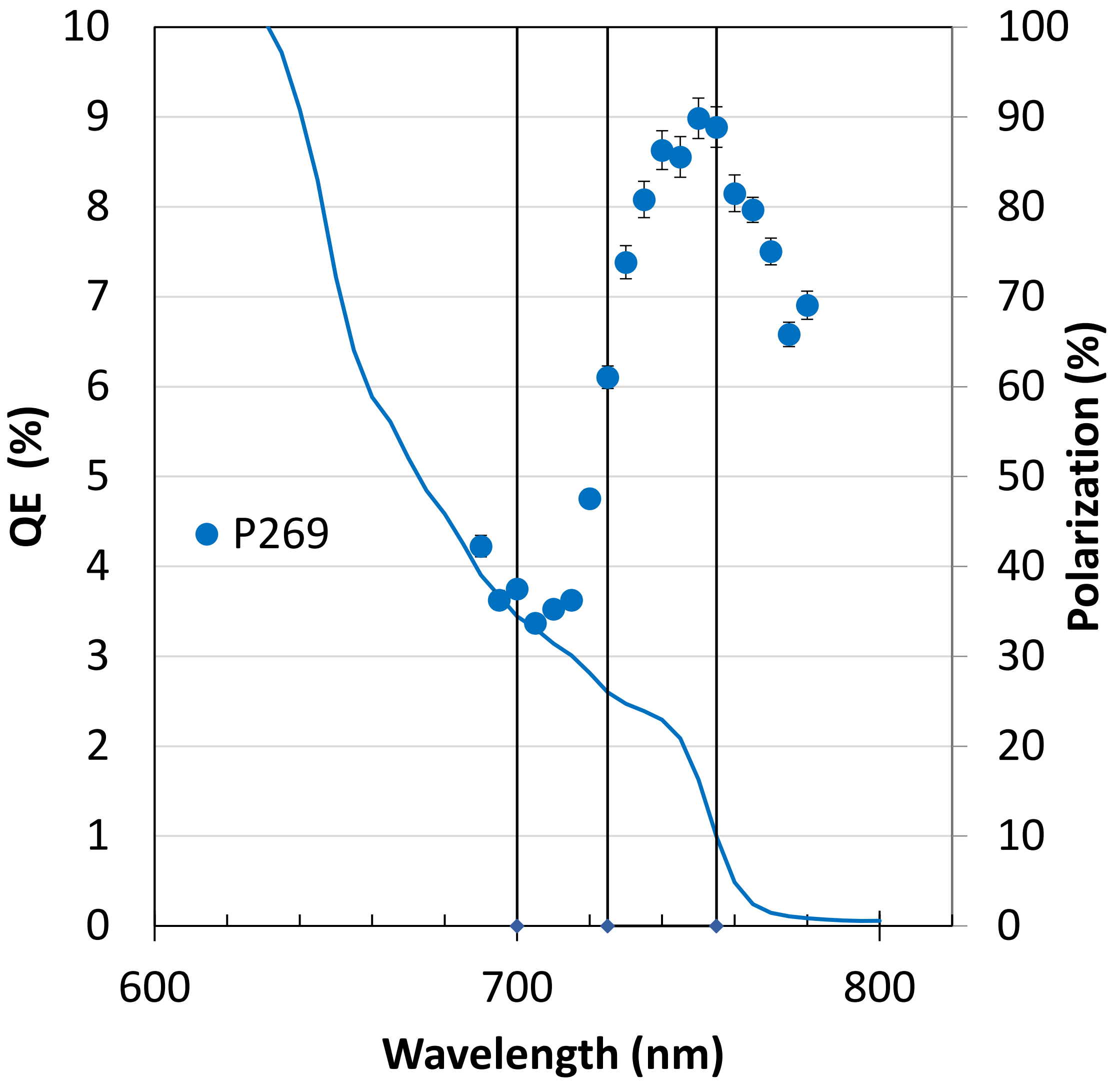
Digital alloy #271

Δ = ~79 meV hole splitting

74% Pol, 0.88% QE

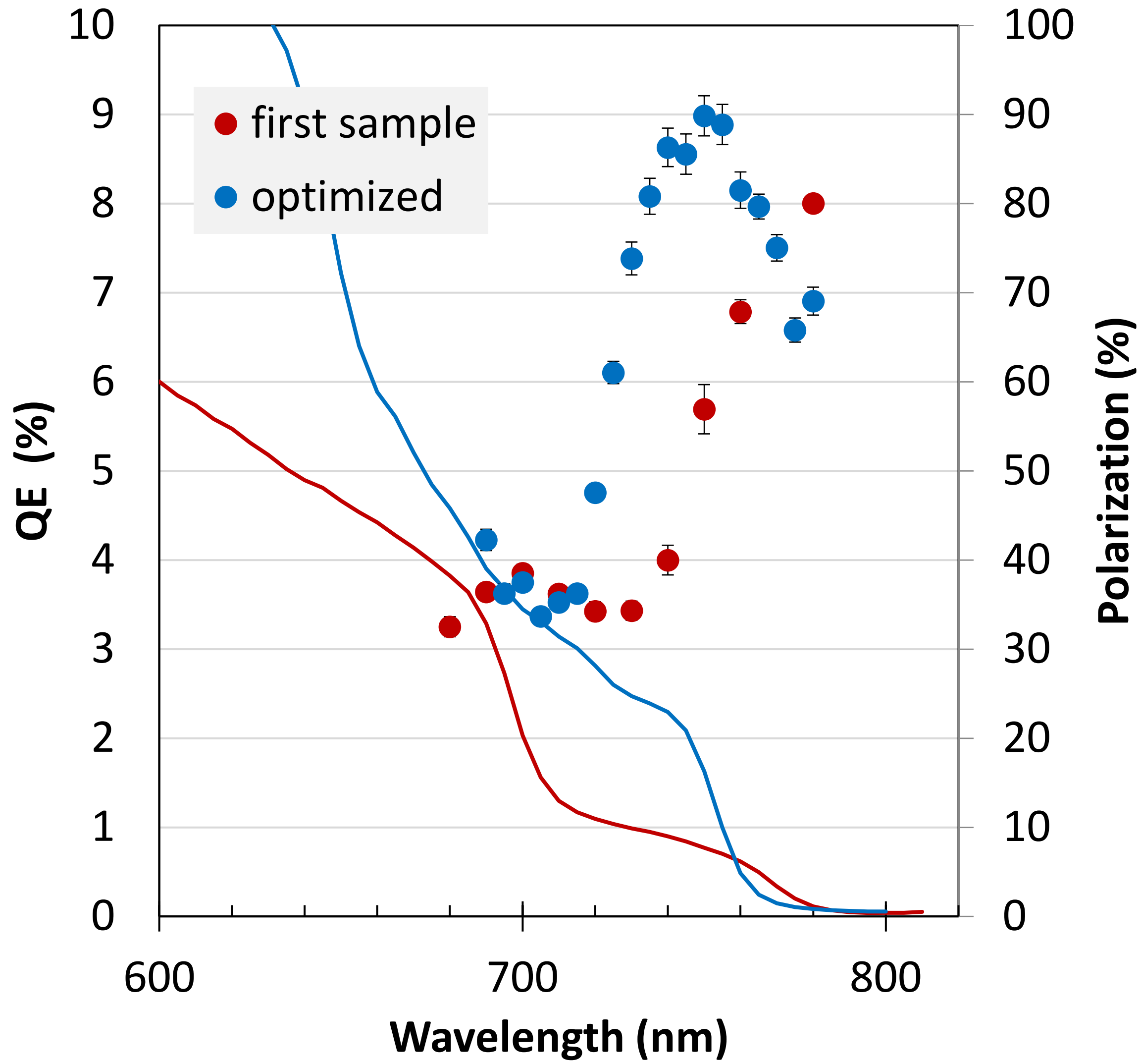
Full parametric study, and most recent "standard" material





Optimized temperature growth

- Polarization
  - P = 89.9 ± 2.3 % ***(93% laser corrected)***
    - Laser polarization only ~96% at 750 nm
- High QE – no DBR
  - QE = 2.08% at 750 nm
- Hole splitting
  - Δ = ~68 meV
  - Random alloy
  - Digital alloying can increase splitting



Project Summary

JLab: Polarimeter working reliably

- Sharing with ODU project
- Measuring final UCSB samples

UCSB:

- Aaron has graduated, new student Yu Wu
- MBE or CBE for GaAs/GaAsP not optimal
- MBE InAlGaAs/AlGaAs has advantages
  - Strain and band gap independent
  - Digital alloying for both SSL and DBR
  - Easy to arsenic cap
  - Standard setup for commercial vendors
- Seeking funding to continue

Many Thanks to Aaron Engle for photocathode growth, characterization and slides, and Chris Palmstrøm for guidance

Backup slides