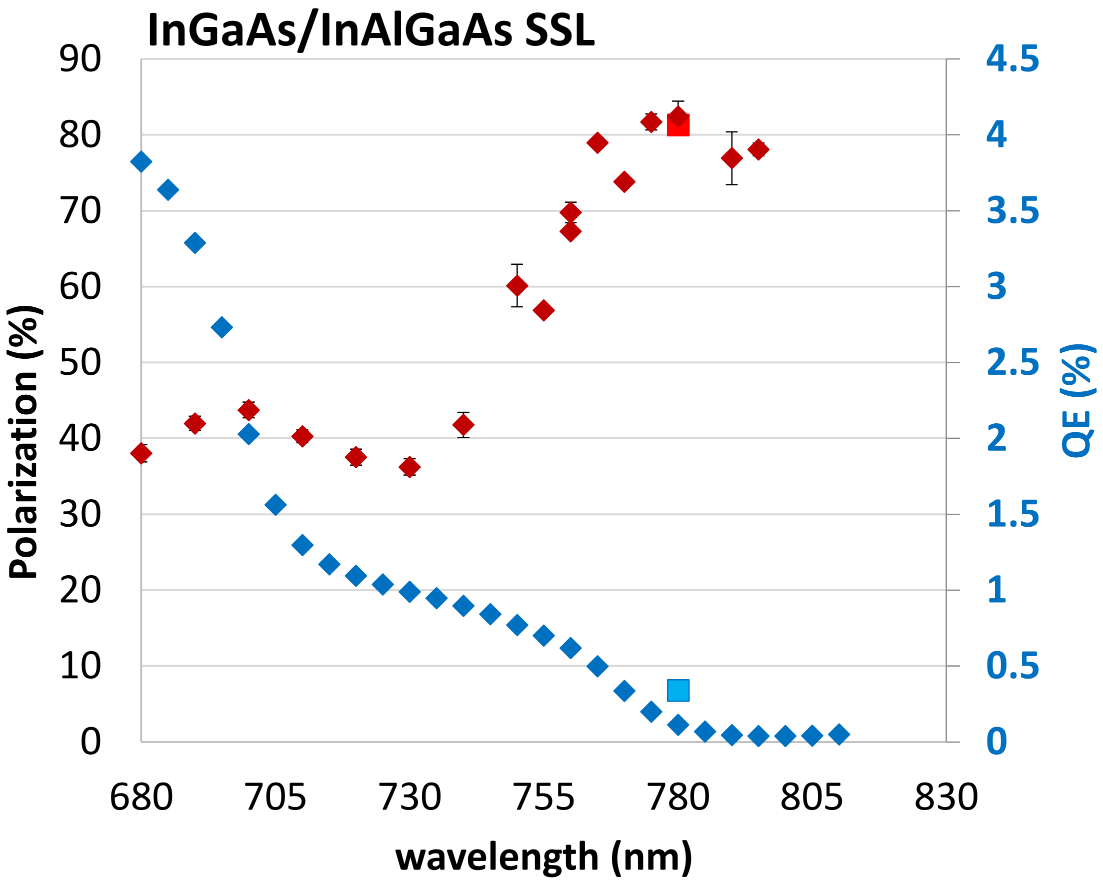
Strained Superlattice photocathodes with CBE

SPIN 2023

25th International Symposium on Spin Physics



Marcy Stutzman, Jefferson Lab

Chris Palmstrøm and Aaron Engel, UCSB

Greg Blume, Old Dominion University

Jefferson Lab

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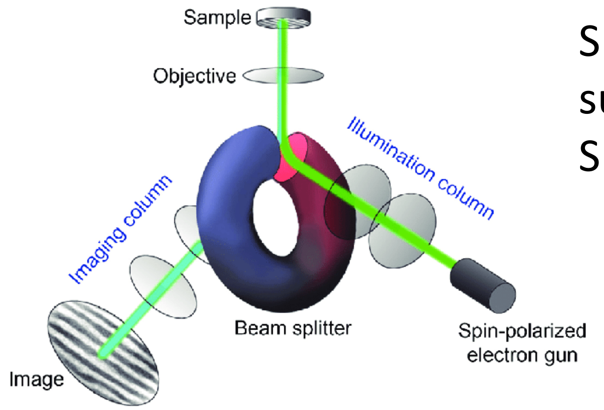
JSA

Why we want polarized electros

25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM

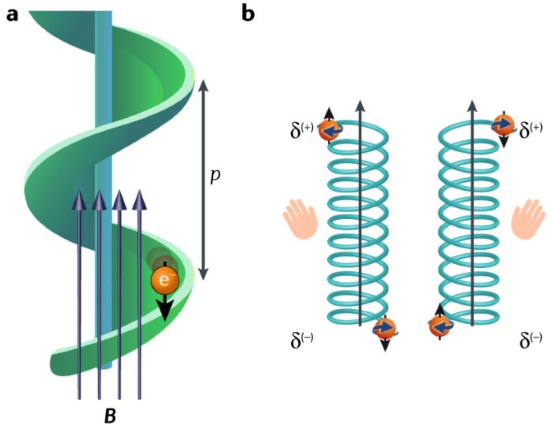
- Nuclear and High Energy physics experiments
- Atomic physics
- Surface analysis: Spin polarized LEEM, TEM, …
- Spintronics



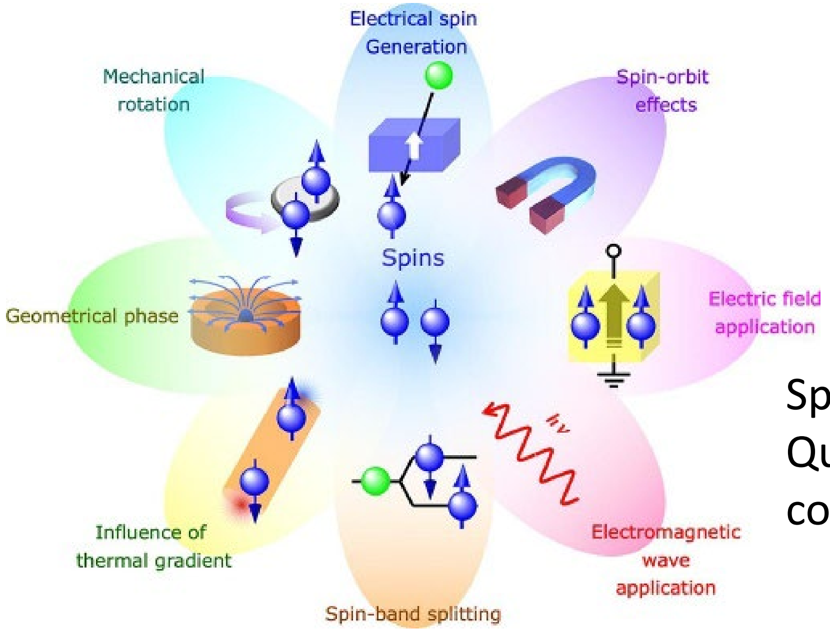
Spin resolved surface analysis: SPLEEM

Rougemaille, N. & Schmid, A., (2010) The European Physical Journal Applied Physics. 50. 10.1051/epjap/2010048.

Chiral Molecules



Naaman, R., Paltiel, Y. & Waldeck, D.H., *Nat Rev Chem* **3**, 250–260 (2019). https://doi.org/10.1038/s41570-019-0087-1



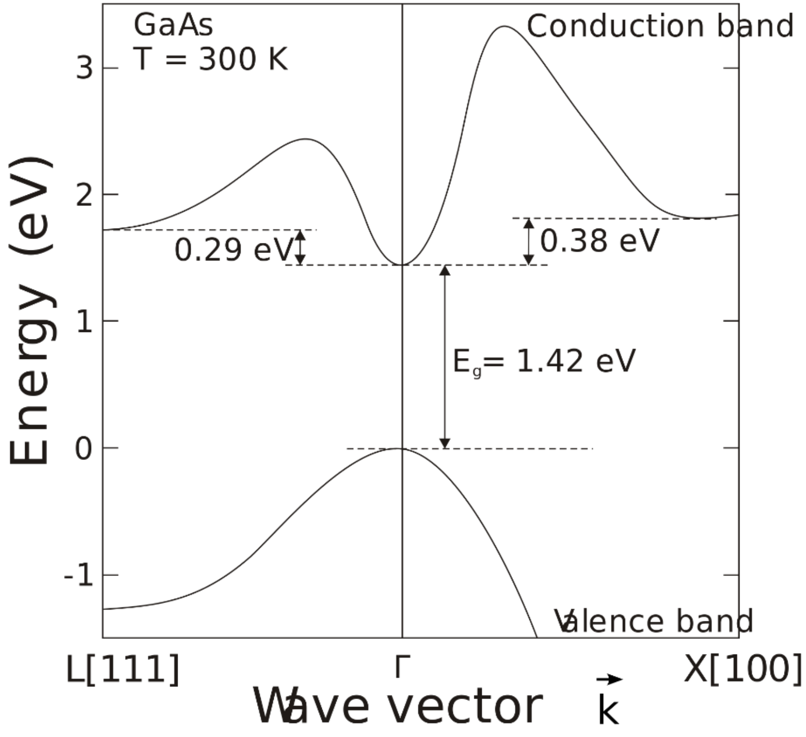
Spintronics, Quantum computing

A. Hirohata et al., Journal of Magnetism and Magnetic Materials, **509**, (2020), 166711. https://doi.org/10.1016/j.jmmm.2020.166711.

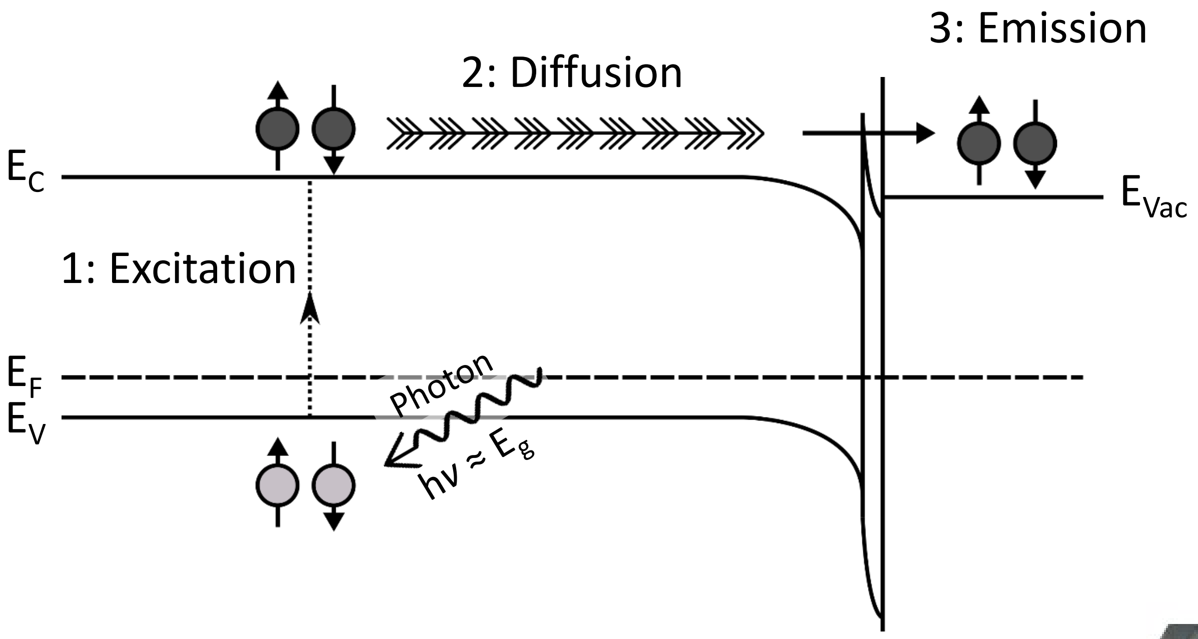
Photoemission from GaAs

Direct Band Gap

- Photoexcitation promotes carriers to conduction band

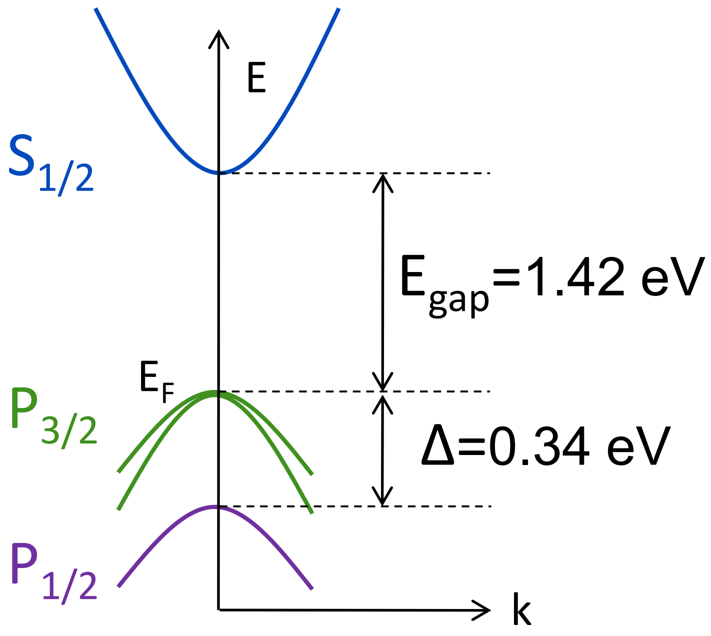


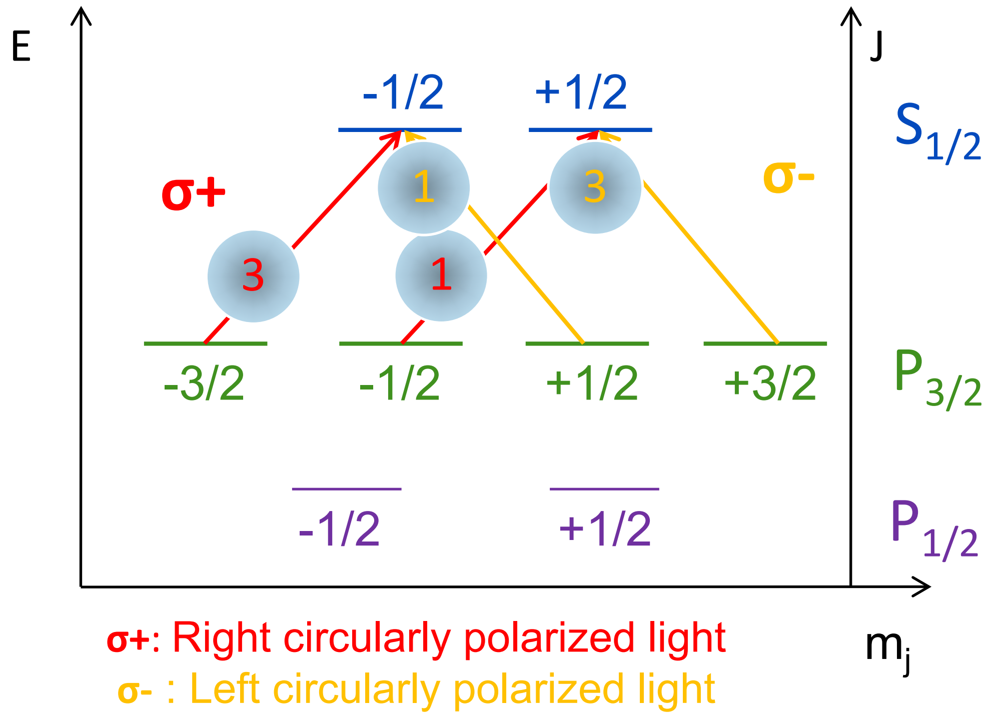
Three step photoemission from GaAs



W.E. Spicer, *Phys Rev* **112**, 114 (1958)
C.N. Berglund and W.E. Spicer, *Phys Rev* **4A,** A1030 (1964)

Spin Polarized Photoemission from Bulk GaAs

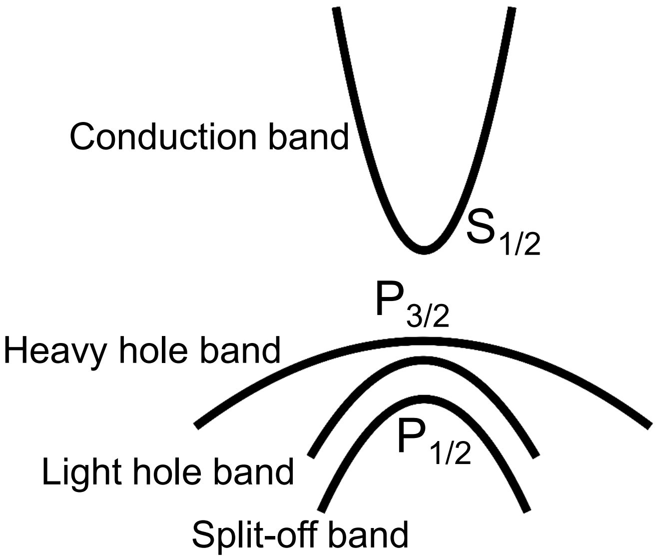


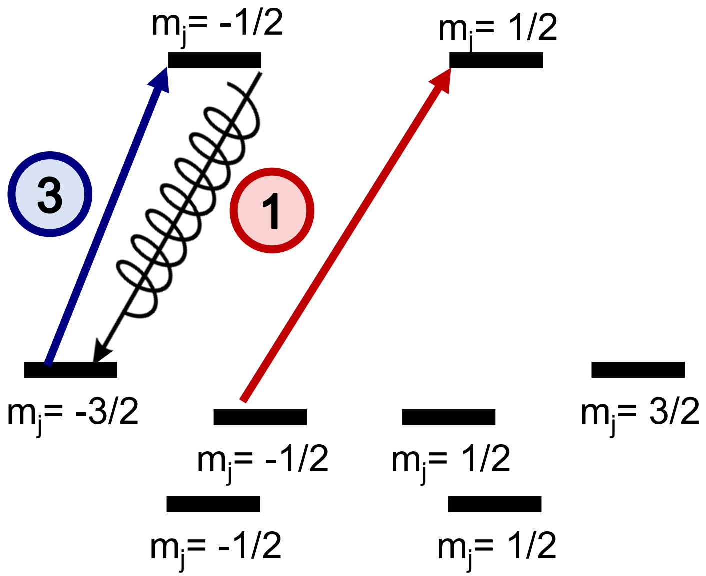


- Laser excitation from $P_{3/2}$ to $S_{1/2}$: $E_{gap} < E_\gamma < E_{gap}+\Delta$
- Electron Polarization: $P_e < \frac{3-1}{3+1} = 50\%$
- Reverse electron polarization by reversing light polarization

How does spin selectivity arise in III-Vs?

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





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

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

η_{ESP} =

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Strained Superlattice Development through SBIR program

- SVT SBIR Partnerships with SLAC or JLab for high polarization photocathodes:
  - Phase 1: 2001, 2005, 2007, 2012, 2013
  - Phase II: 2002, 2008, 2013, 2014
- Compositions
  - **GaAs/GaAsP**
  - GaAsSb
  - AlGaAs/GaAs
  - *Distributed Bragg Reflector*

Parameters

- Quantum Well thickness
- Barrier thickness
- Dopant concentration
- Number of periods

SVT no longer producing

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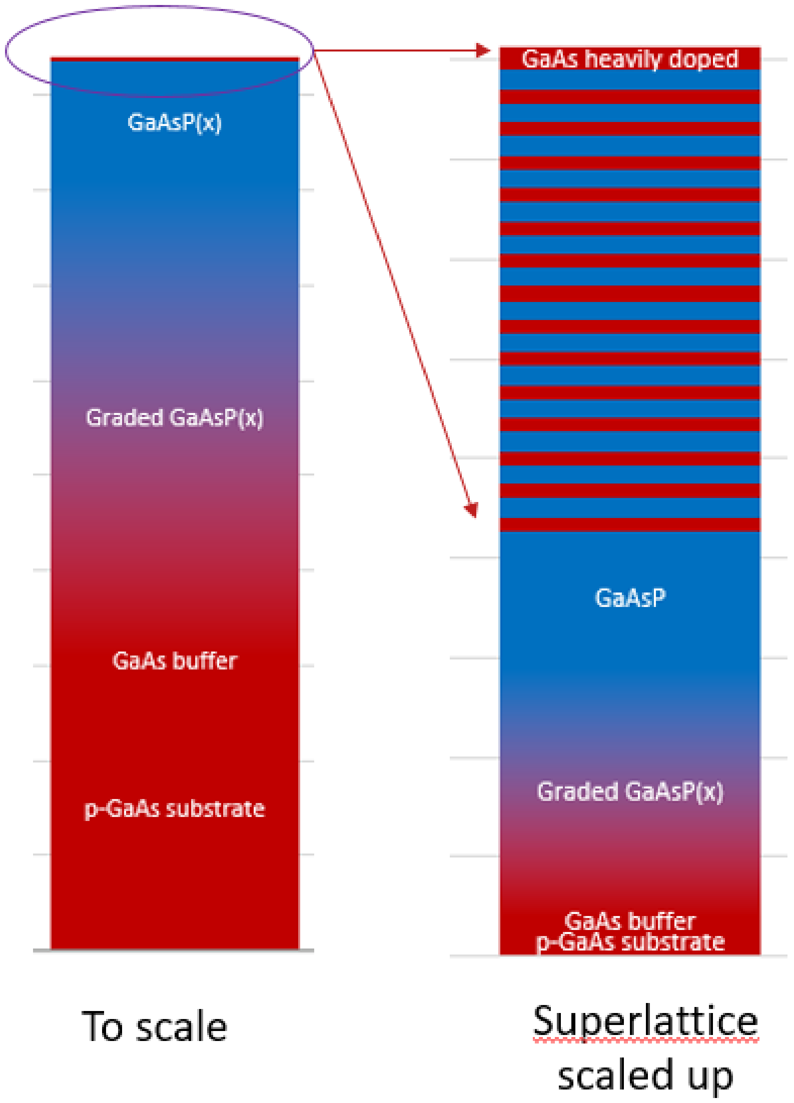
FOA 20-2310: Initiative to restore high polarization photocathode supply



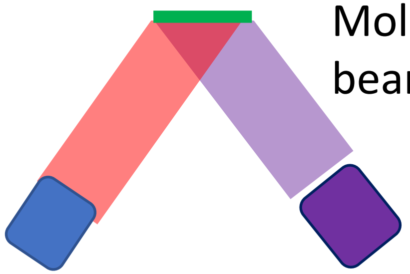
MBE, GSMBE, CBE and MOCVD

MBE

Molecular Beam Epitaxy

elemental As, P, Ga

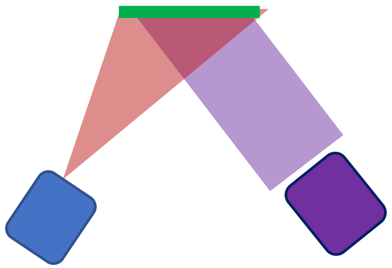
- Pressure ~10^{-8} mbar
- Growth rates ~ 1 μm/hr
- Very precise control



GSMBE

Gas Source Molecular Beam Epitaxy

AsH_3, PH_3, elemental Gallium



CBE

Chemical Beam Epitaxy

AsH_3, PH_3, triethyl gallium (TEGa) or elemental Gallium

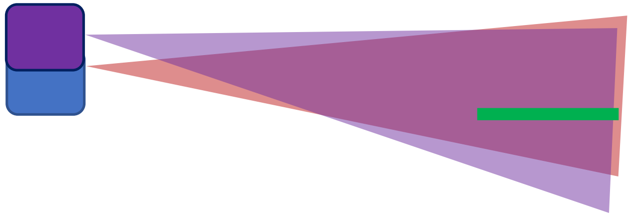
- Pressure <10^{-4} mbar
- Growth rates 0.5-1 μm/hr

MOCVD

Metal organic chemical vapor deposition

AsH_3, PH_3, trimethylgallium (TMGa)

- Pressures >100 mbar during growth
- Growth Rates 10 μm/hr
- Traditionally difficult to get sharp interfaces



Photocathode Growth at UCSB

U California Santa Barbara

Semiconductor Deposition System

- CBE and MBE growth
- ARPES, XPS, STM, LEED, Auger analysis
- Half-metal Heusler Alloys – potential 100% photocathode
- Collaborators for growing GaAs/GaAsP SSL

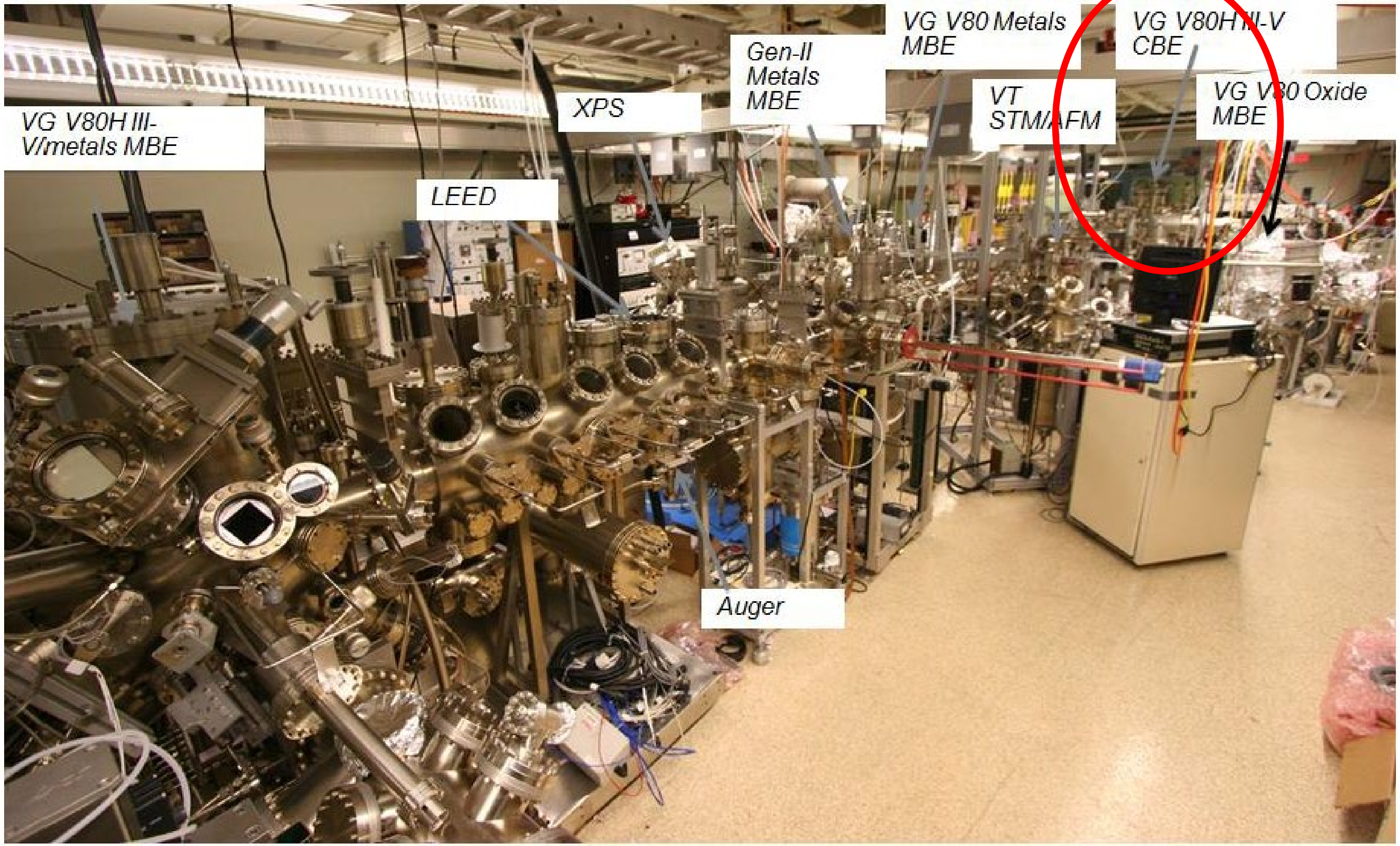
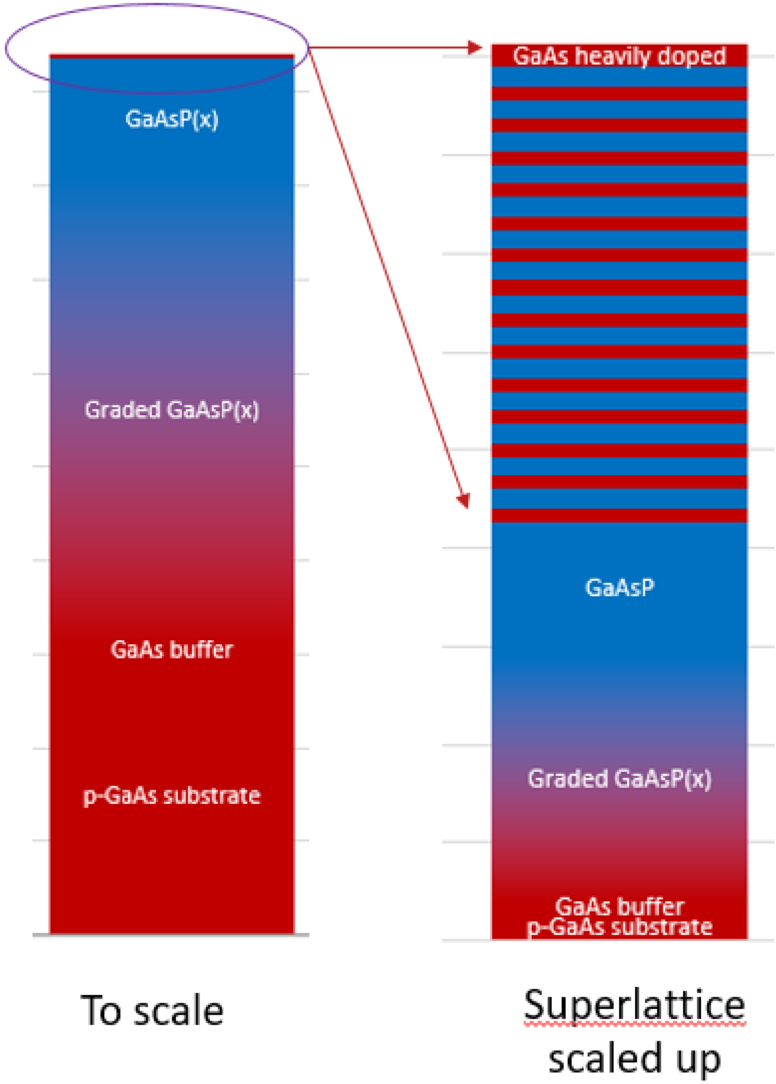


Figure 2 Semiconductor deposition system at Chris Palmstrom's lab at UCSB. The CBE system for the growth of this material is shown at the back and labelled "VG V80H III-V CBE".

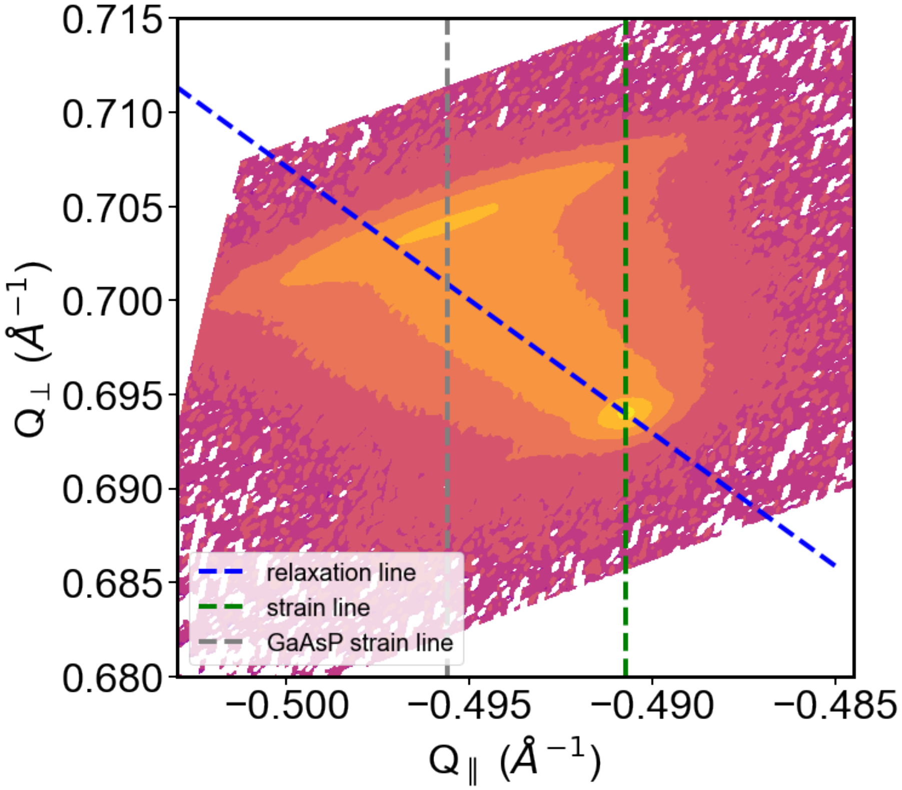
Original Research Plan



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



X-ray Reciprocal space mapping
- Plot of lattice distance during growth
- Graded Layer with minimal strain
- GaAs layer (5-10 nm) strained: lattice constant that of 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
  - Photoemissive Layer
  - Non-emissive lattice mismatched layer

Benefits of InAlGaAs/AlGaAs

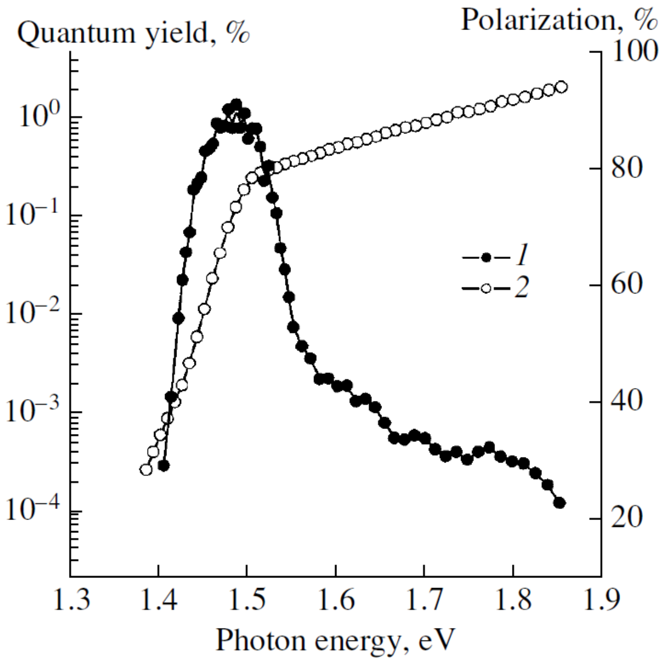
- No virtual substrate necessary
  - AlGaAs almost perfectly lattice matched to GaAs: Grow directly on GaAs
  - No lateral undulations from virtual substrate
- Best cathodes comparable with best GaAs/GaAsP
  - Large sample-sample variations
  - Terminated with GaAs

Easily tunable DBRs

AlAs/AlGaAs for DBR

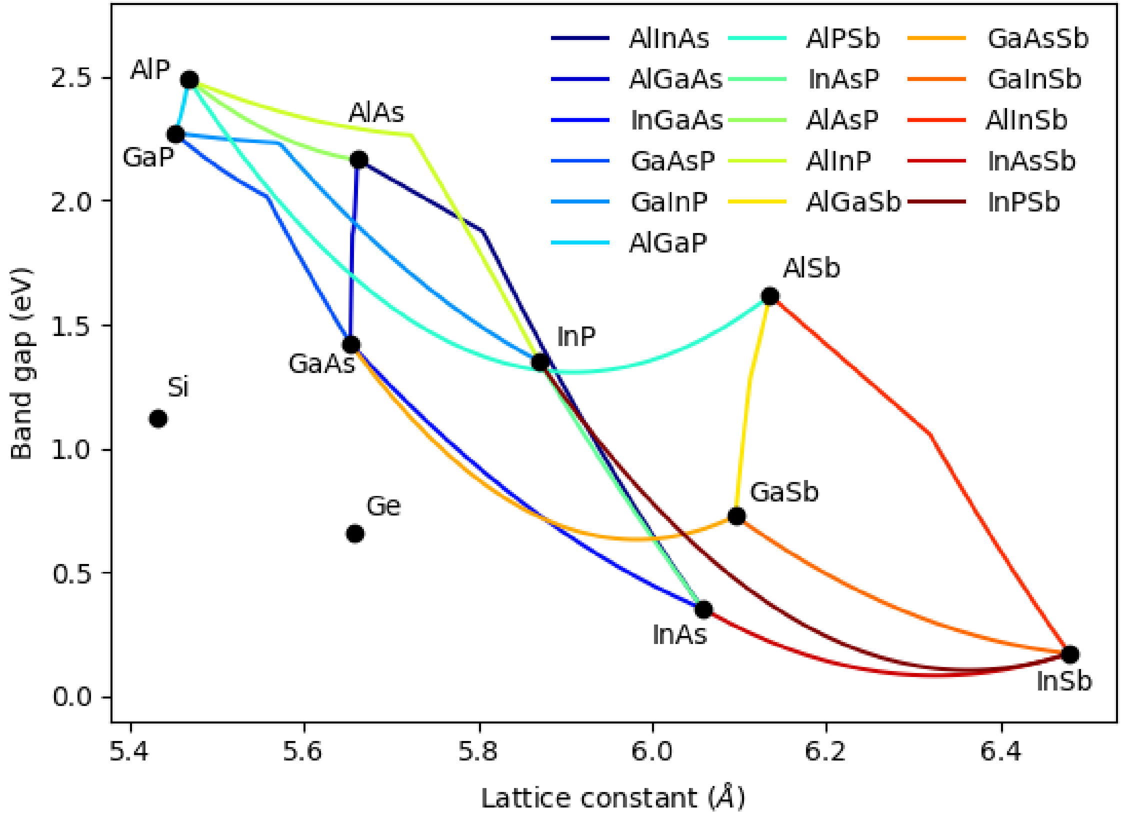
well characterized optical constants

abrupt interfaces



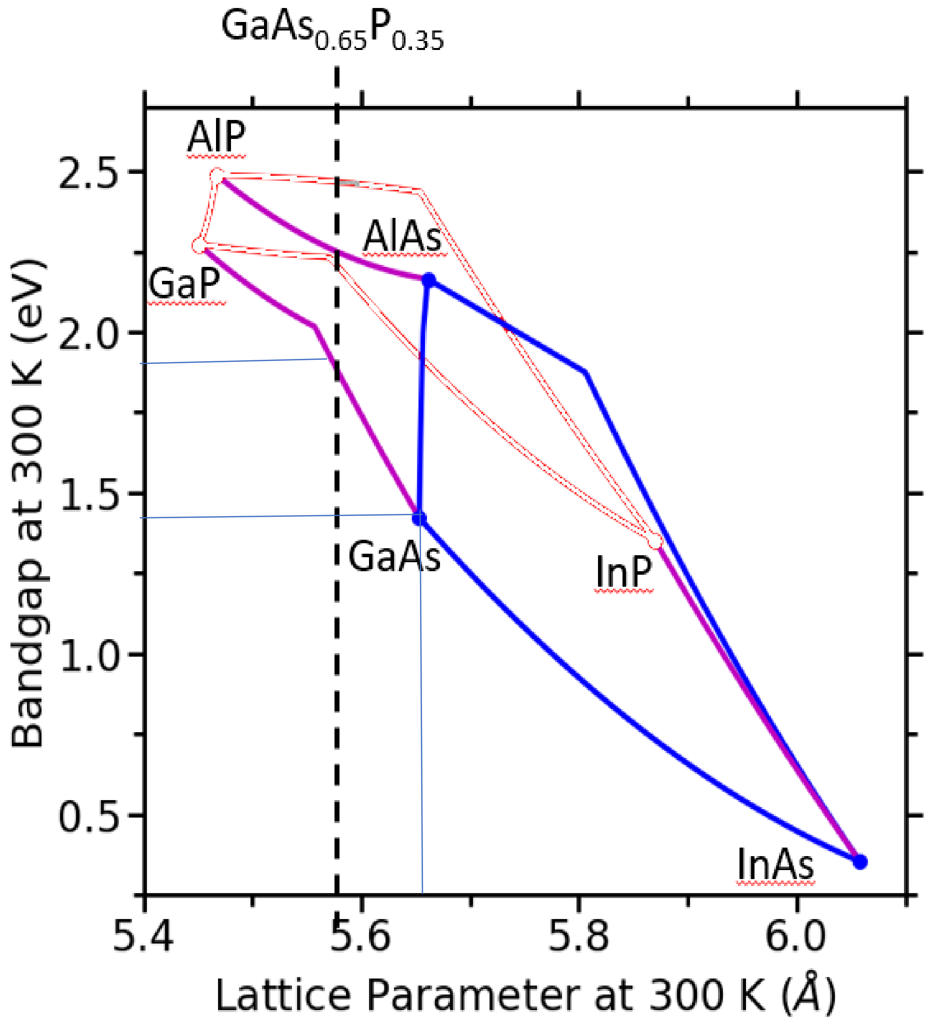
[1] L. G. Gerchikov, *et al. Semiconductors* **40**, 1326–1332 (2006)

Strained well: GaAs/GaAsP



III-IV semiconductor alloys: Band gaps and lattice constants

- Strain and valence band offset coupled: both fixed by virtual substrate



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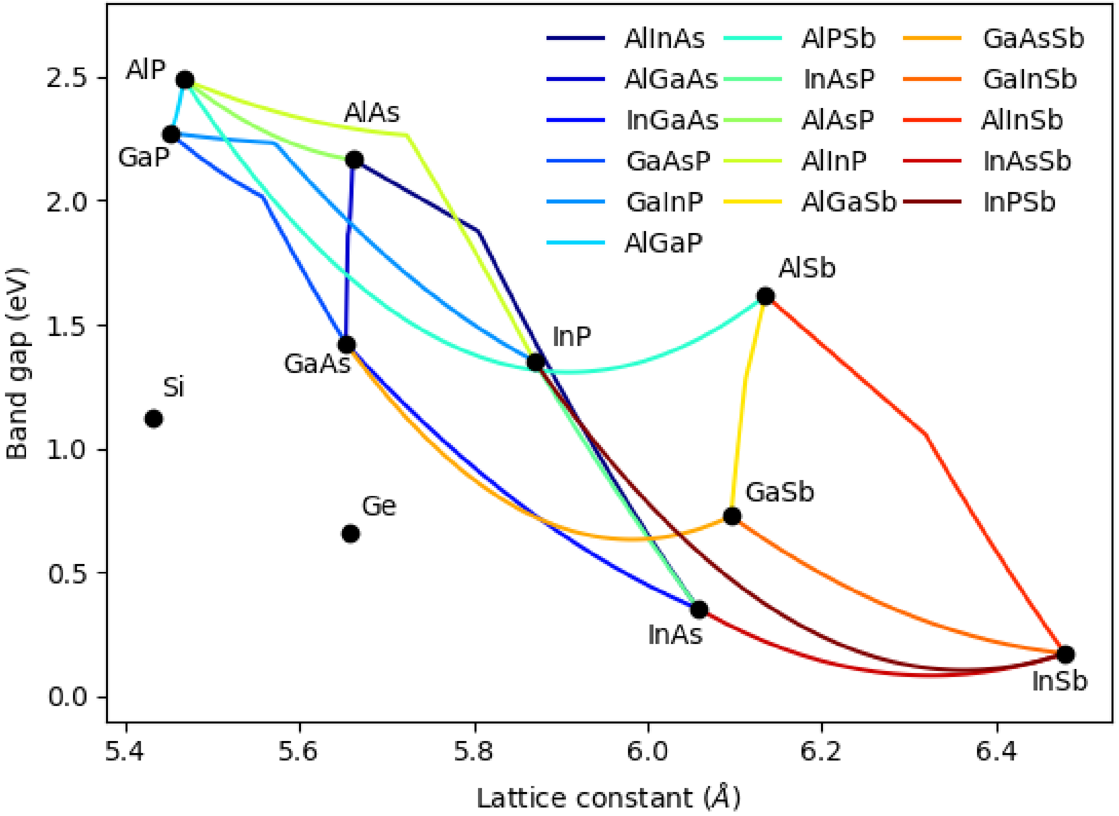
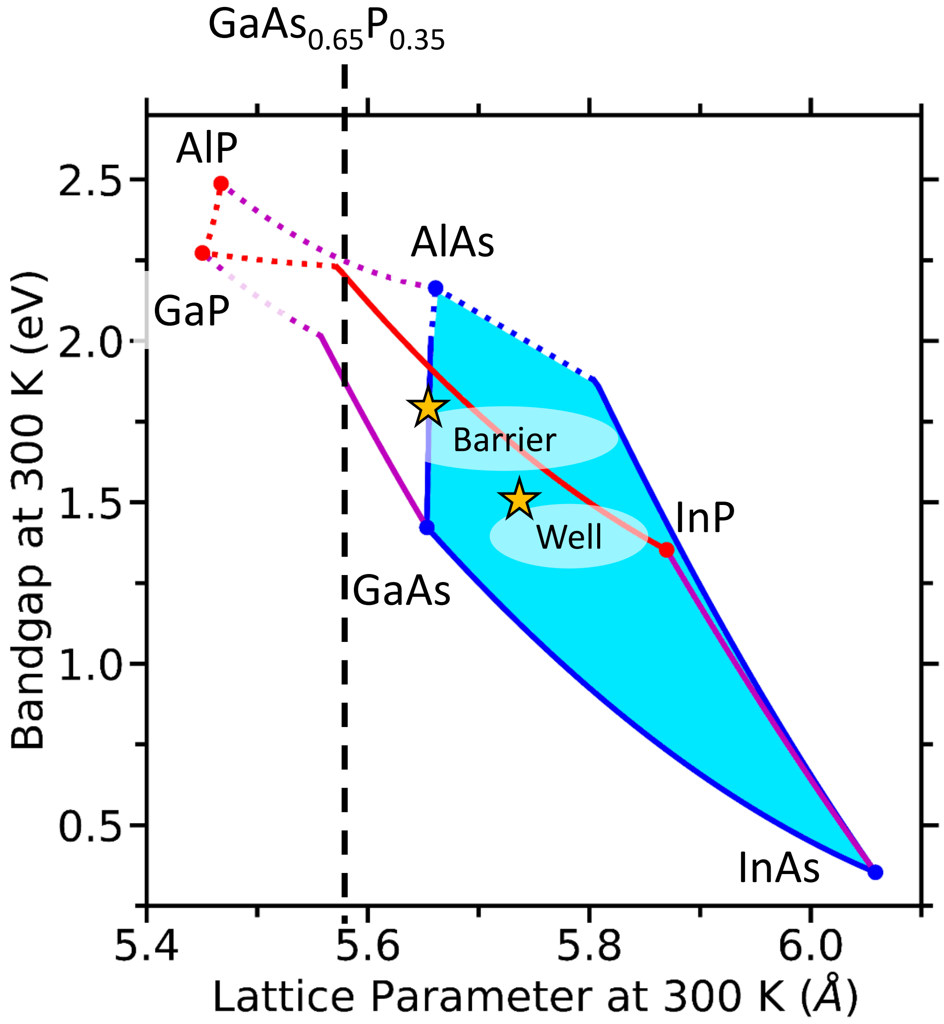
Strained well: InAlGaAs/AlGaAs

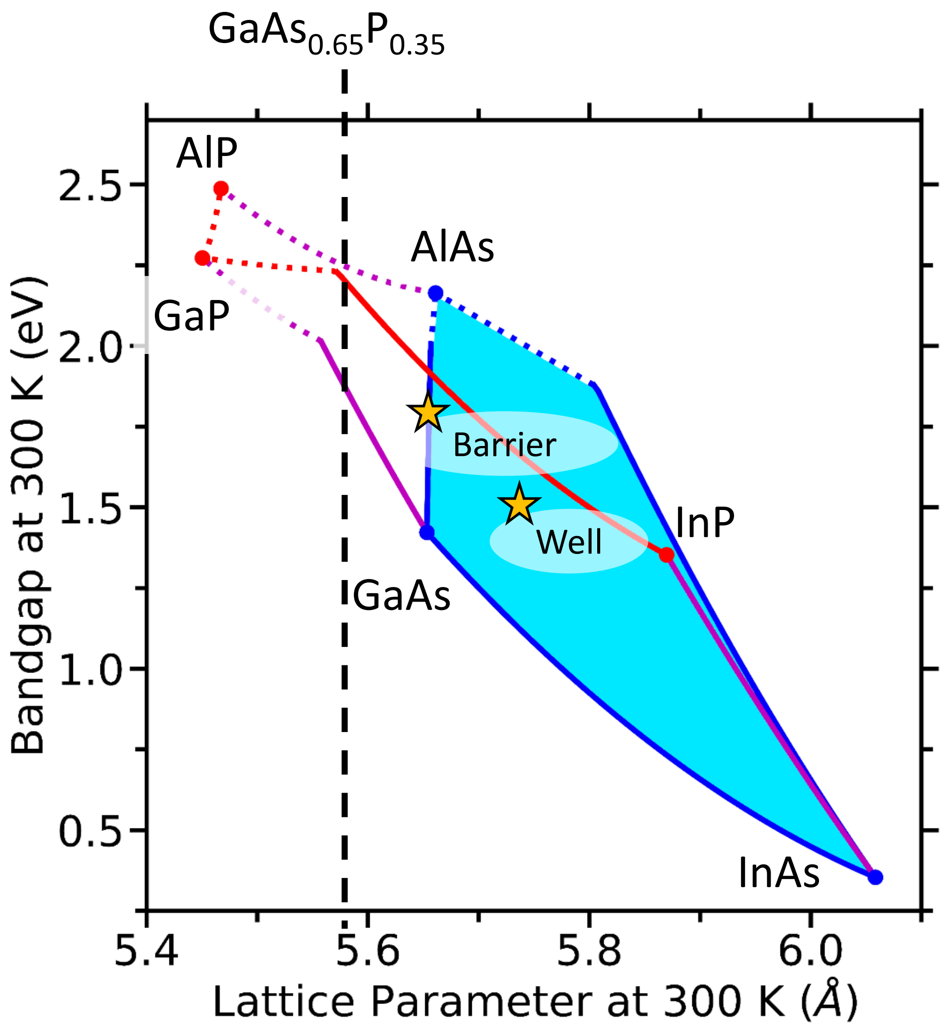


III-IV semiconductor alloys: Band gaps and lattice constants



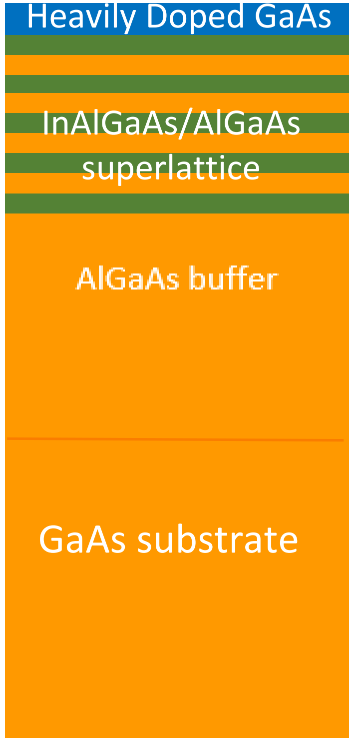
Strained well: InAlGaAs/AlGaAs

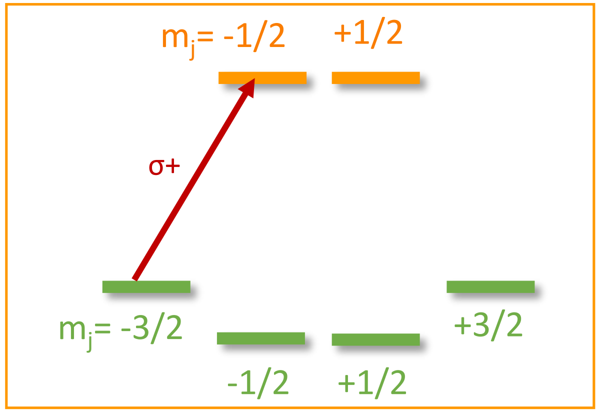
- No virtual substrate necessary!
- Much more band engineering possible
  - Zero conduction band offset [1]
  - Graded barrier heights
- Better growth temperature agreement
- Best reported InAlGaAs/AlGaAs photocathodes are comparable to GaAs/GaAsP
- Easily tunable DBRs in AlAs/AlGaAs system



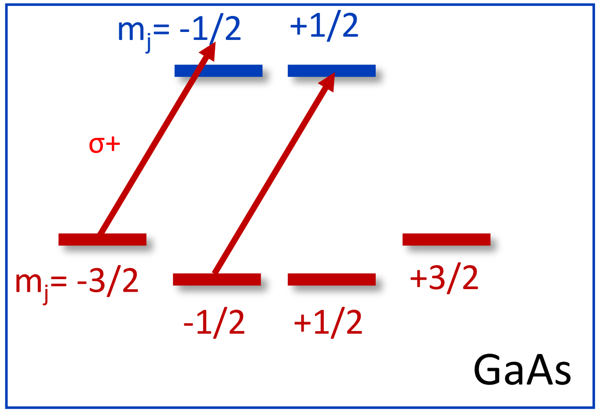
[1] L. G. Gerchikov, *et al. Semiconductors* **40**, 1326–1332 (2006)

Polarized Emission from InAlGaAs/AlGaAs

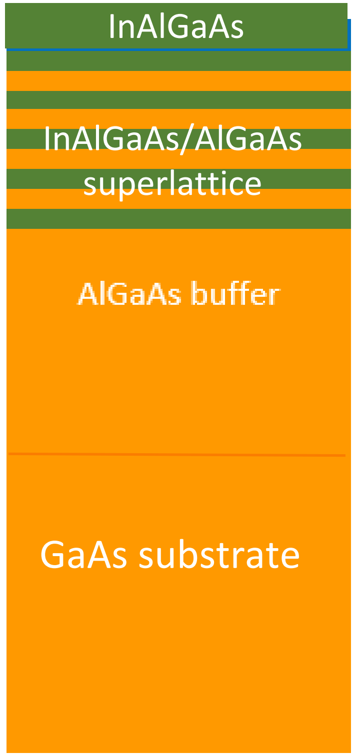




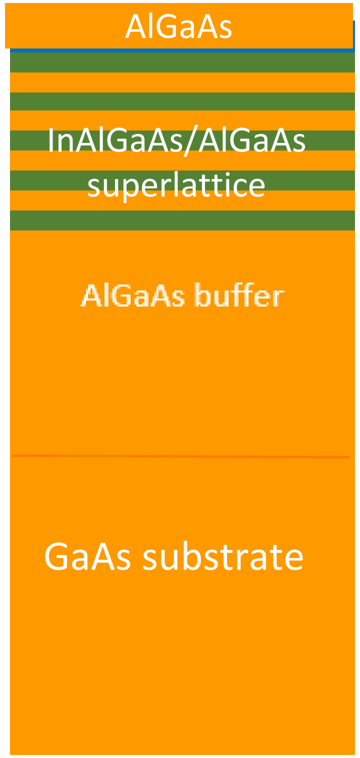
InAlGaAs



- InAlGaAs has larger band gap than GaAs
- Additional photon energy will excite both GaAs bands InAlGaAs/GaAs superlattice



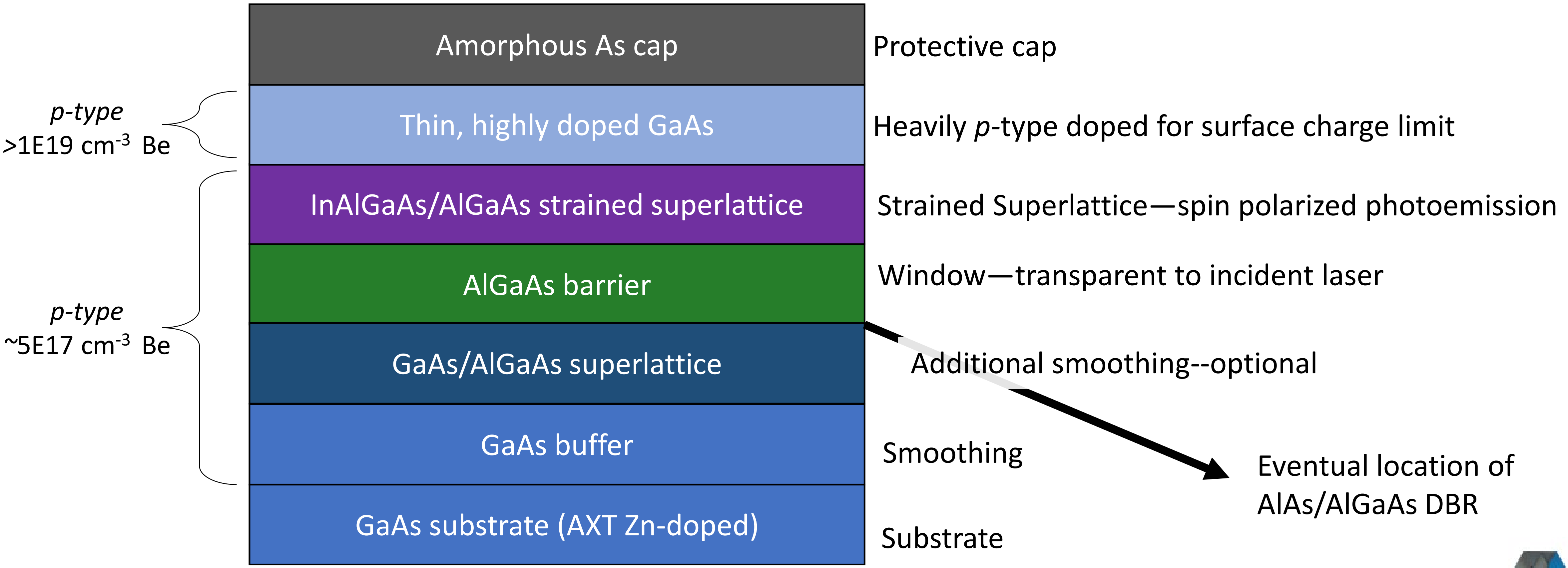
Excites to same channel as superlattice



Completely transparent to pump light

“Excites to opposite channel as superlattice”

UCSB InAlGaAs/AlGaAs Structure



Based on Mamaev et al., Appl. Phys. Lett. 93, 081114 (2008) and
https://www.slac.stanford.edu/pubs/slacpubs/11250/slac-pub-11403.pdf

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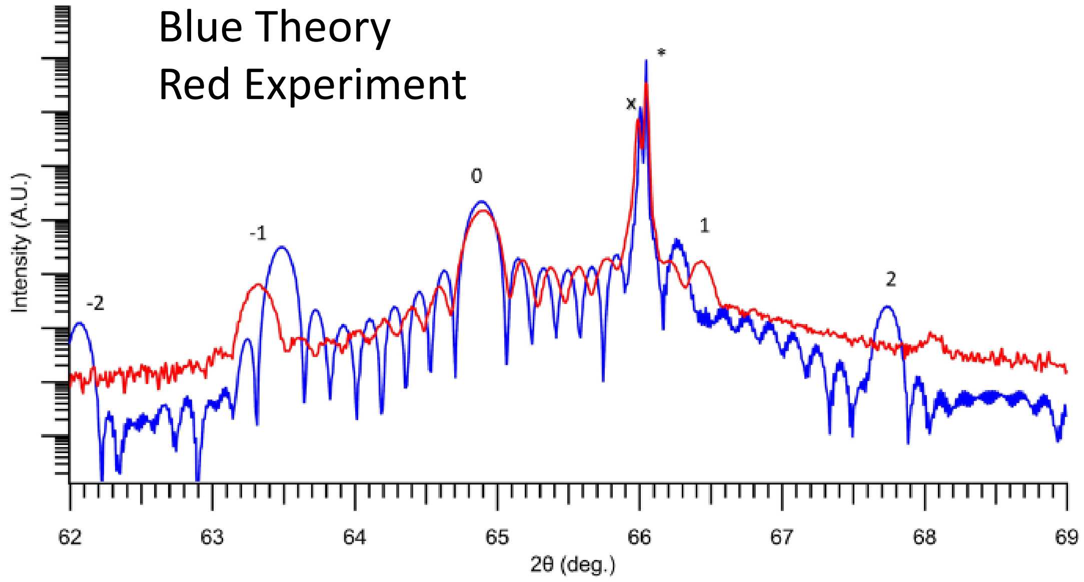
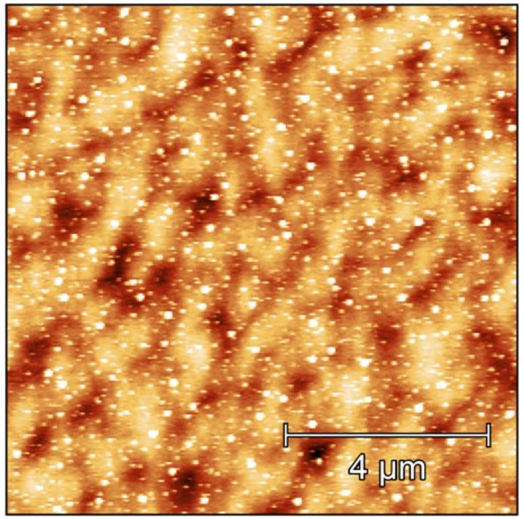
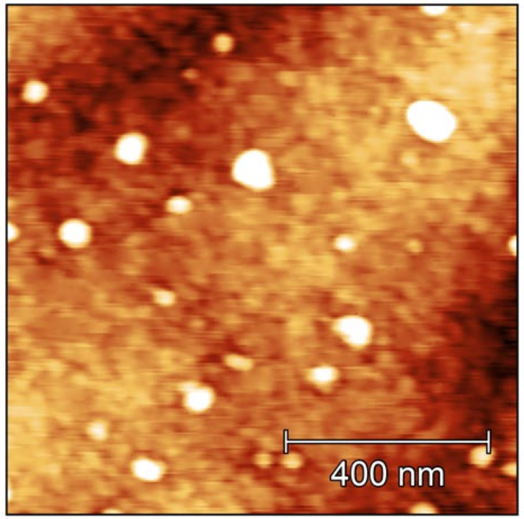
First photocathode

X-ray Diffraction (XRD): Lattice spacing
Blue Theory
Red Experiment







X-ray diffraction measurement of Superlattice
- Fully strained
- Superlattice period good - 8% less than goal

Atomic Force Microscope surface morphology
- Verification of arsenic cap coverage
- Some excess As –
  will desorb in first heat cycle

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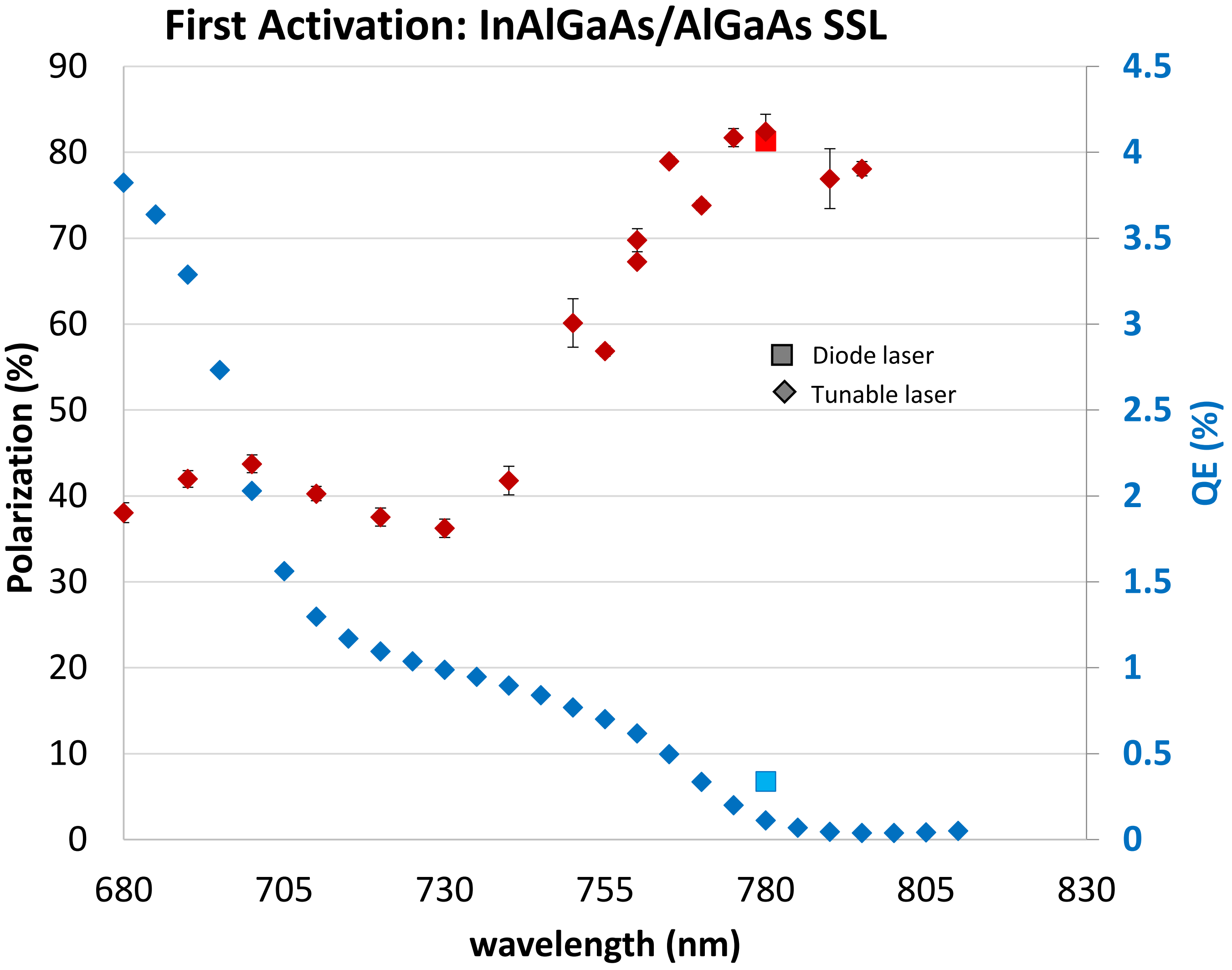
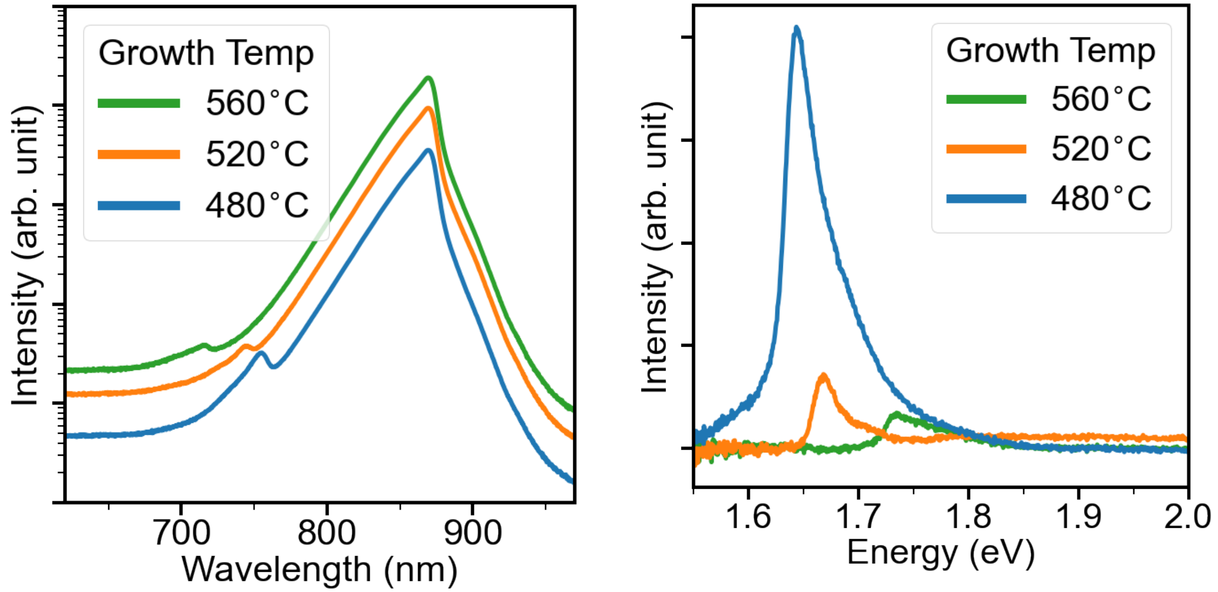
First Activation InAlGaAs/AlGaAs SSL

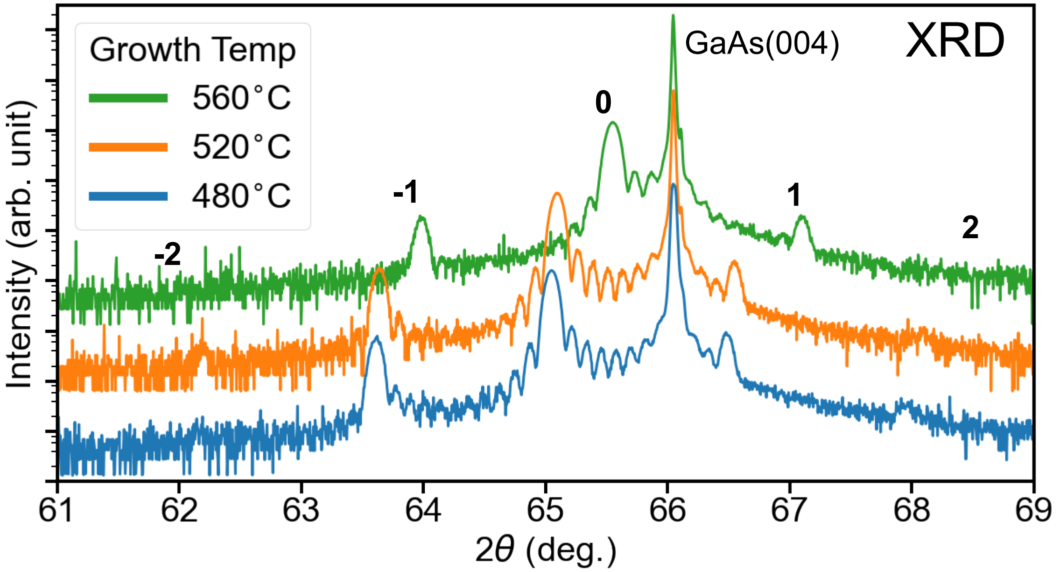


Max Polarization > 82.5%
Max QE at max: 0.34%

Vary Growth Temperature for InAlGaAs/AlGaAs

Photoluminescence



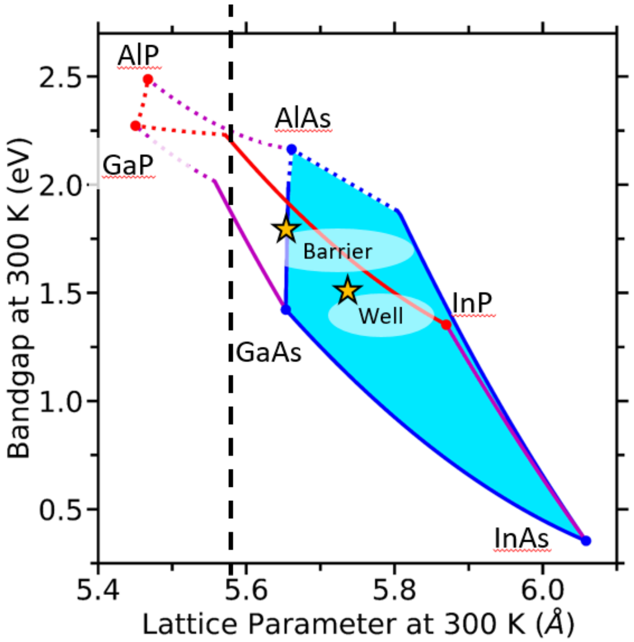


- Lower temperature growth produces more intense PL from superlattice

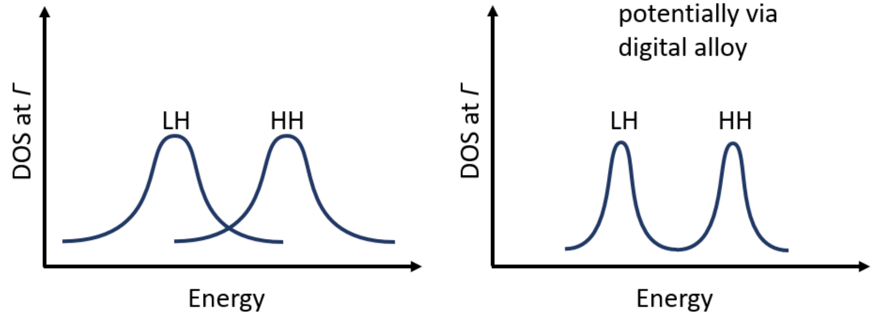
- XRD shows more visible fringes in films grown at lower temperature, indicating sharper interfaces

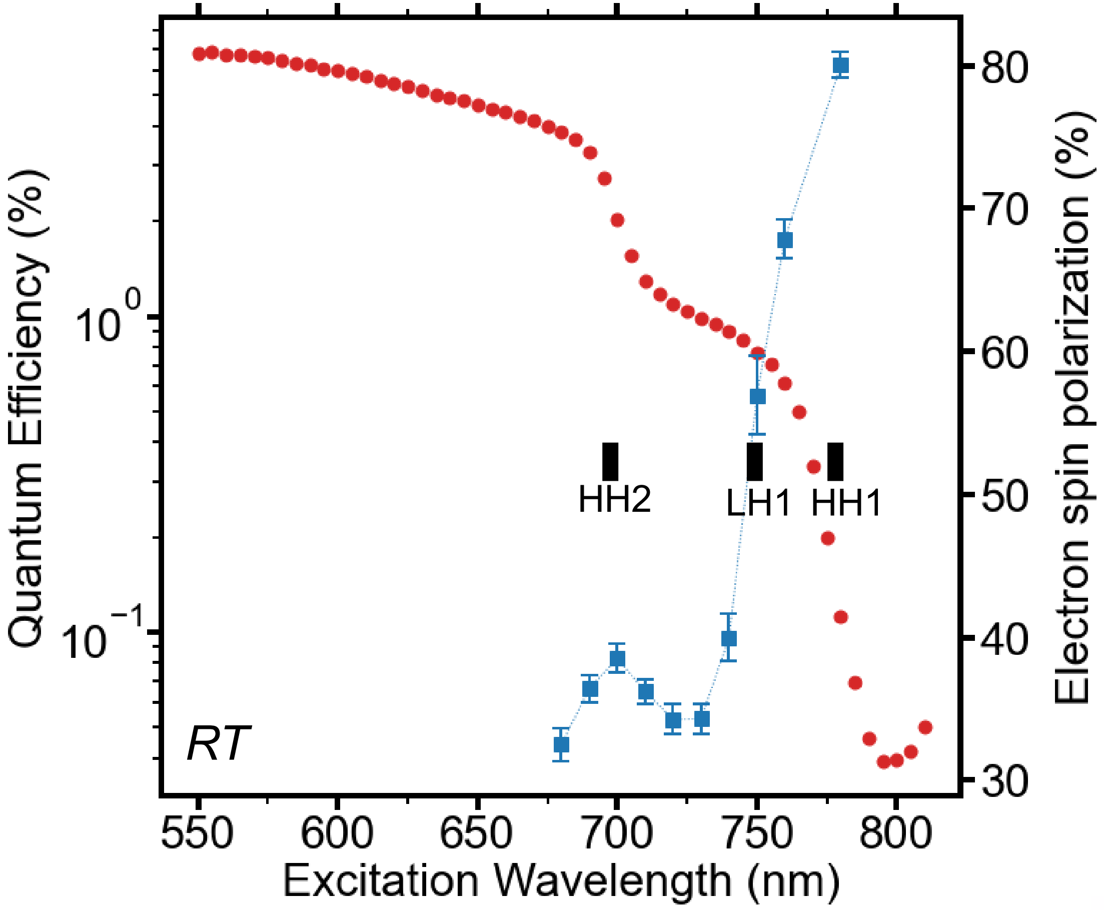
520°C sample tested, 480 and 560°C in the queue

Random Alloy Disorder



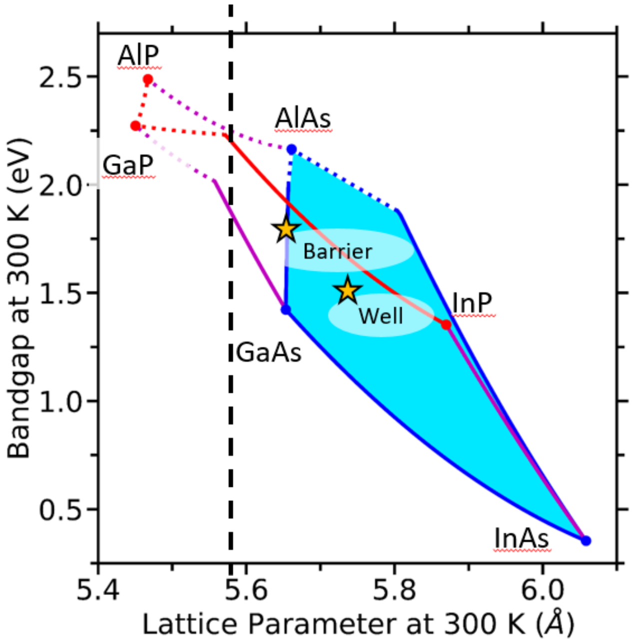
- Quaternary well (InAlGaAs) adds random alloy disorder
  - increased bandwidth
  - decreased spin polarization





- ~50 meV hole splitting

Random Alloy Disorder



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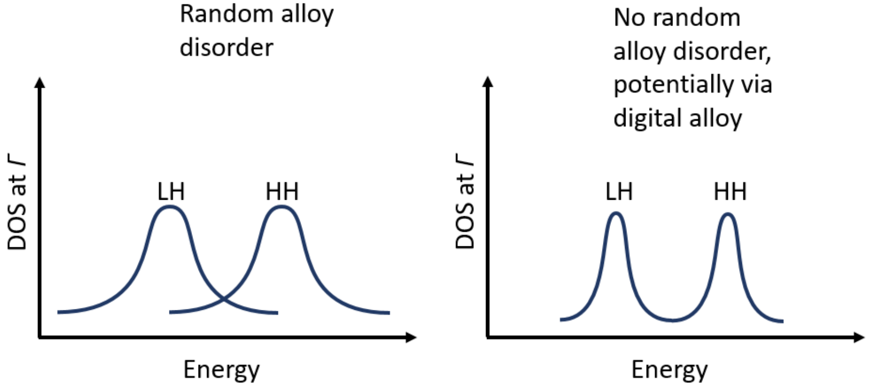
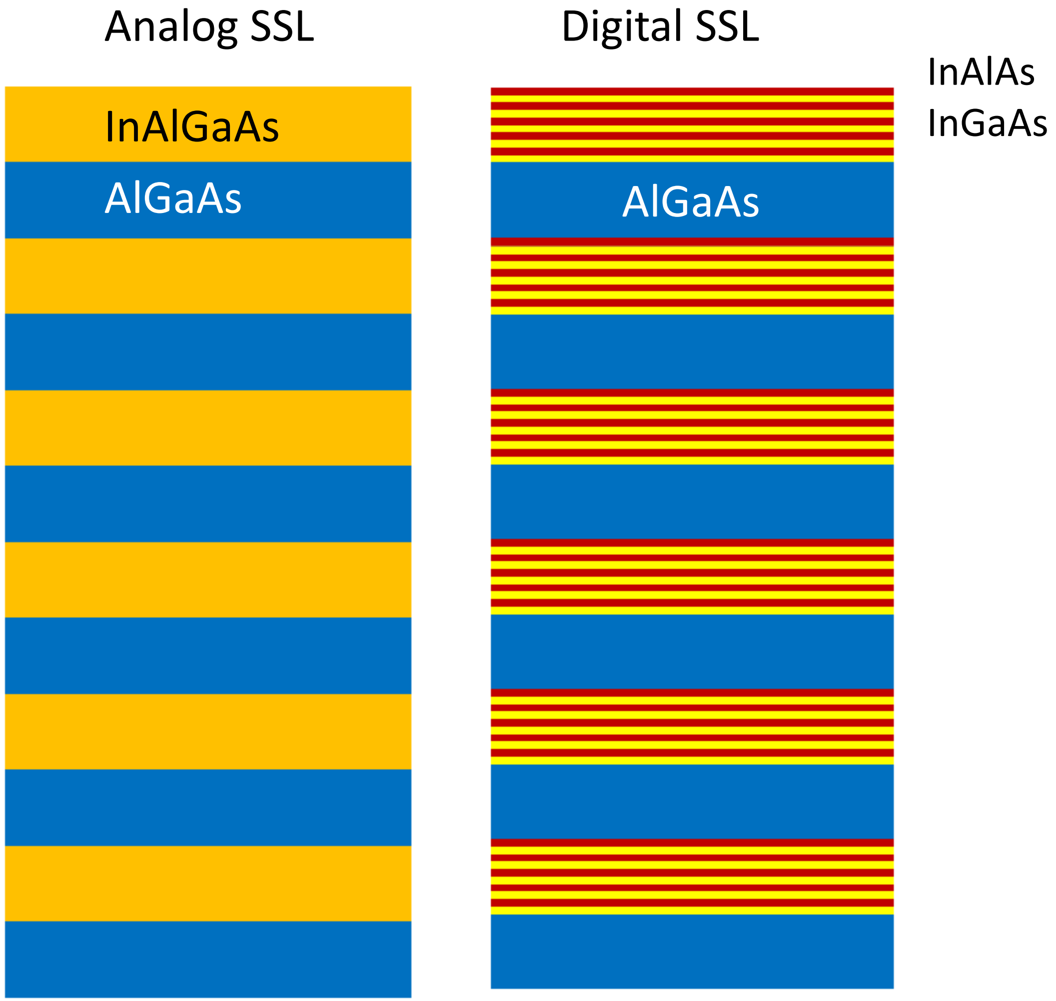
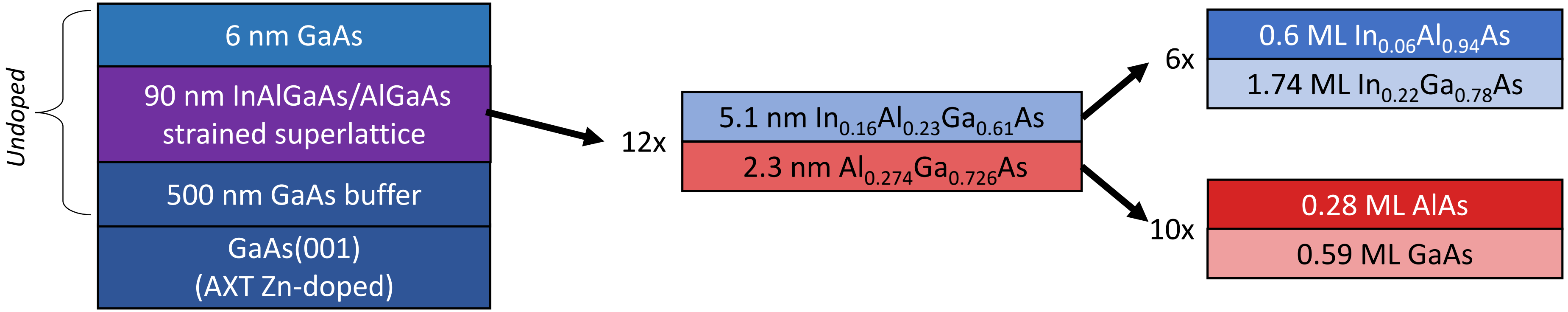
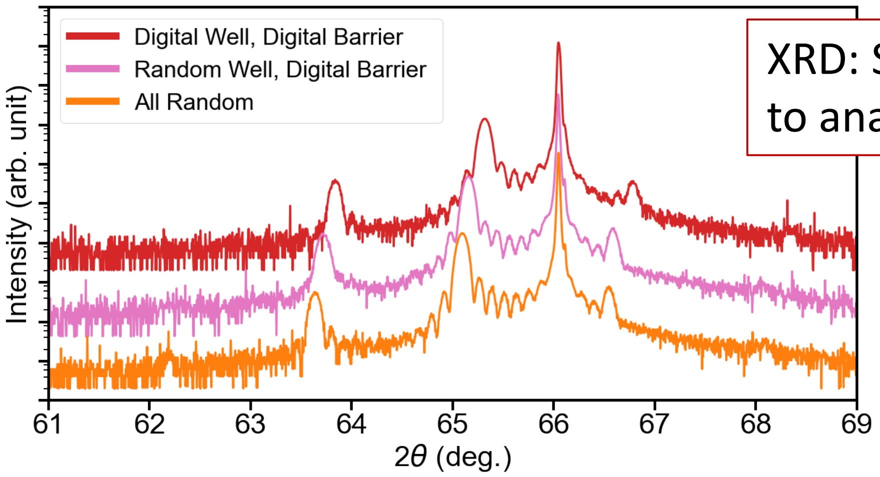


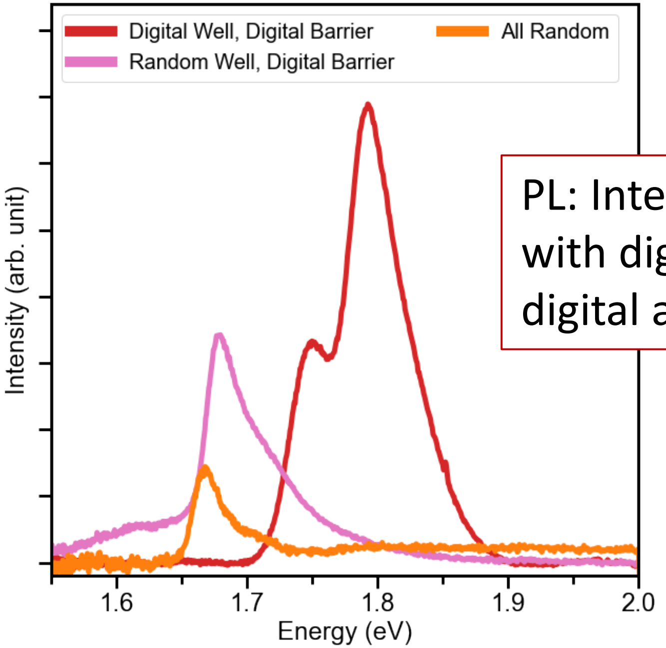


Digital Alloy Test





XRD: Similar to analog



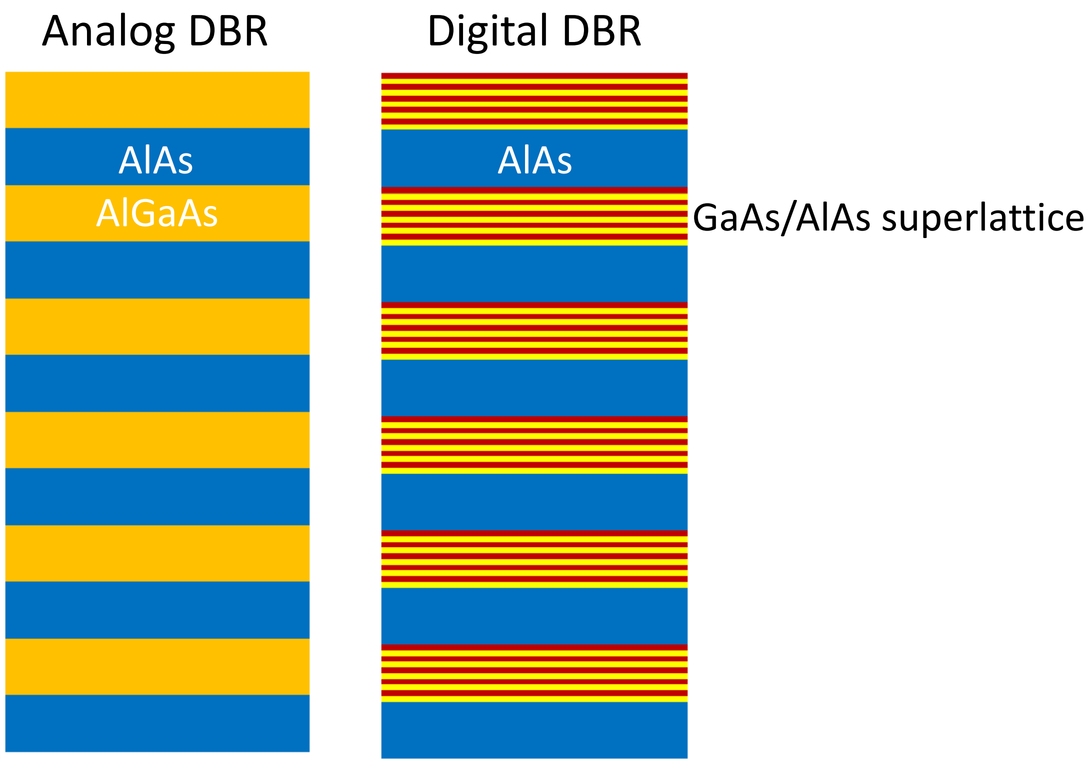
PL: Intensity improvement with digital alloy barriers and digital alloy wells

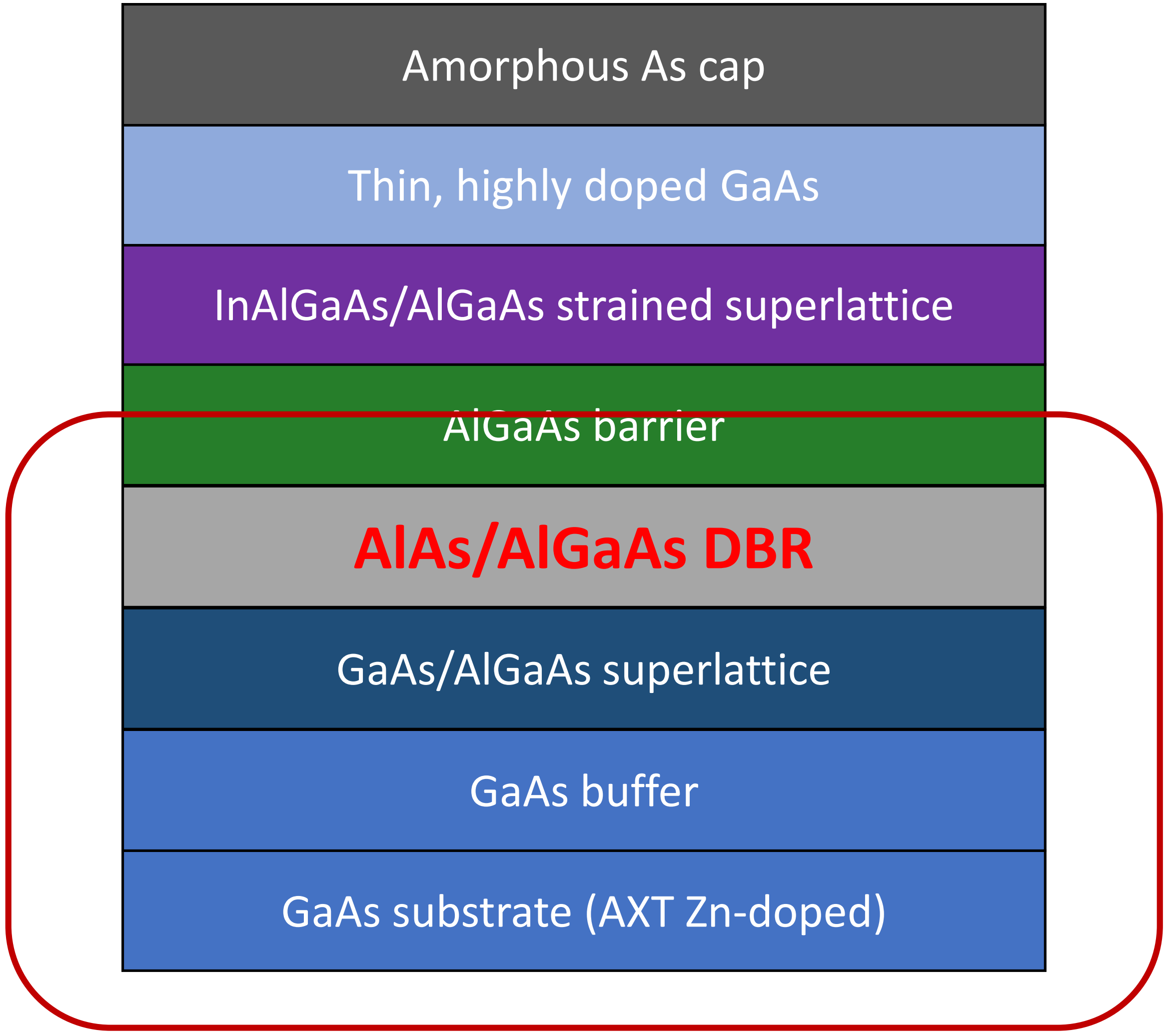
- Digital alloy barrier layer at JLab to test

Successful DBR Structures

Distributed Bragg Reflector

- Enhance QE by reflecting light for several passes through SSL
- Designed for peak reflectivity at 770 nm
- Analog and Digital AlAs/AlGaAs DBR structures designed and tested
- Digital Alloy: better uniformity across wafer





UCSB Photocathodes

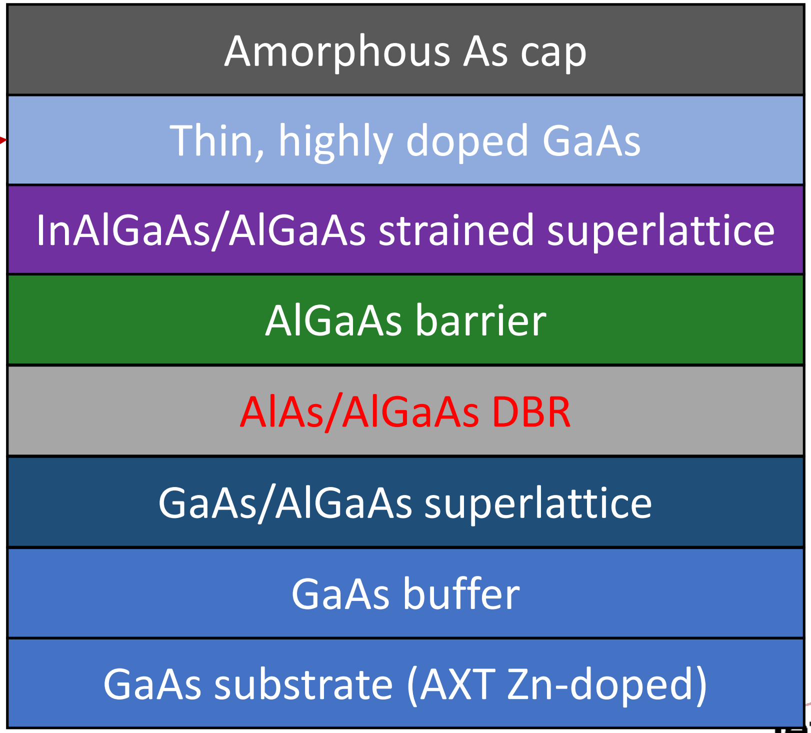
- Varied growth temp: Samples 198, 199
- Increase strain: Sample 144
- Higher dopant top & band gap shift: Sample 143
- Digital alloy barrier layer: Sample 202

At JLab awaiting testing

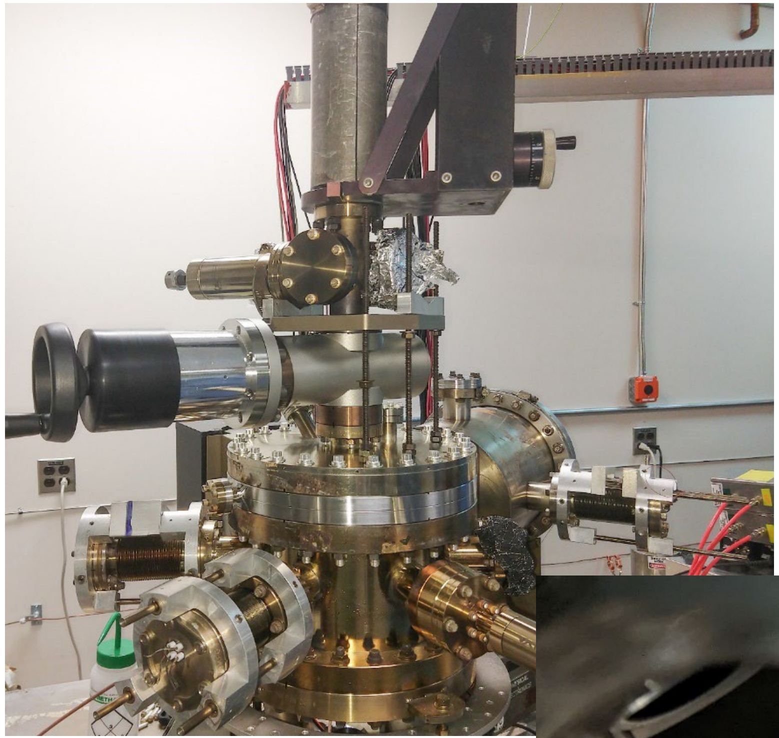
Next

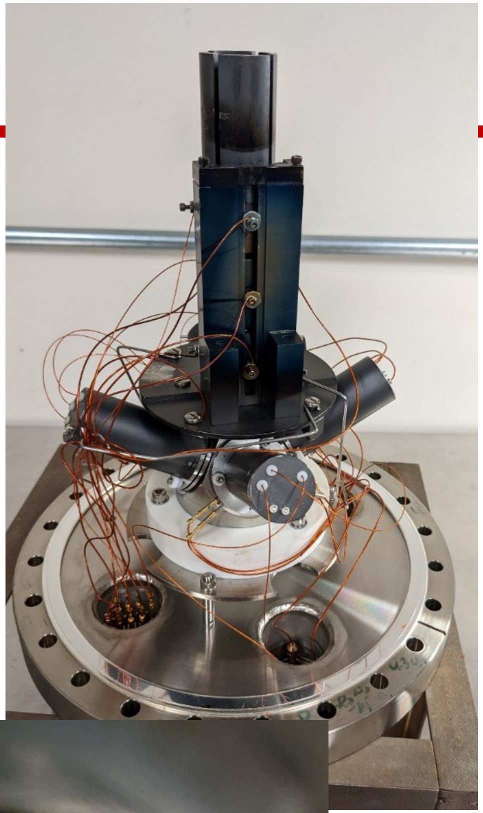
- Different Top Layer
- Distributed Bragg Reflector Photocathode
- Lots of parameters to optimize

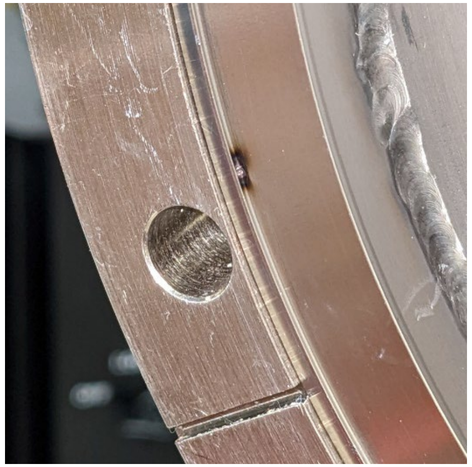
FOA timeline over but more samples coming
- awaiting JLab polarization measurments

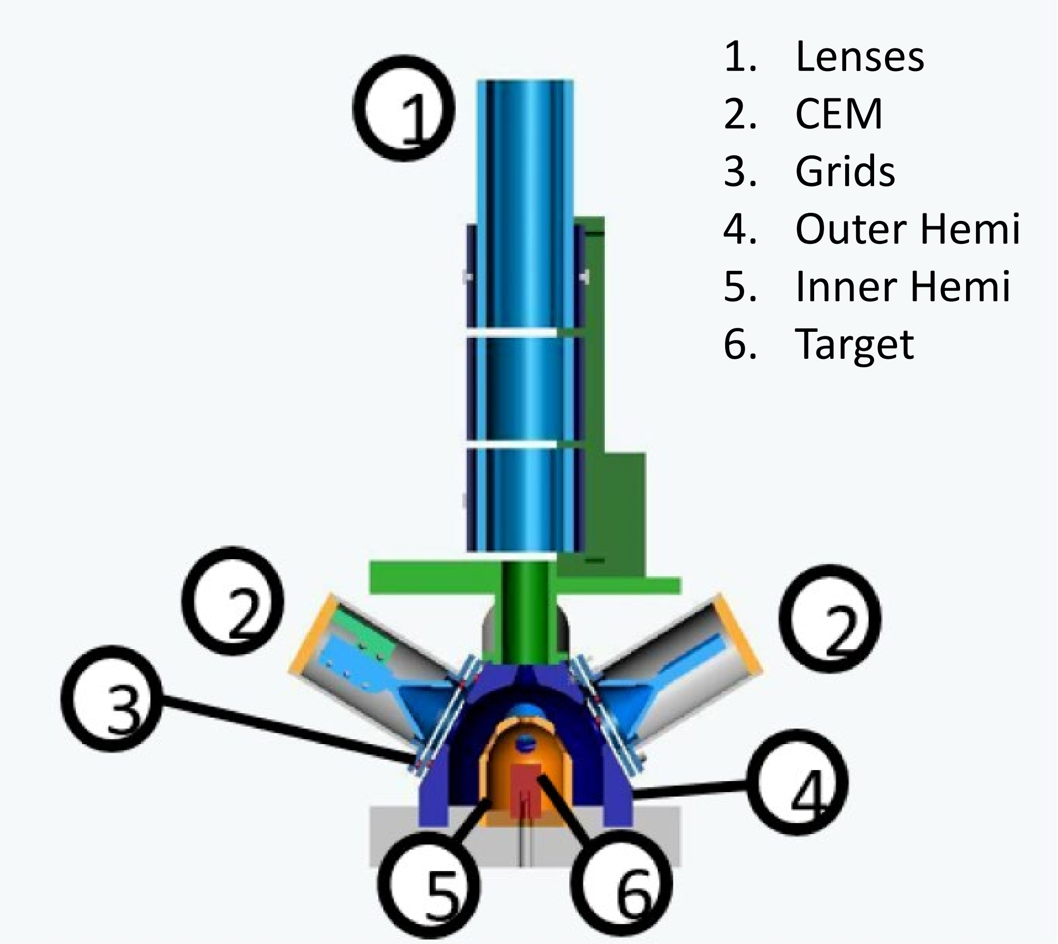


JLab Tests: MicroMott

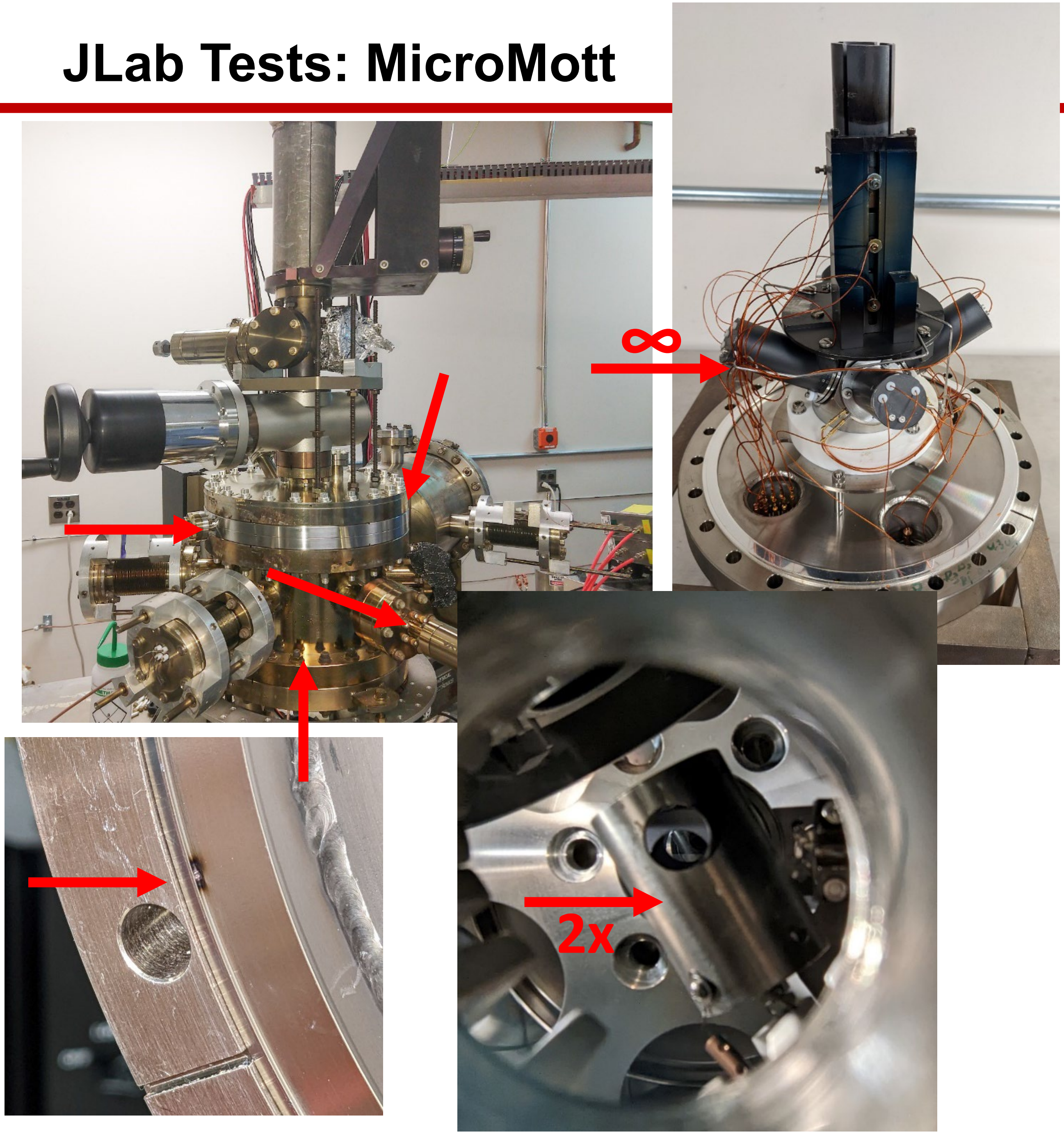








JLab Tests: MicroMott



MicroMott Polarimeter
—A Series of Unfortunate Events

- Multiple issues during refurbishment
- Nearly there!

- Wish List: more robust polarimeter with JLab puck load-lock

Project Summary

JLab: First UCSB sample tested

Polarimeter nearly ready to continue

UCSB

- Initial GaAs/GaAsP growth characterized
  - Extensive chamber maintenance to remove phosphorous compounds
- InAlGaAs/AlGaAs superior in many aspects
  - Temperature compatibility
  - Strain and band gap independent
  - Higher dopant potential
  - Digital structures for both SSL and DBR
- More to come

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