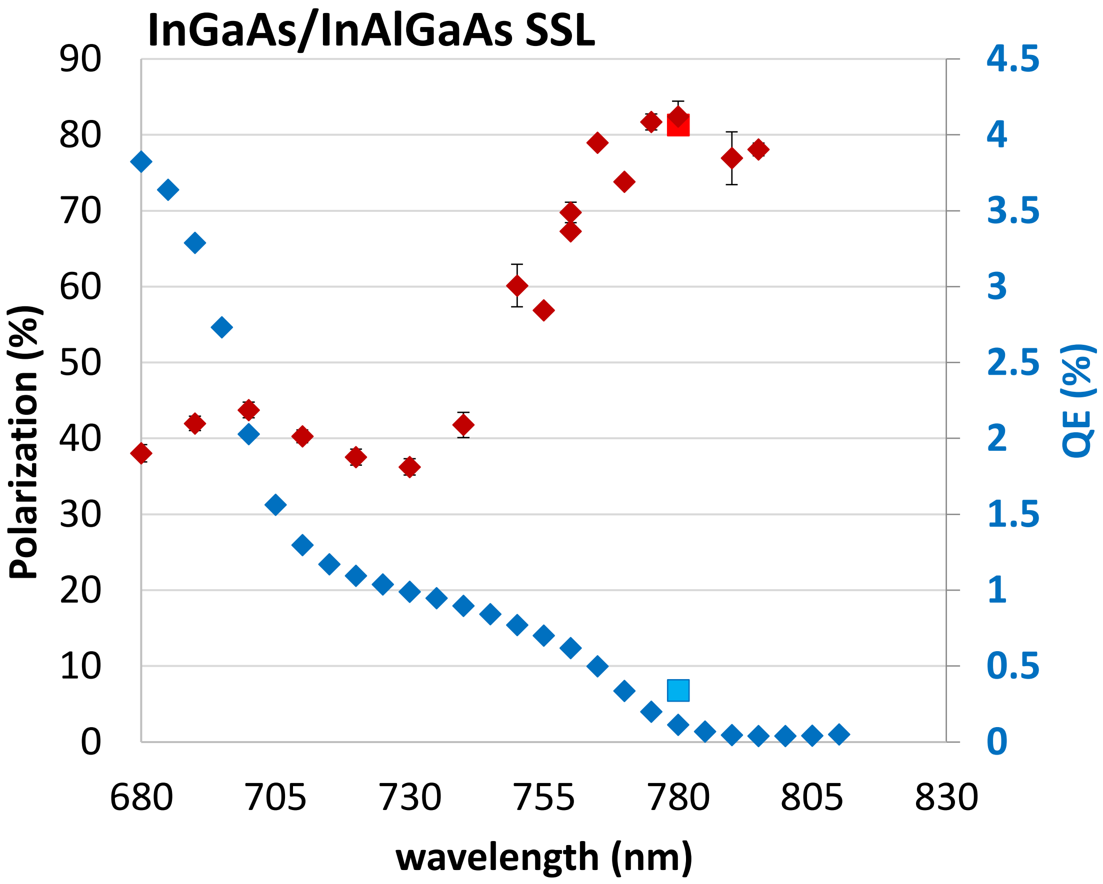
Strained Superlattice photocathodes with CBE

Annual NP Accelerator R&D PI Exchange meeting

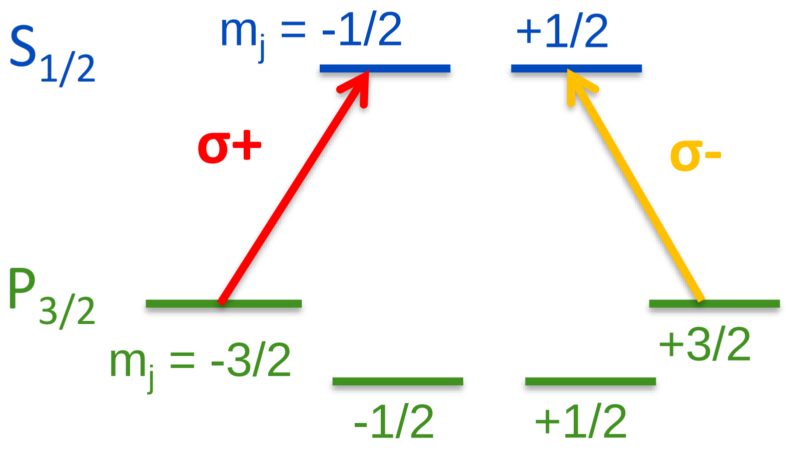


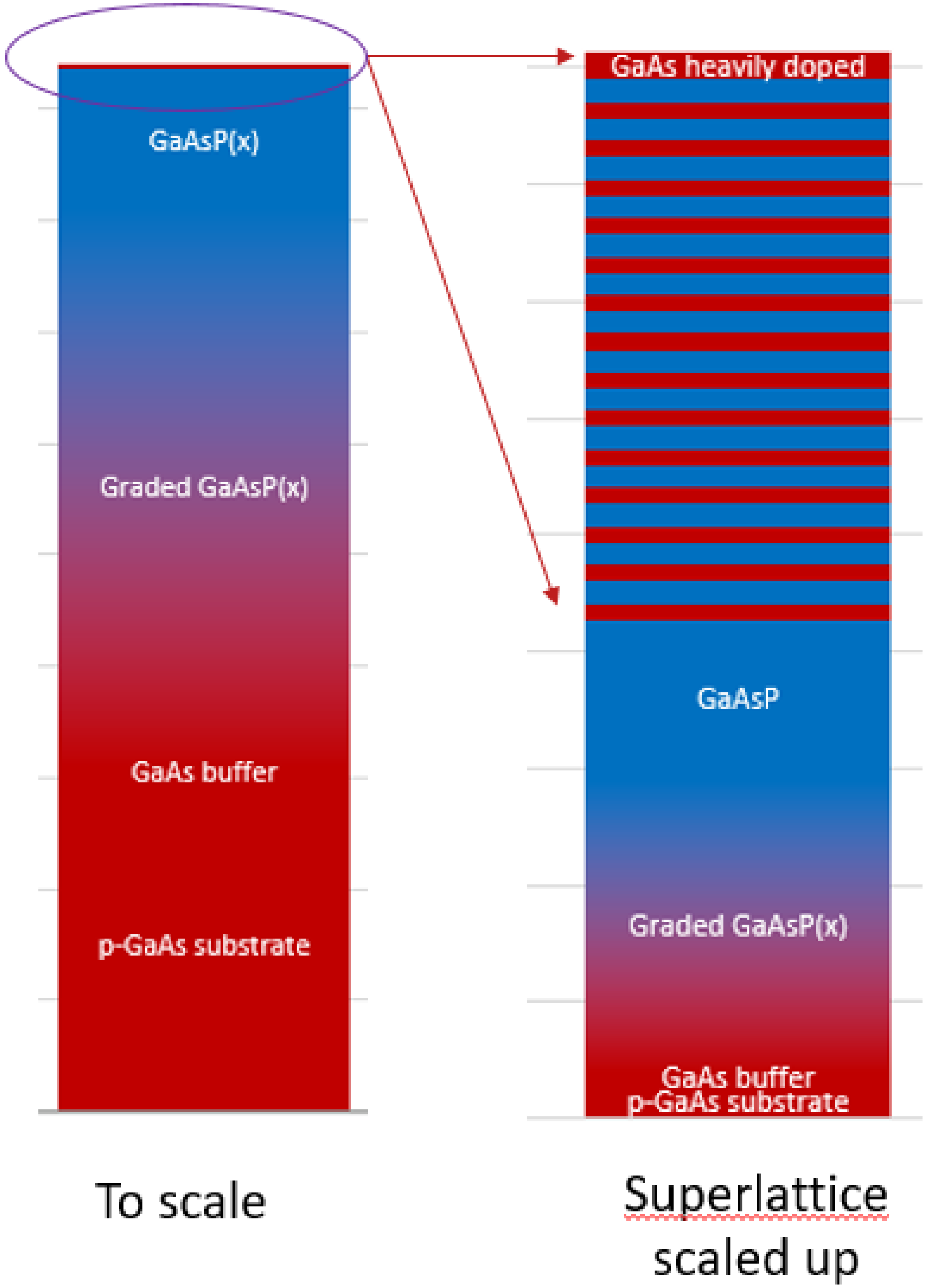
Marcy Stutzman, Jefferson Lab

Chris Palmstrøm and Aaron Engel, UCSB

Motivation

Polarized electron accelerators use strained superlattice GaAs structures to emit polarized electrons.





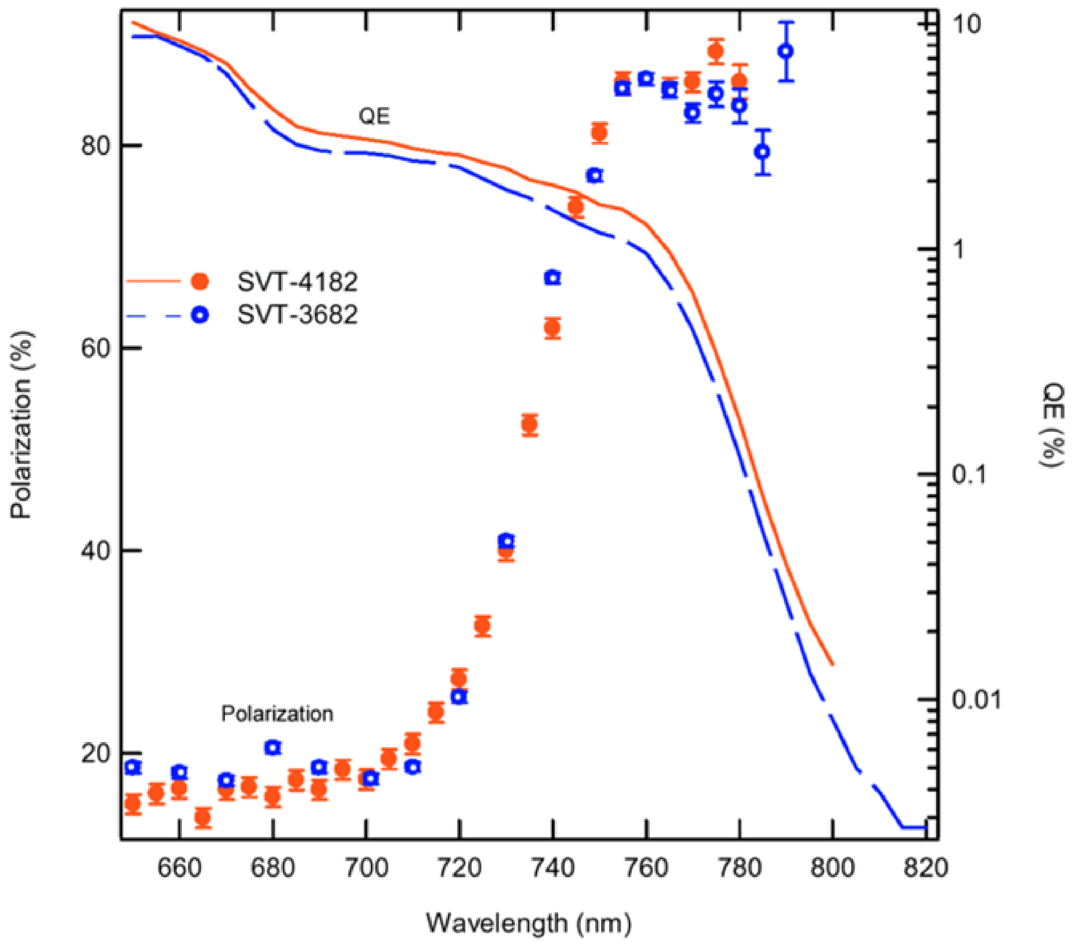
Innovation through SBIR program

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

Variations

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

No longer available



AlGaAs/GaAs, A. Moy 2009

Efforts to restore supply

- DOE Funding Opportunity 20-2310
  - MOCVD (*metal organic chemical vapor deposition*)
    - JLab: M. Poelker and M. Stutzman
    - BNL: E. Wang
    - ODU: S. Marsillac, B. Belfore
  - CBE (Chemical Beam Epitaxy)
    - JLab: M. Stutzman
    - UCSB: C. Palmstrøm, A. Engel
- MBE SSL GaAs/GaAsP Distributed Bragg Reflector
  - Sandia National Lab: Center for Integrated Nanotechnology
    - BNL: L. Cultrera
- Acken Optoelectronics Ltd., Suzhou China
  - Yiqiao Chen, formerly of SVT Associates
  - SSL GaAs/GaAsP photocathodes on order for evaluation

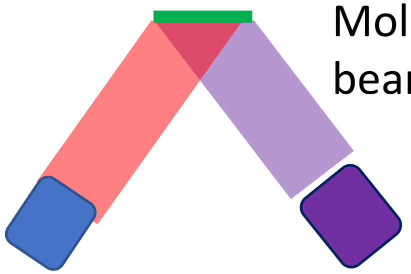
MBE, GSMBE, CBE and MOCVD

MBE

Gas Source Molecular Beam Epitaxy

elemental As, P, Ga

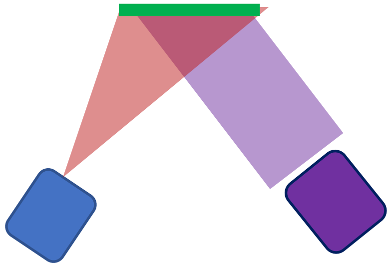
- Pressure ~10^{-8} mbar
- Growth rates ~ 1 µm/hr
- Very precise control



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

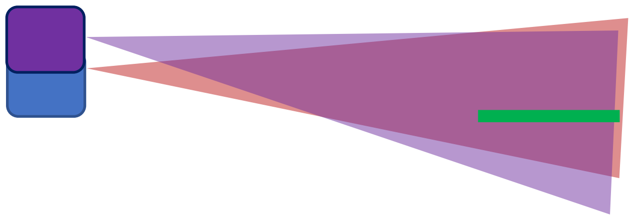
- Pressure <10^{-4} mbar
- Growth rates 0.5-1 µm/hr

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

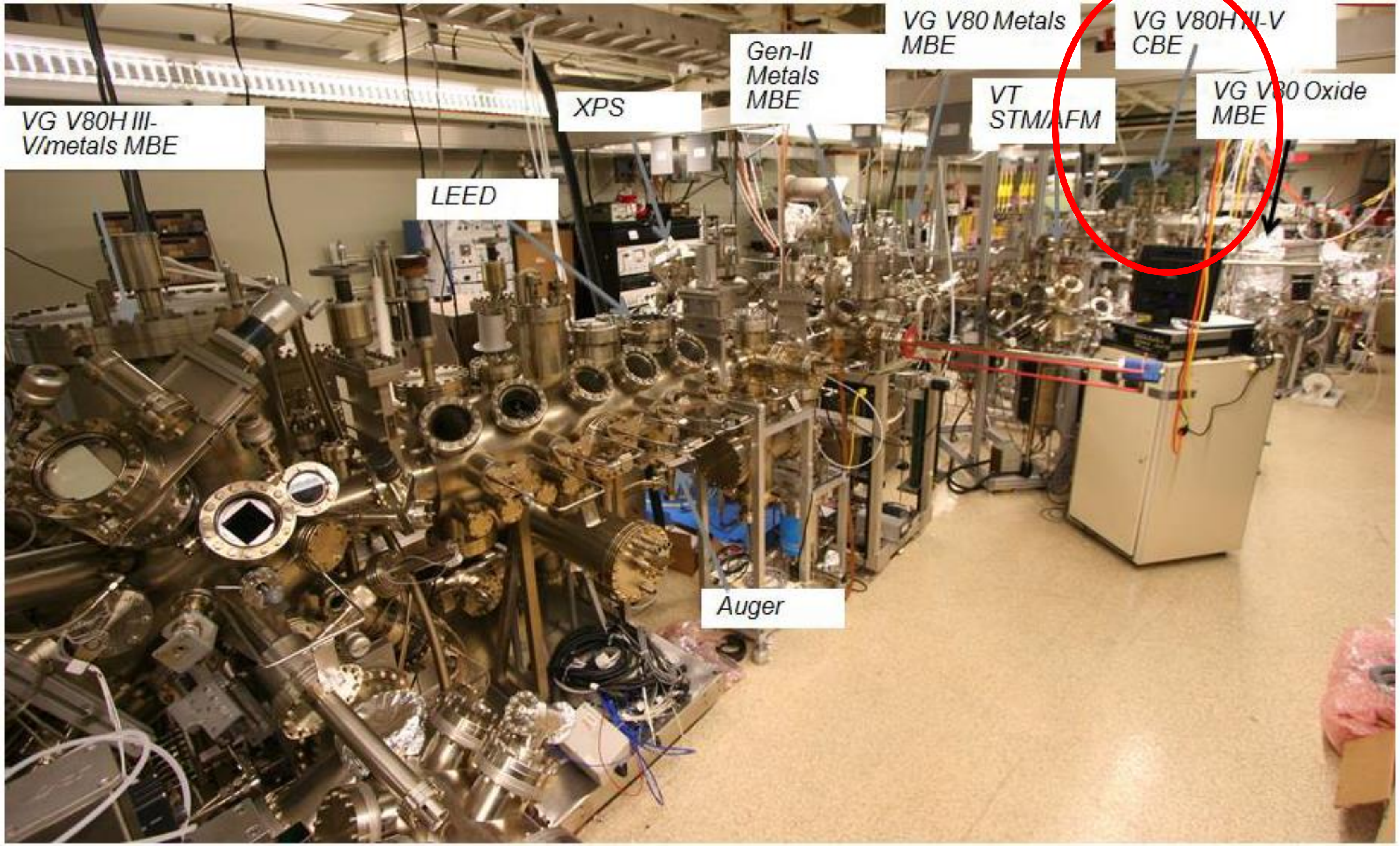


Figure 2 Semiconductor deposition system at Chris Palmstrom's lab at UCSB. The CBE system for the growth of this material is shown at the back and labelled "VG V80H III-V CBE".

Original Research Plan

UCSB

- Calibrate GaAs/GaAsP superlattice layer growth
- Develop graded layer process
- Characterize samples with surface and crystal analysis
- Grow strained superlattice material

Jefferson Lab

- Replace depleted microMott detectors
- Upgrade microMott polarimeter
- Measure samples for QE and polarization when they arrive
- Train students on polarization measurement

Budget Shortfalls & delays + COVID = modified scope

	Proposal		Actual	
	2020	2021	2020	2021
UCSB	$150,000	$150,000	$0	$150,000
JLab	$126,200	$127,137	$126,200	$126,200
	$276,200	$277,137	$126,200	$276,200
	Total	$553,337		$402,400

UCSB and JLab contract: Funding began February 2021 (4 month delay)

Tasks and timeline

	FY21 Q2	FY21 Q3	FY21 Q4	FY22 Q1	FY22 Q2	FY22 Q3	FY22 Q4	FY23 Q1	FY23 extension
JLab									
MicroMott: maintainance, repair	✓						✓	✓	
MicroMott upgrade: Design,build									
Test Superlattices								✓	
Train UCSB Student: MicroMott									
UCSB									
Graded layer		✓							
Superlattice depo. calibration	✓								
Chamber maintenance			✓	✓	✓				
Research – AlGaAs/InAlGaAs				✓	✓				
Grow & Deliver AlGaAs/InAlGaAs						✓			
Grow superlattice variations						✓	✓	✓	
GaAs/GaAsP								?	?

UCSB Research Plan

UCSB proposed

- Calibrate GaAs/GaAsP superlattice layer growth
- Develop graded layer process
- Characterize samples with surface and crystal analysis
- Grow & deliver strained superlattice material

UCSB delivered

- ✓ GaAsP/GaAs superlattice growth calibration
- ✓ Graded layer GaAs to GaAsP
- ✓ Characterize superlattices
- ❑ Find triethyl-gallium and P make high vapor pressure residue -> solid source Ga
  - ✓ Chamber maintenance
- ❑ Research prior work
  - ✓ InGaAs/InAlGaAs has good QE, Pol. & better growth compatibility
- ✓ Grow InGaAs/InAlGaAs samples with variations in temperature, thickness, composition

JLab Research Plan

Jefferson Lab Proposed

- Replace depleted microMott detectors
- Upgrade microMott polarimeter
- Measure samples for QE and polarization when they arrive
- Train student on polarization measurement

Jefferson Lab actual

✓Detectors replaced

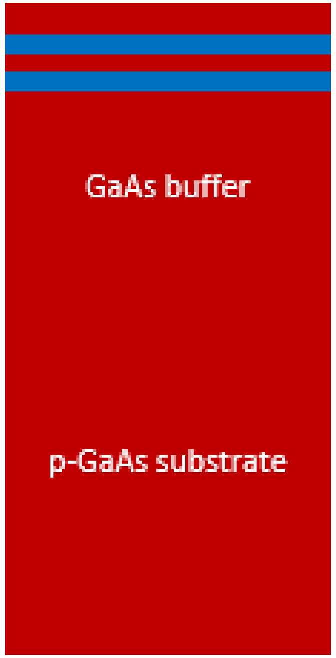
✓Find wiring shorts, repair
  - No polarimeter upgrade design or build

✓Measured QE and polarization of samples
  - First sample done
  - Five samples ready to test

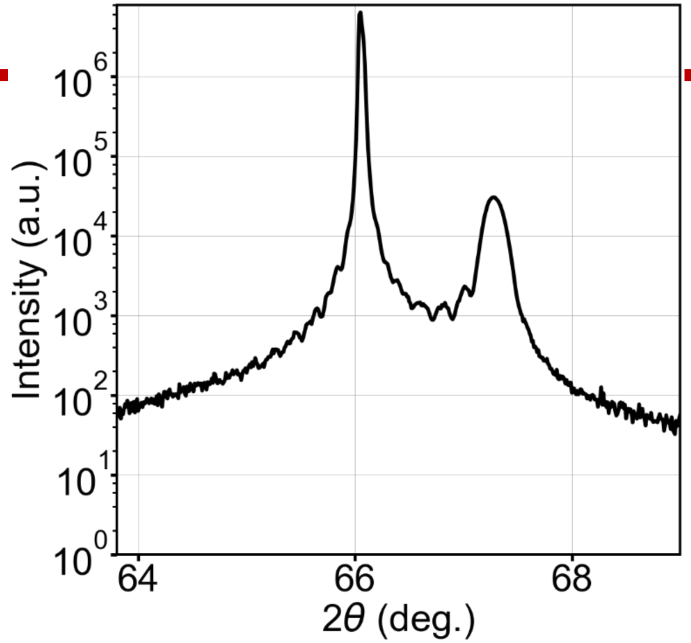
- Student travel delayed

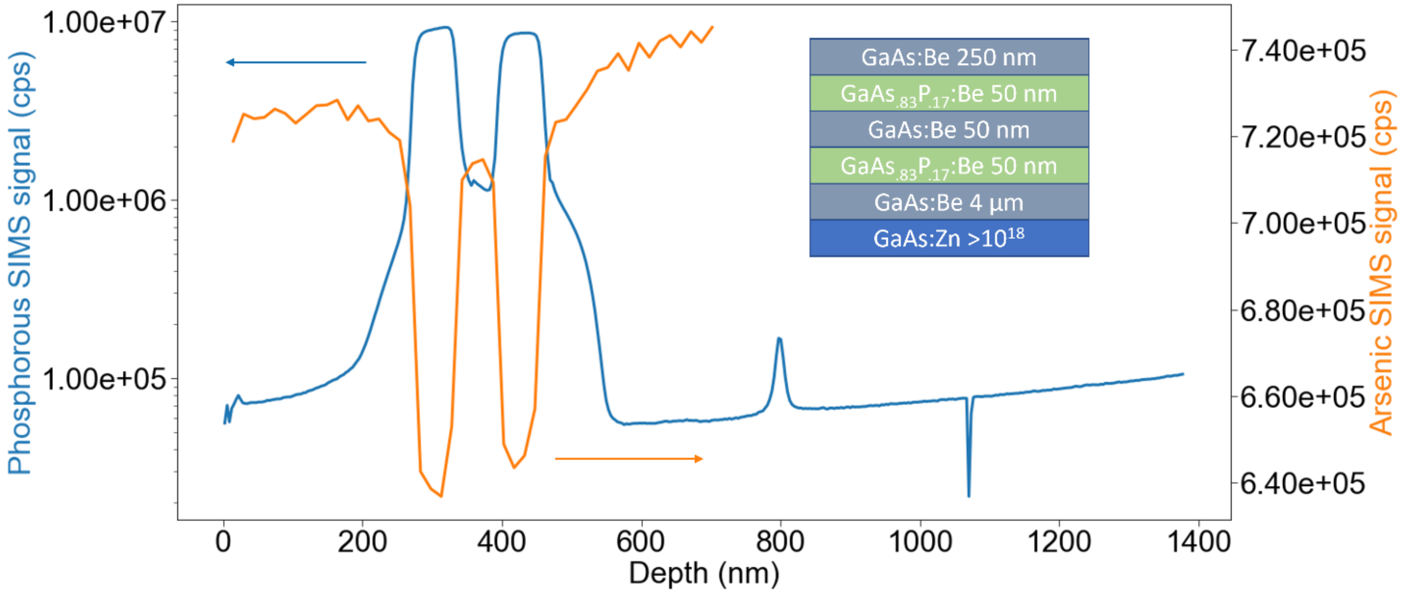
UCSB Highlights

GaAsP superlattice on GaAs



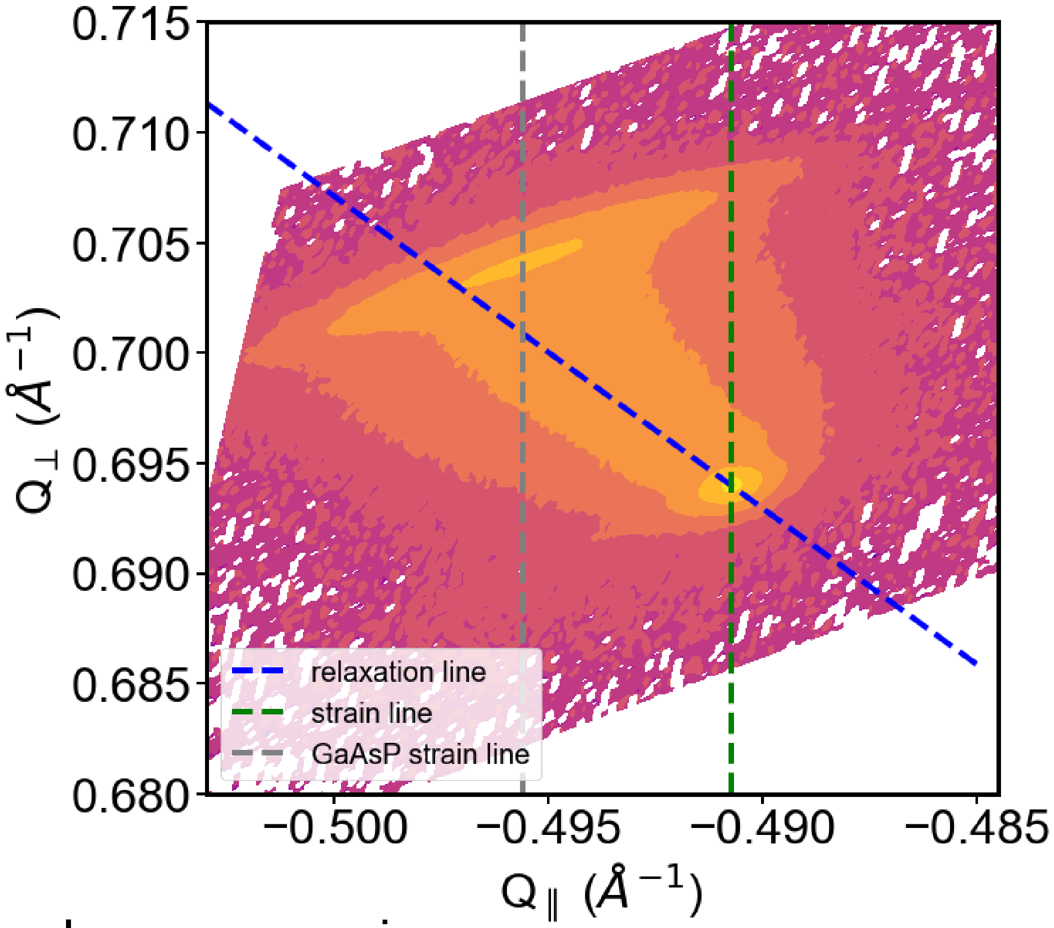
XRD Pendellösung fringes: crystal spacing





SIMS profile: Superlattice thickness and interface measurement

UCSB Highlights: Graded layer GaAs to GaAsP



X-ray Reciprocal space mapping

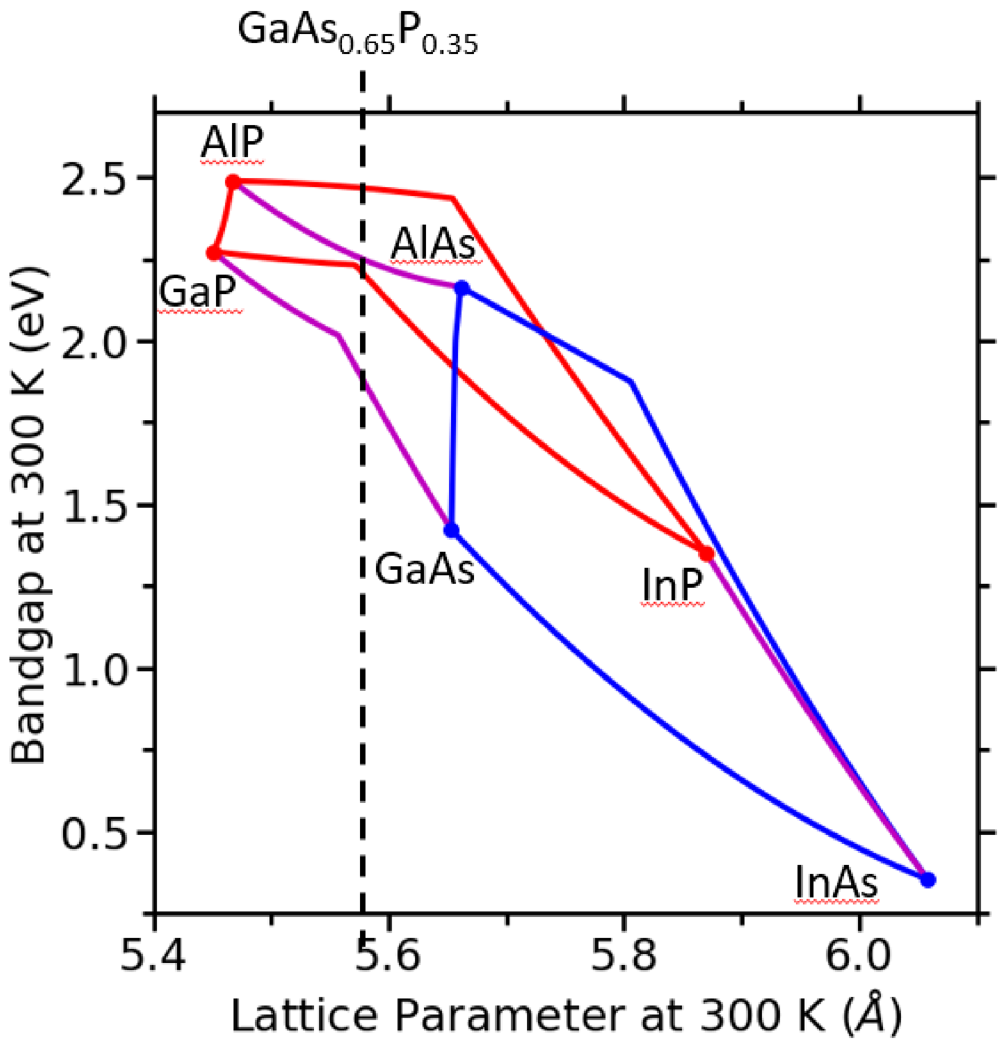
— Plot of lattice distance during growth
— Graded Layer with minimal strain
— GaAs layer (5-10 nm) strained: lattice constant that of GaAsP

- Equipment repair and upgrades due to GaAsP growth residue
- Rebuild system, recalibrate growth parameters with new heaters & sources

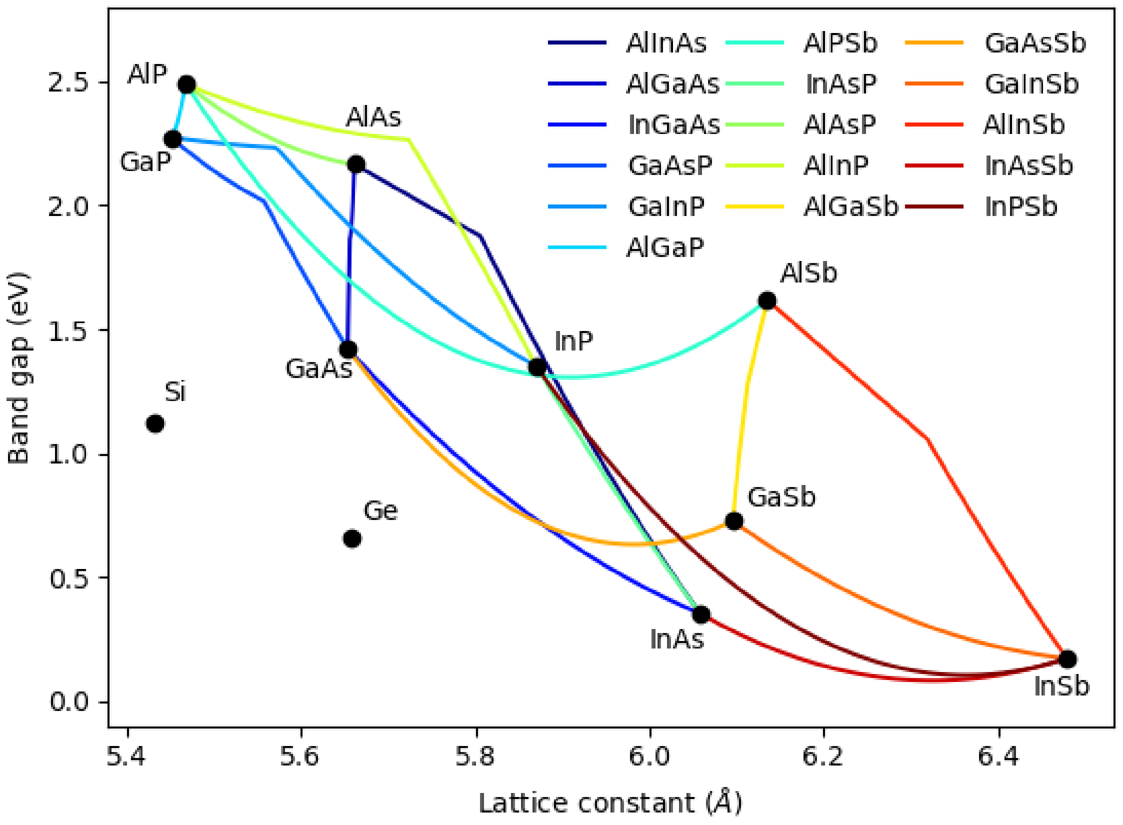
- Research InGaAs/InAlGaAs
  - grown at St. Petersburg
  - used at Mainz: polarization and QE excellent

Downsides of GaAs/GaAsP

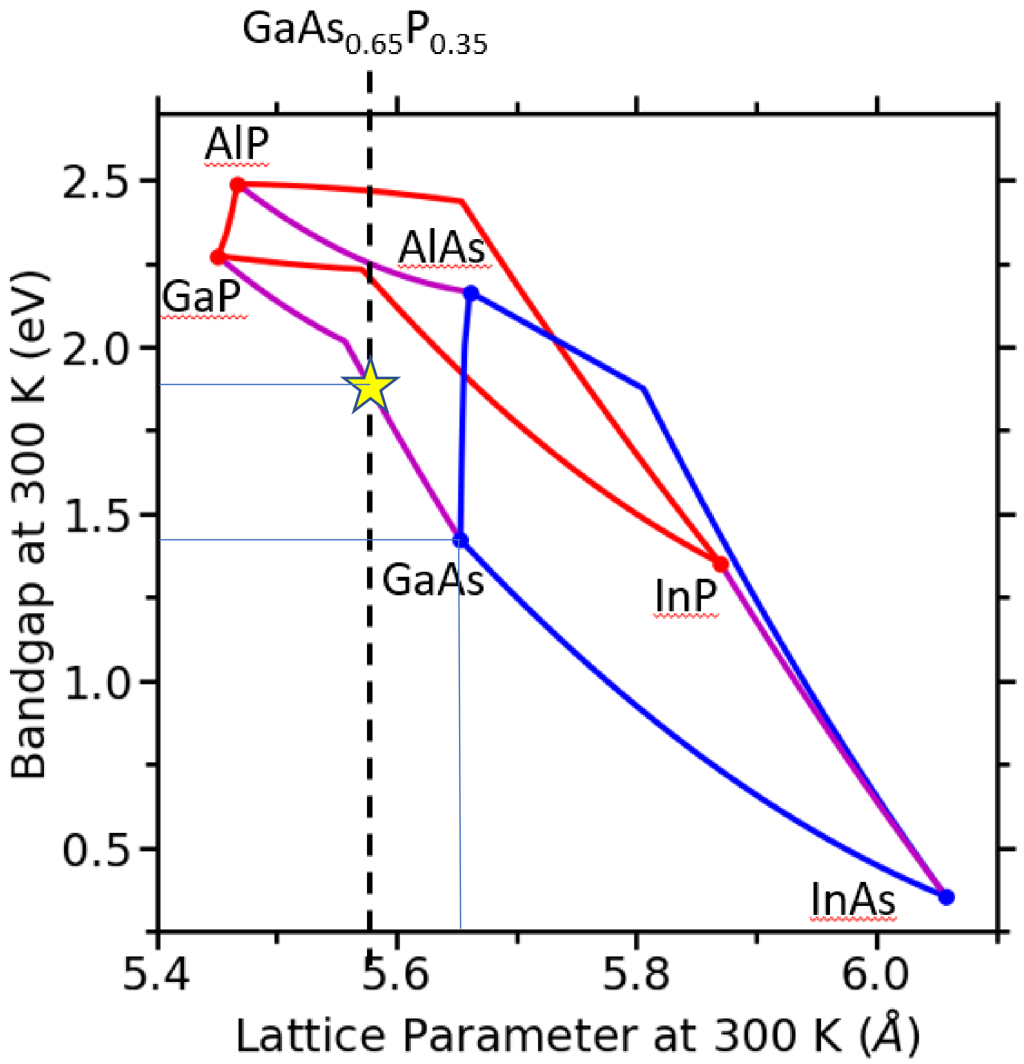
- Relaxed GaAsP virtual substrate grown on GaAs
  - Many threading dislocations
- As:P ratio in barrier is fixed by virtual substrate composition
- Strain and valance band offset in GaAs well layer are both fixed by virtual substrate



Band gap and Lattice Constant diagram

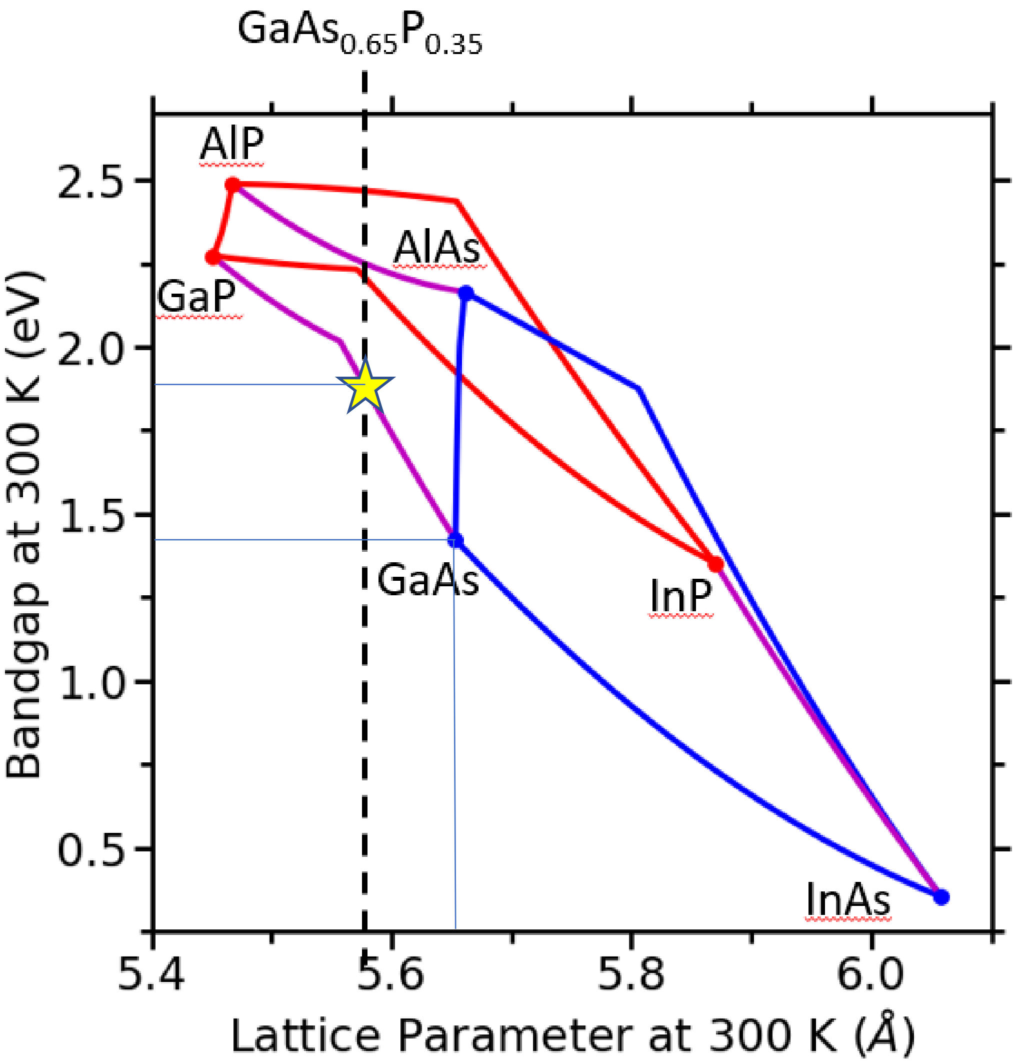


III-IV semiconductor alloys: Band gaps and lattice constants

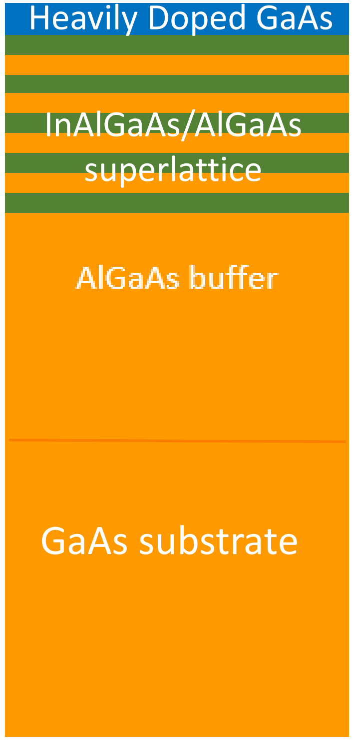


Downsides of GaAs/GaAsP

- Relaxed GaAsP virtual substrate grown on GaAs
    - Many threading dislocations
- As:P ratio in barrier is fixed by virtual substrate composition
- Strain and valance band offset in GaAs well layer are both fixed by virtual substrate

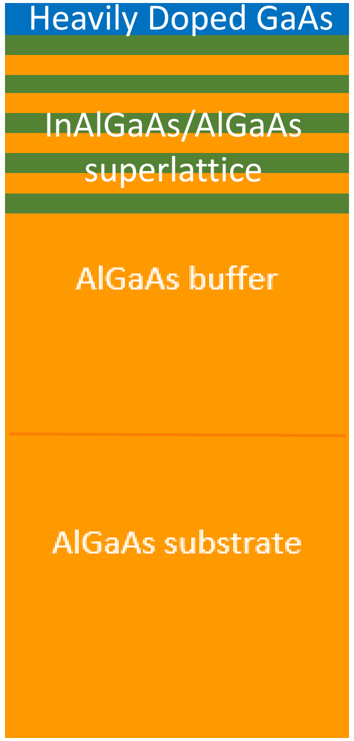


Benefits of InAlGaAs/AlGaAs

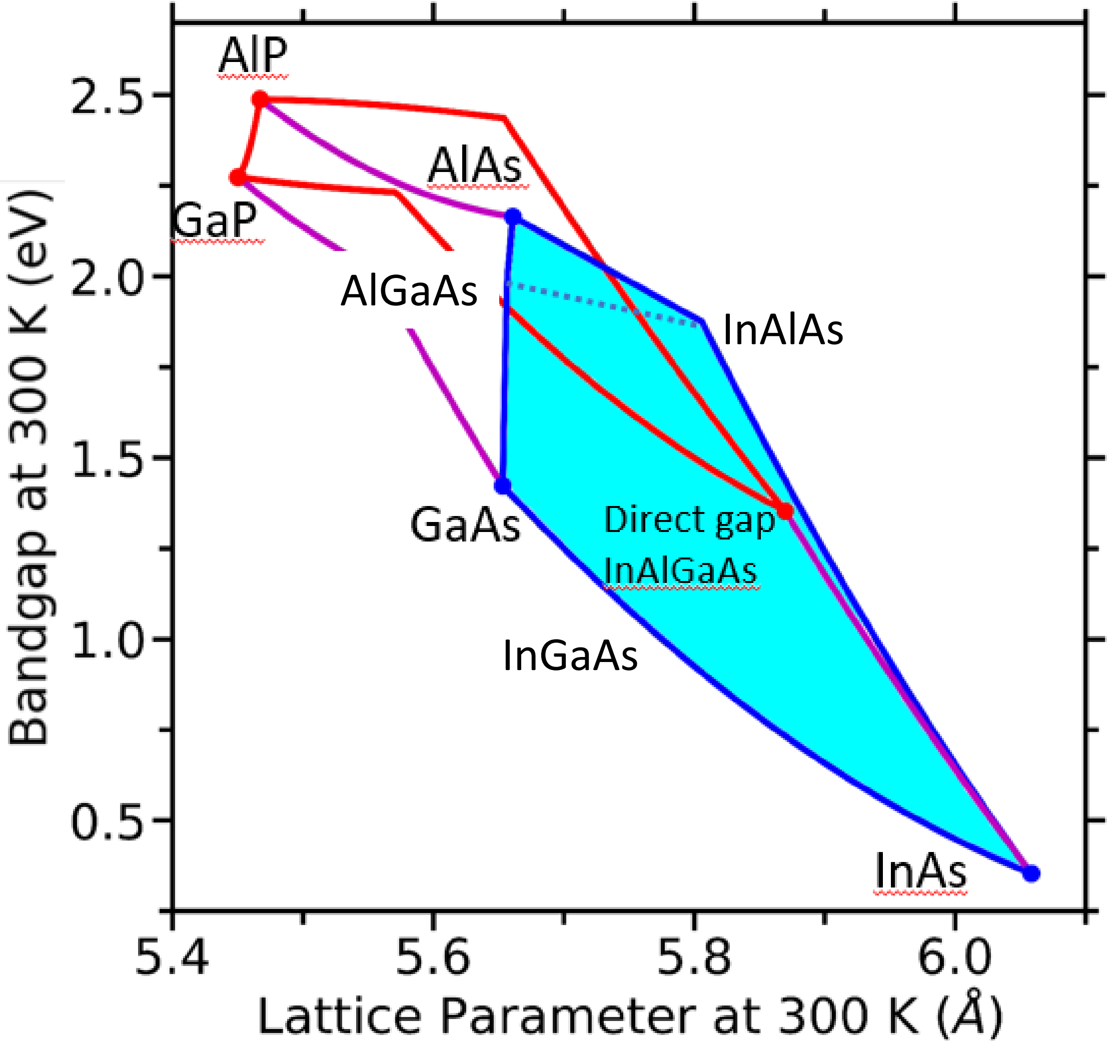


- No virtual substrate necessary
  - AlGaAs almost perfectly lattice matched to GaAs: Grow directly on GaAs
  - No lateral undulations from virtual substrate
- Easier to buy commercially than phosphides
- Potentially sharper interfaces due to same Group V sublattice
- Easily tunable DBRs
  - AlAs/AlGaAs for DBR
  - well characterized optical constants
  - abrupt interfaces

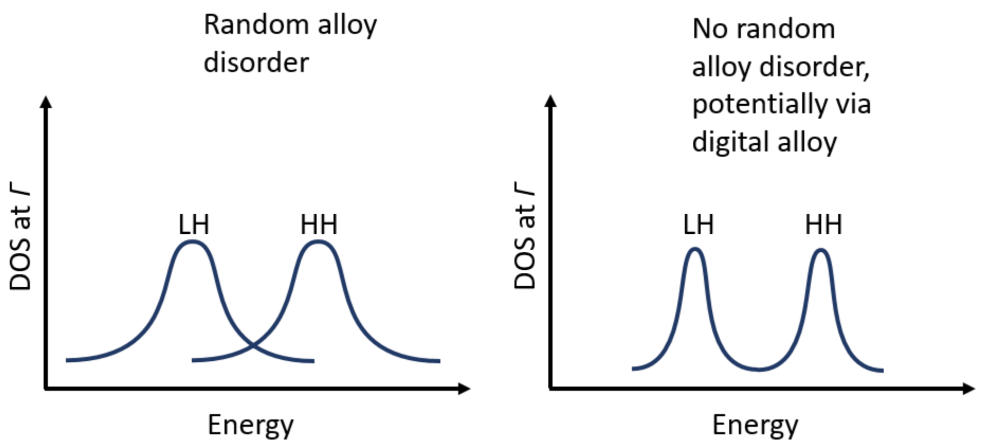
Benefits of InAlGaAs/AlGaAs

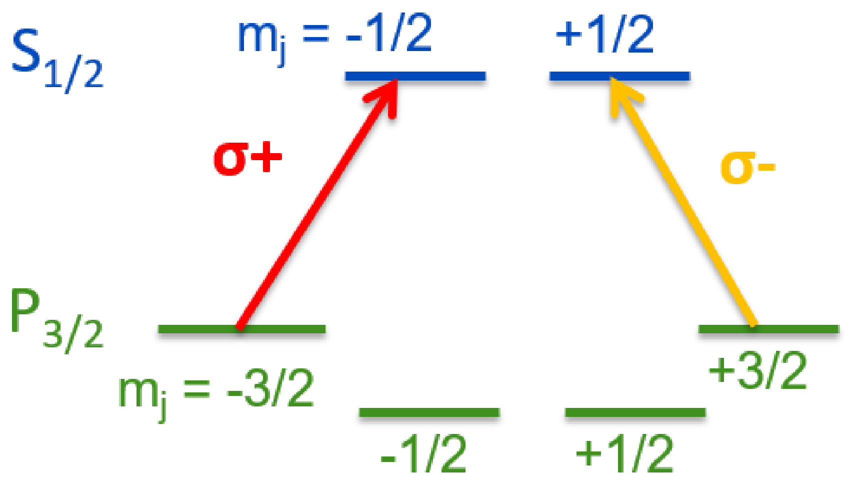


- Wavelength tuning
  - Vary Ratio of Al in superlattice layers
  - Tunes emission wavelength independent of strain
  - Tunes valance band and conduction band offsets

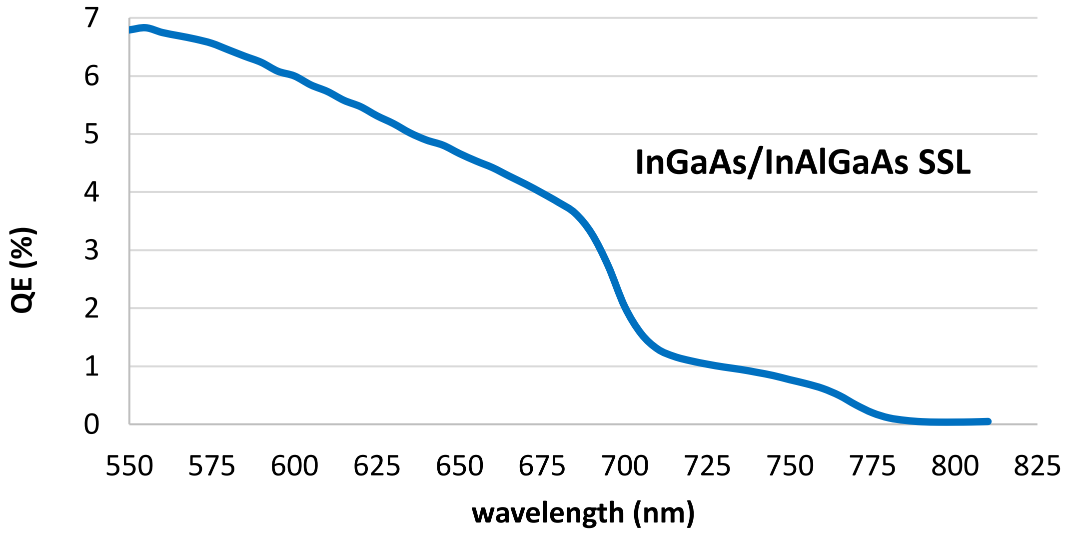


InAlGaAs/AlGaAs: Potential downside

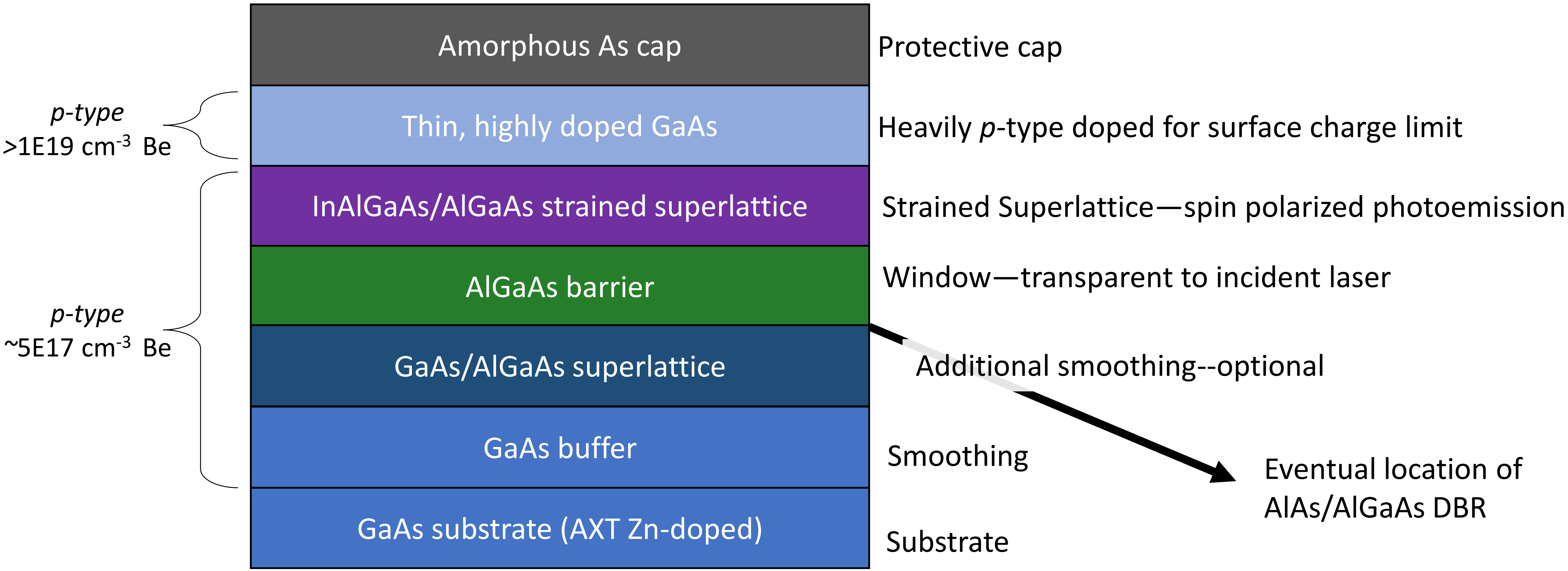




- Quaternary well (InAlGaAs) adds random alloy disorder, could increase bandwidth and thus hole overlap
  - Would decrease spin polarization
  - Potentially solved by digital alloy rather than analog alloy
- Initial QE measurements show double step in QE: hole overlap is not a limiting factor

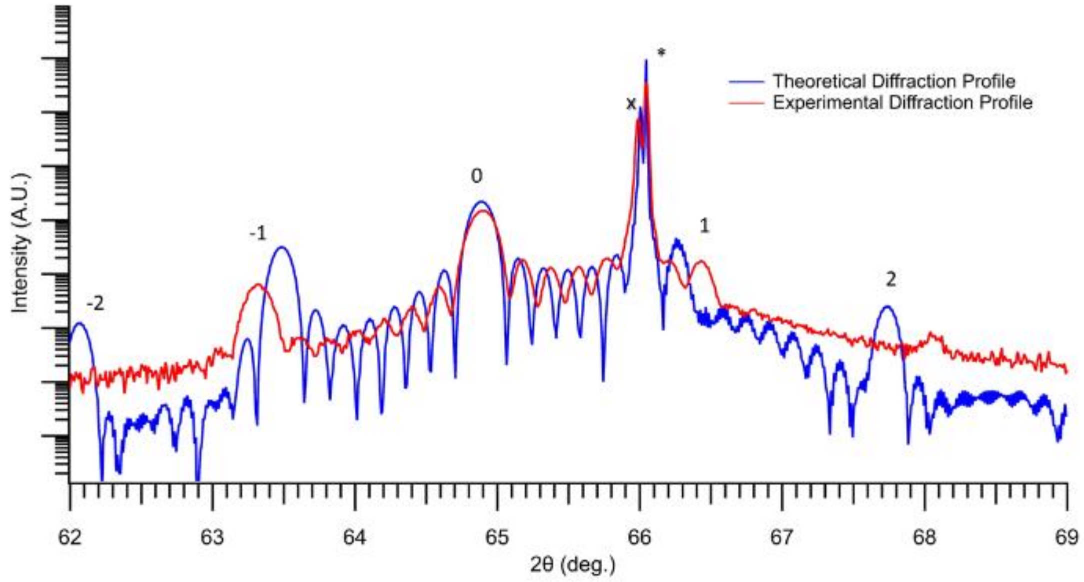


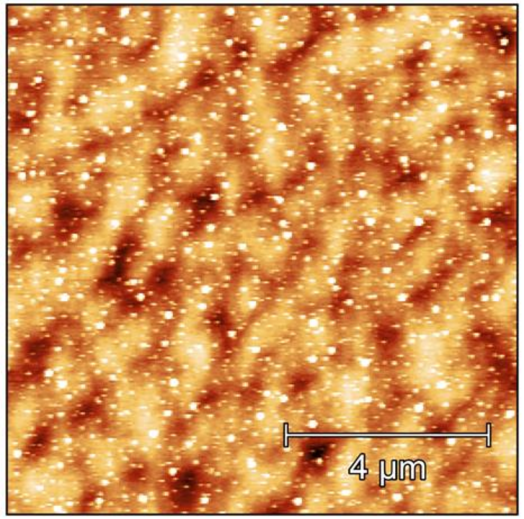
UCSB InAlGaAs/AlGaAs Structure

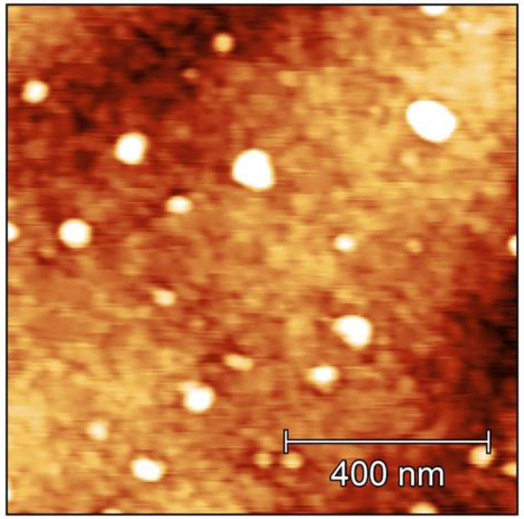


Based on Mamaev et al., Appl. Phys. Lett. 93, 081114 (2008) and
https://www.slac.stanford.edu/pubs/slacpubs/11250/slac-pub-11403.pdf

UCSB highlights







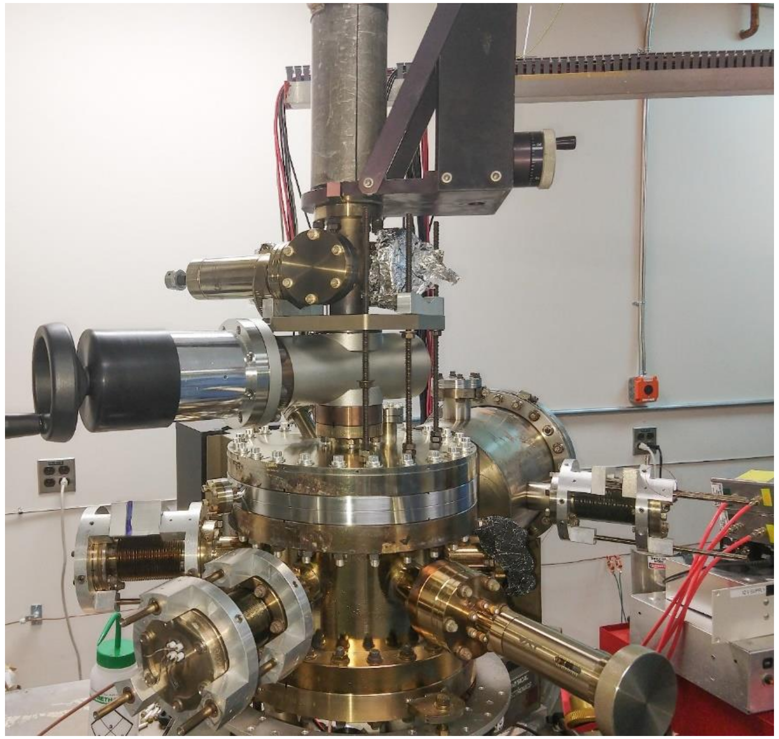
X-ray diffraction measurement of Superlattice

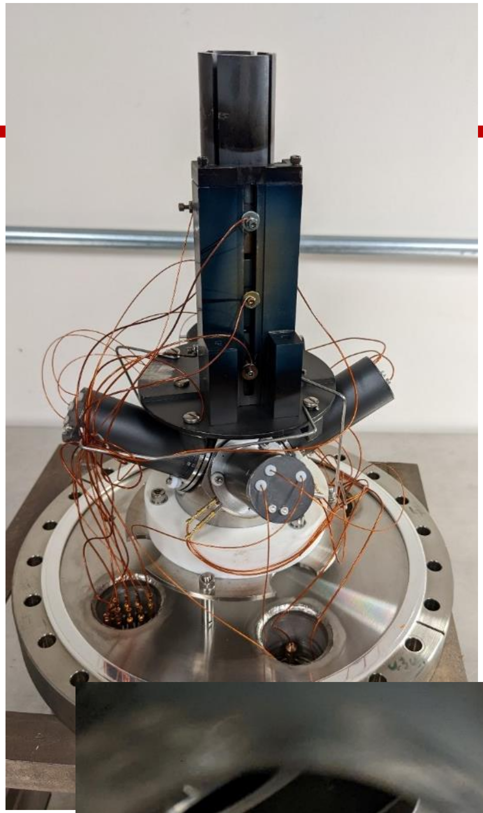
- Fully strained
- Superlattice period good - 8% less than goal

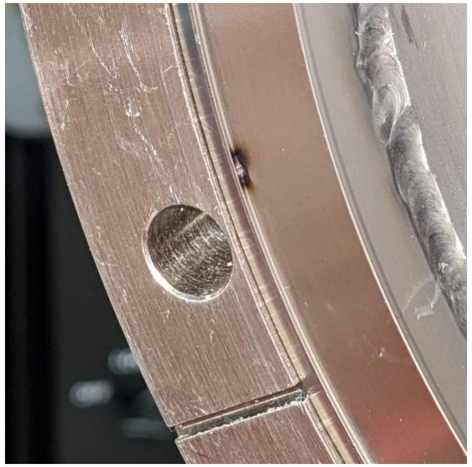
Atomic Force Microscope surface morphology

- Verification of arsenic cap coverage
- Some excess As – will desorb in first heat cycle

JLab Highlights

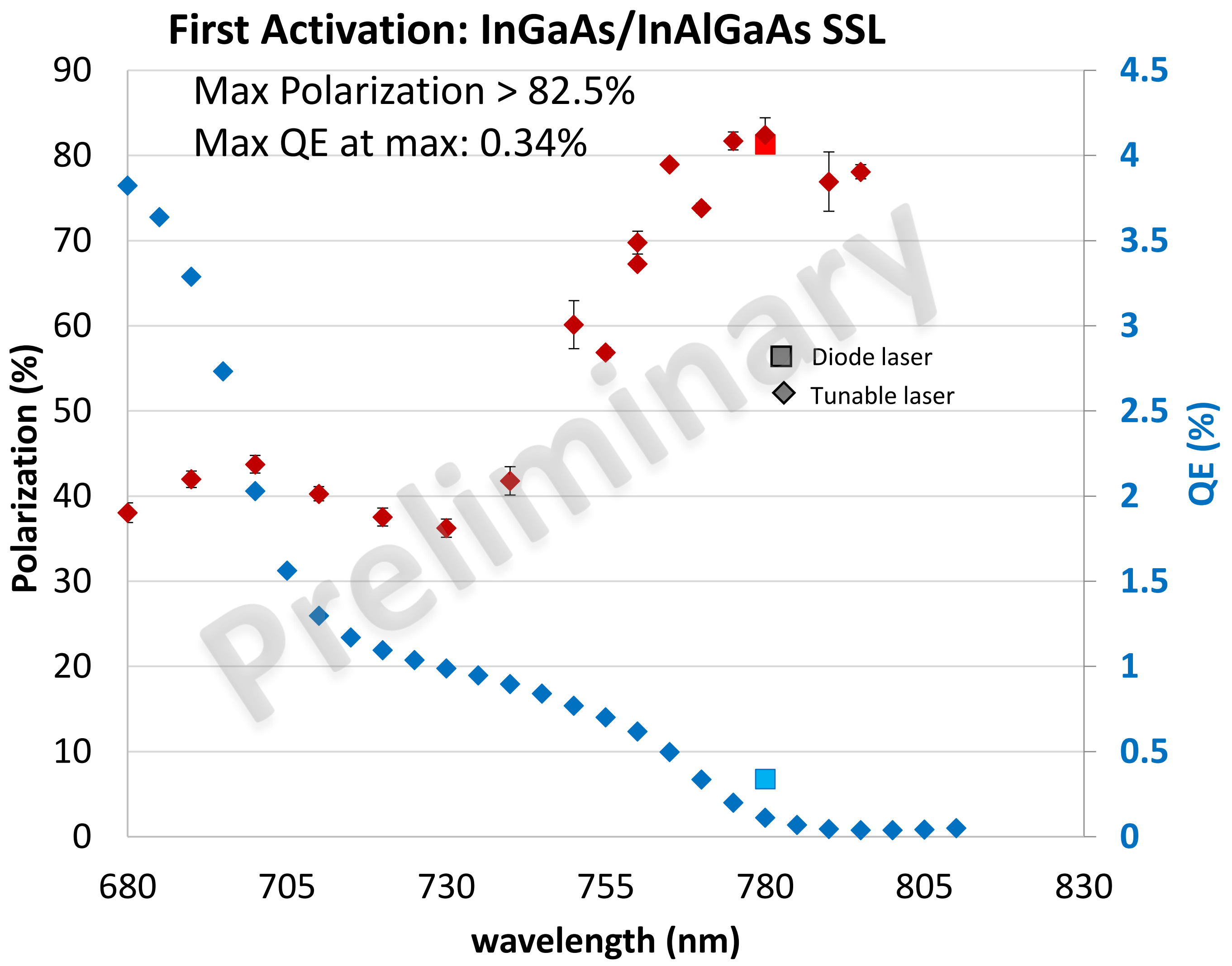






- CEM detectors replaced
- Troubleshooting
  - Lens slippage, realignment
  - Shorted HV wire for detector
  - Bad QE and lifetime: 3x bad leak valves
  - Crossed wires repaired
- De-scoped
  - Upgrade to puck system
  - Rotation to horizontal configuration
  - Designer time not available
- System working as of October 2022

JLab Highlights



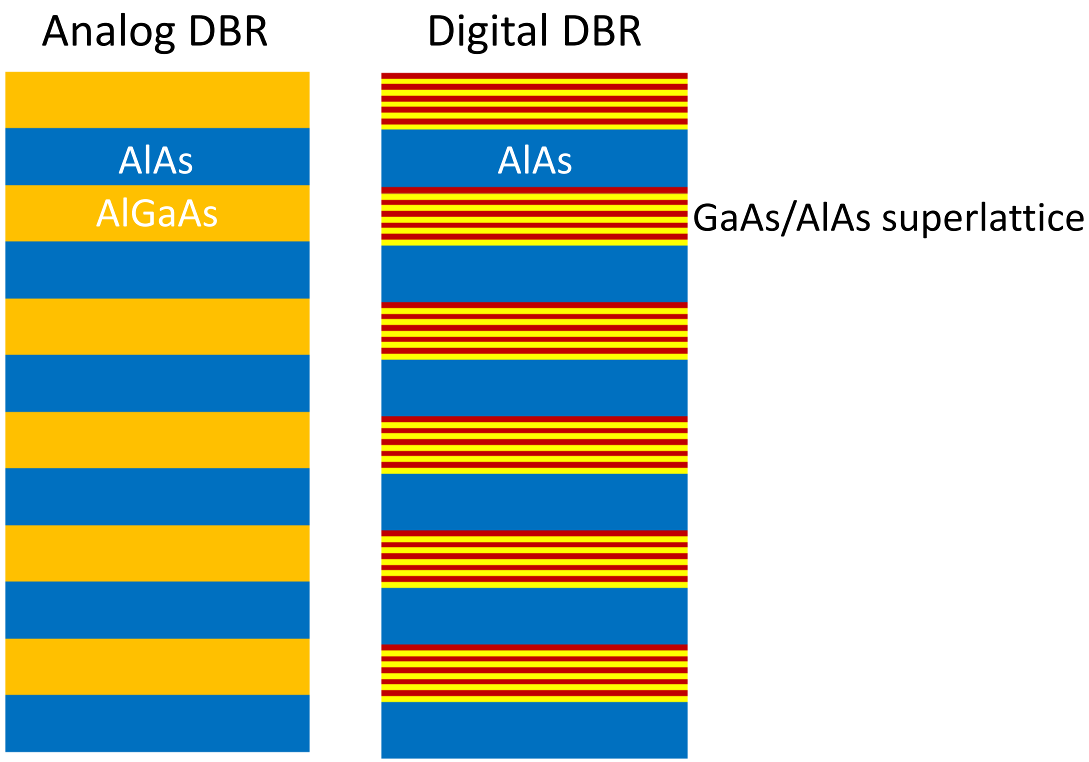
Next Samples to measure

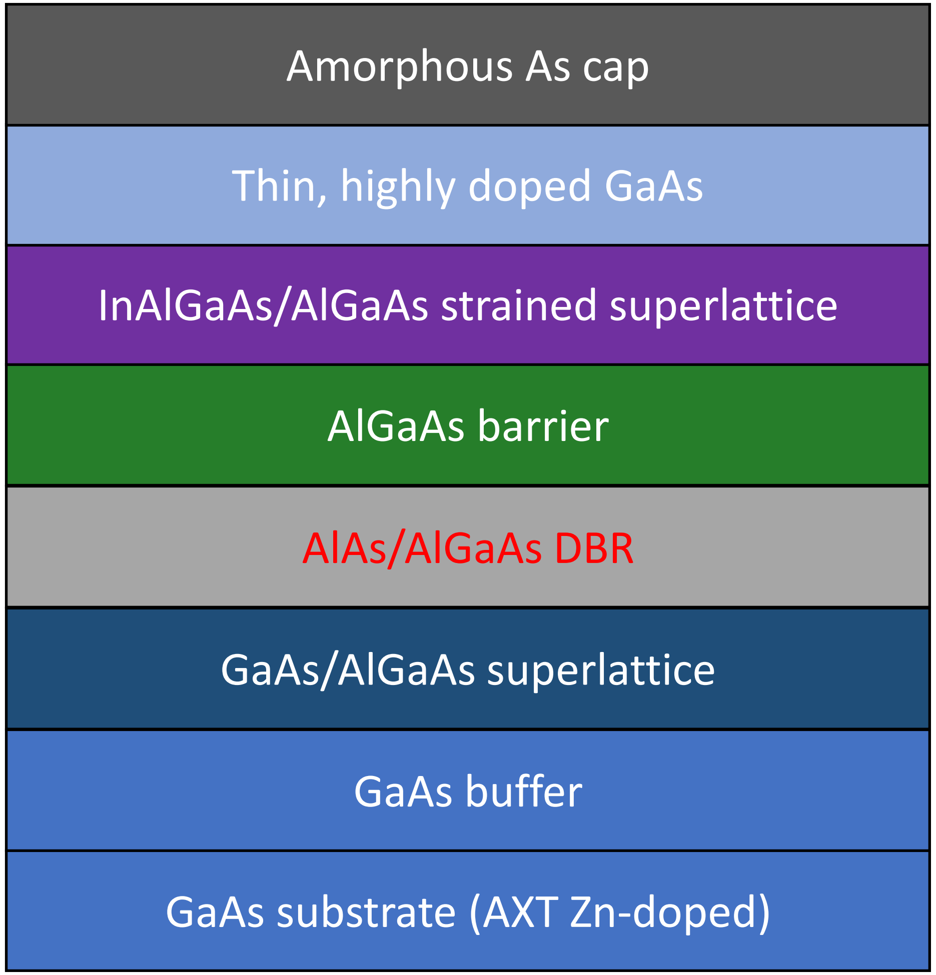
- Varied growth temp: Samples 198, 199
- Increase strain: Sample 144
- Higher dopant top & band gap shift: Sample 143
- Digital alloy barrier layer: Sample 202

UCSB: Successful DBR Structures

Distributed Bragg Reflector

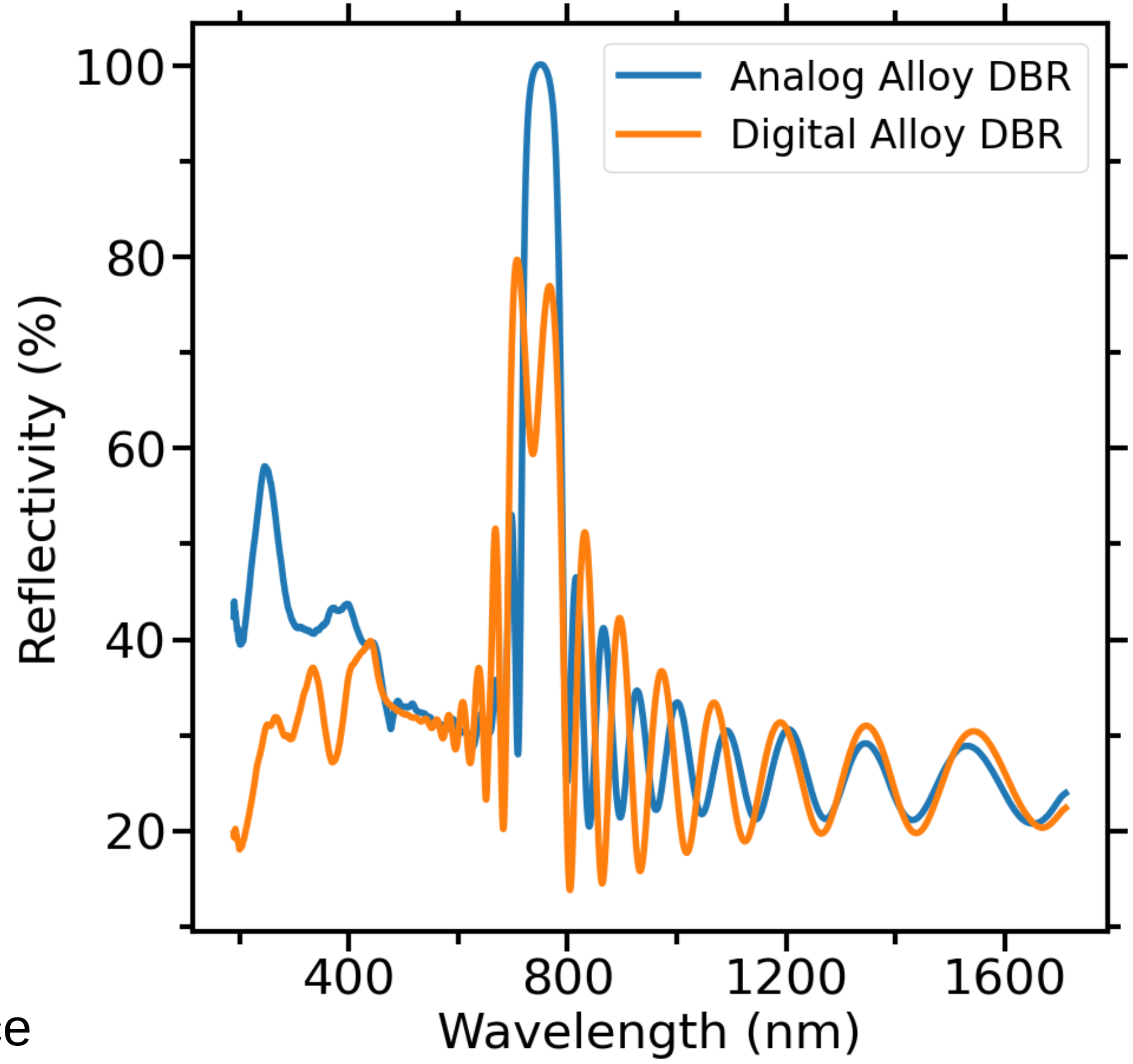
- Enhance QE by reflecting light for several passes through SSL
- Designed for peak reflectivity at 770 nm
- Analog and Digital AlAs/AlGaAs DBR structures designed and tested
- Digital Alloy: better uniformity across wafer





UCSB: Digital vs. Analog DBR first results

- Digital alloy
  - potentially higher uniformity across wafer
  - GaAs Absorption in the digital alloy
    - Not viable structure
- Analog alloy
  - Peak reflectivity varies by ~30 nm across sample (¼ of 2” wafer)
    - Needs improvement,
      - rotation while growing will help
      - More periods will improve
  - Average reflectivity peak 20 nm from design
  - Structure can be designed to meet requirements (another benefit of AlAs/AlGaAs)



Next samples

- Add DBR to photocathode
- Optimize photocathode structure
- Digital alloy well and/or barrier in SSL could reduce the random alloy disorder, increase splitting

Budget summary

	FY20 ($k)	FY21 ($k)	Totals ($k)
a) Funds Allocated	126.2	276.2	402.4
b) Actual Costs to date	126.2	130.3	229.5

~4 month delay starting project

Extension through December 31, 2022: Student funding

Plan to seek further extension
- Funding for student and equipment fees at UCSB
- Travel for student to JLab
- Further testing of superlattice samples

Project Summary

JLab: microMott polarimeter fixed & working

- First UCSB sample tested

UCSB

- Initial GaAs/GaAsP growth characterized
  - Extensive chamber maintenance to remove phosphorous compounds
- InAlGaAs/AlGaAs superior in many aspects
  - Literature shows equivalent QE & Pol
  - Growth requirements more standard
  - Material properties more tunable
- First InAlGaAs/AlGaAs samples delivered to JLab
- Next samples: DBR structure, Digital Alloy layer, optimized SSL in progress