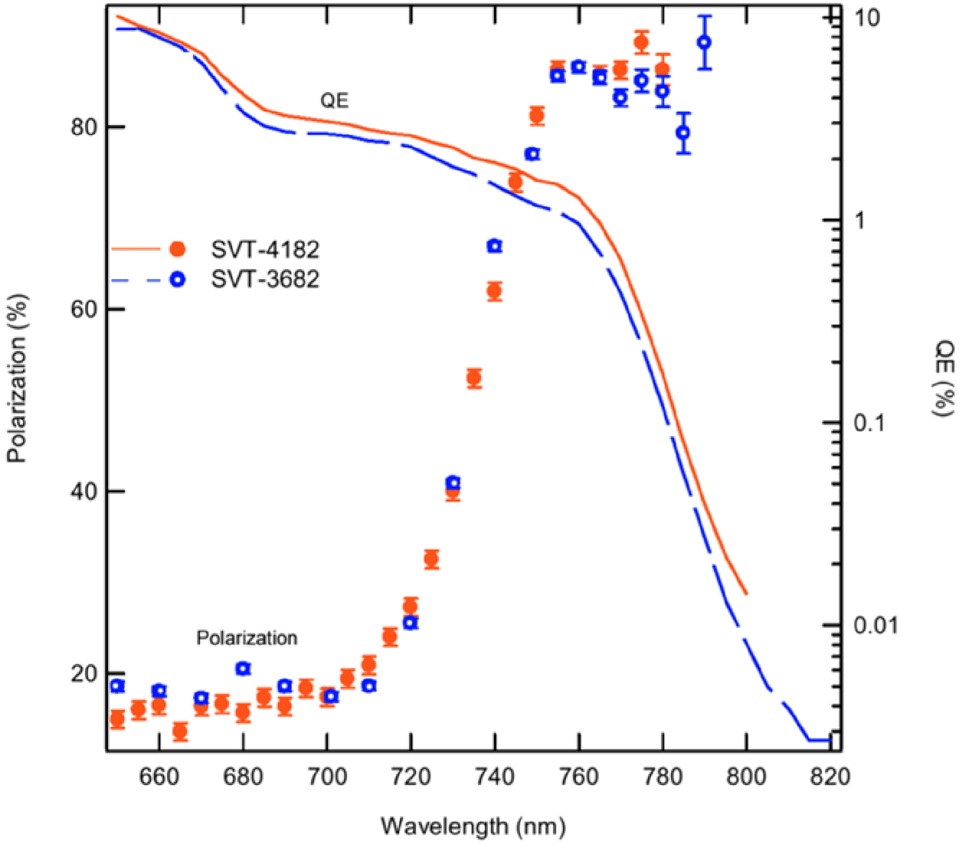
Investigation into chemical beam epitaxy (CBE) for high polarization strained superlattice GaAs/GaAsP photocathodes

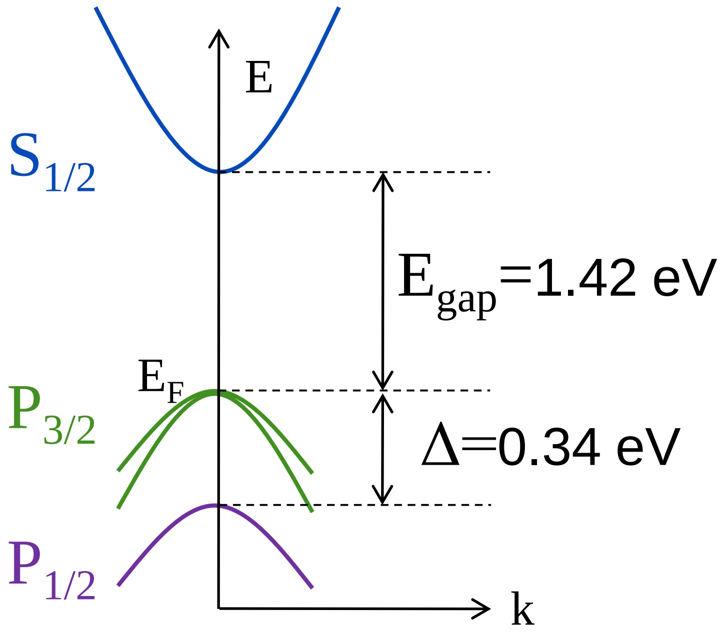
Annual NP Accelerator R&D
and AI/ML PI Meeting
November 30, 2021

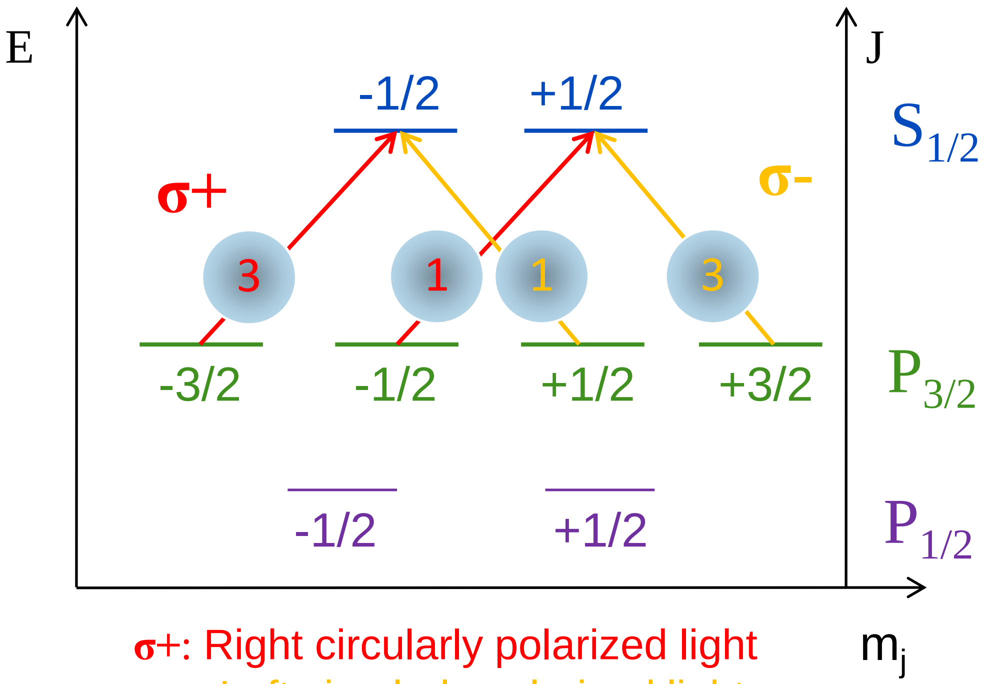


Marcy Stutzman, Jefferson Lab

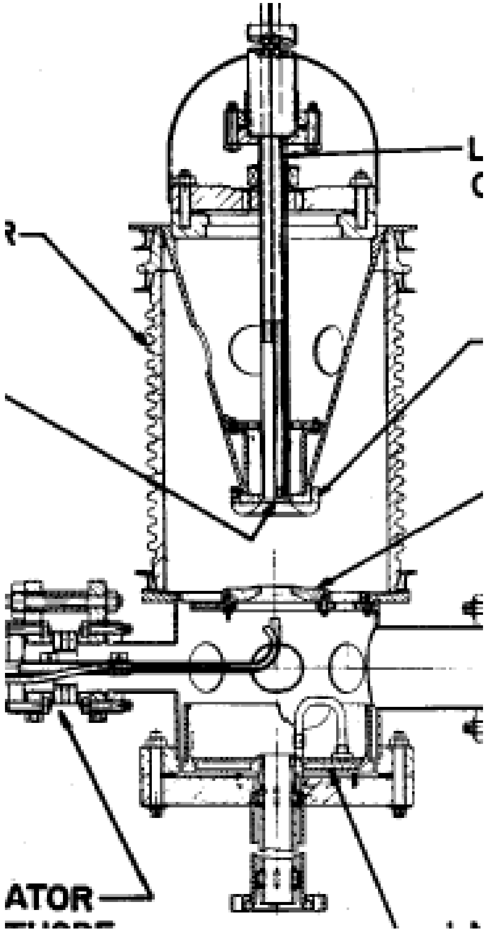
Chris Palmstrøm and Aaron Engle, UCSB

Spin Polarized Photoemission from Bulk GaAs





σ+: Right circularly polarized light
σ- : Left circularly polarized light

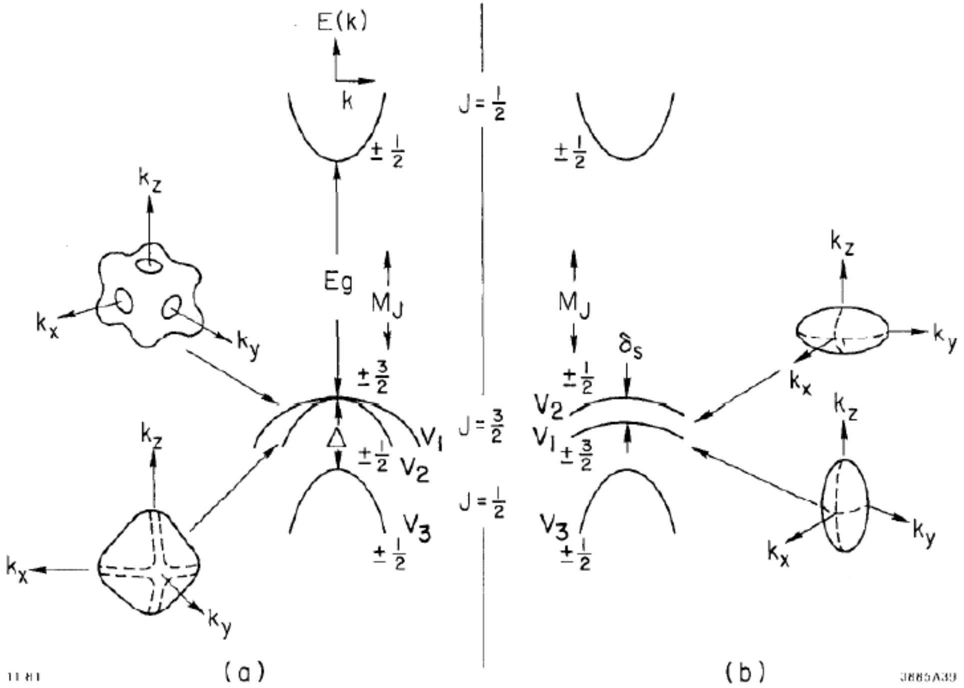


SLAC 1977

Strained GaAs

Breaking the 50% barrier

PhD thesis, Paul Zorabedian, SLAC Report 248, 1982



Application of a uniaxial strain removes the degeneracy of the $P_{3/2}$ state

Eliminate degeneracy of $P_{3/2}$ state via "Interface Stress Method"

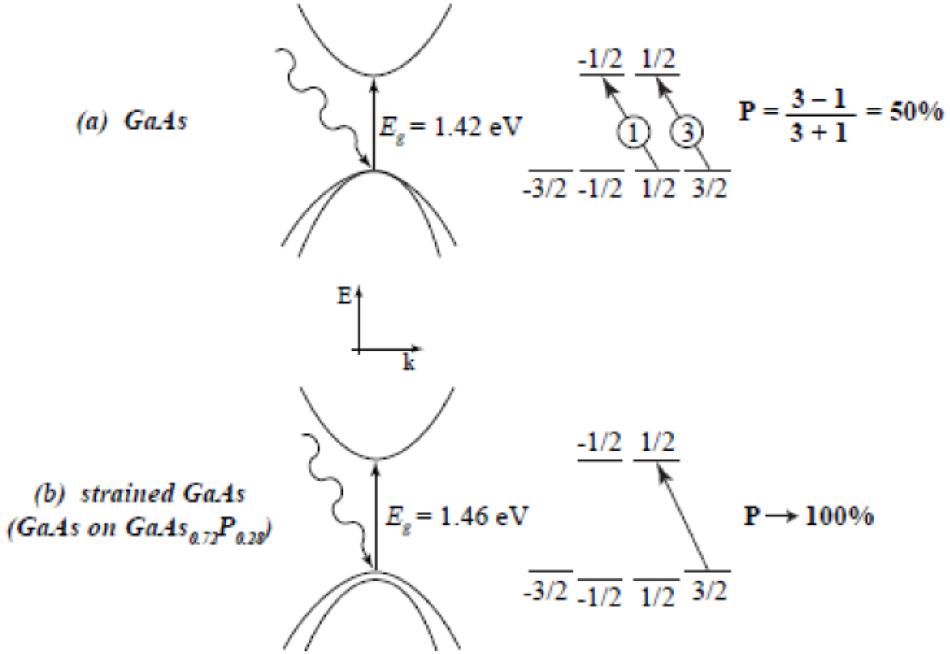
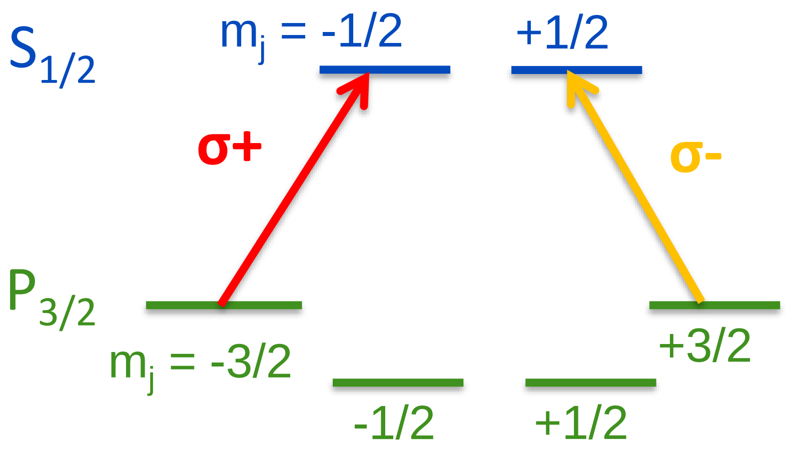
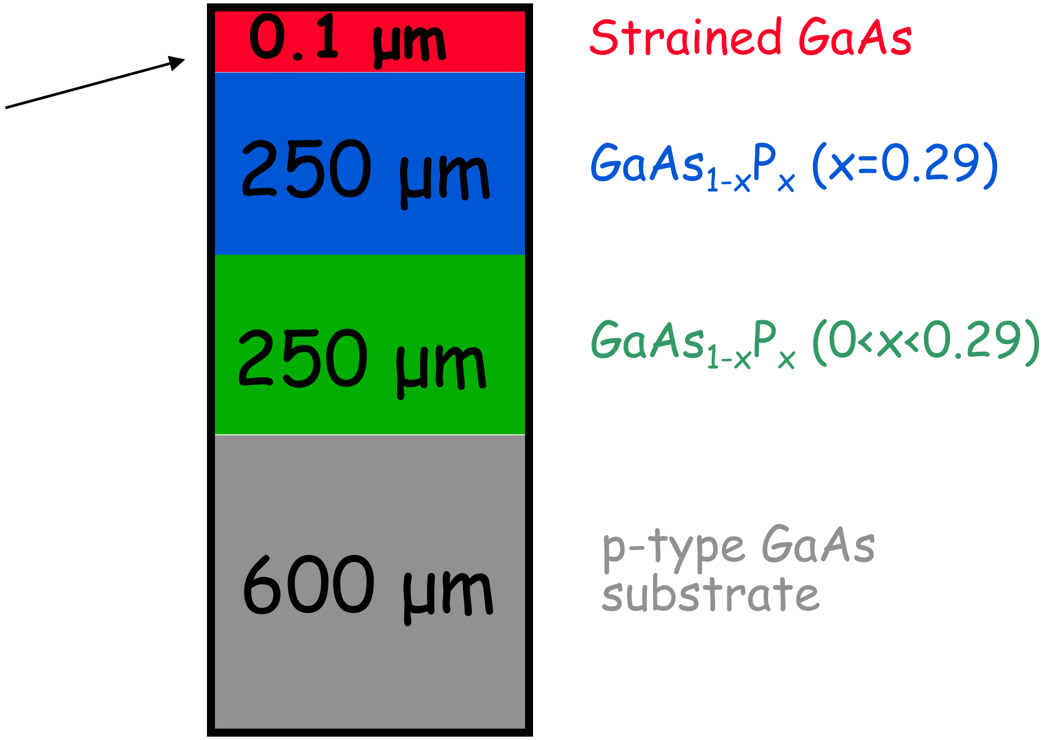


Image from Pablo Saez, PhD Thesis, Stanford University, SLAC Report 501, 1997

Strained layer GaAs



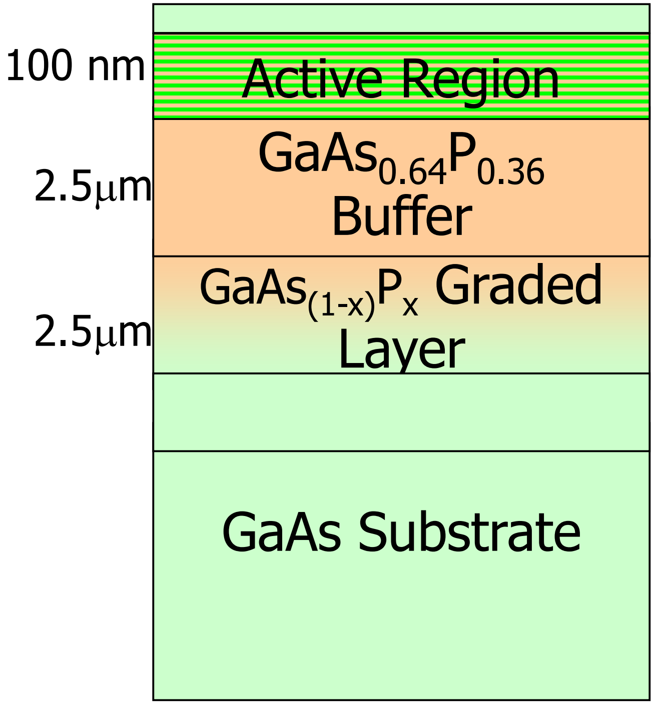


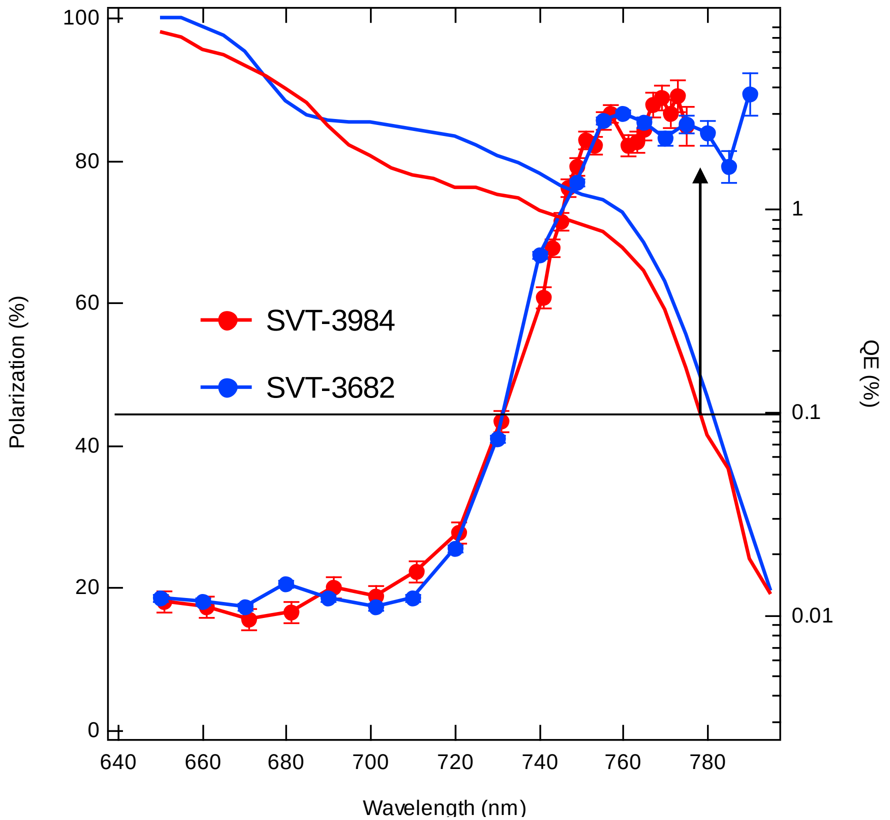
- ✓ Polarization 75% >> 50% ☺
- ✓ Strain relaxes in 100 nm layer
- ✓ QE 0.1%

MOCVD-grown epitaxial spin-polarizer wafer

Maruyama et al., Phys. Rev. B, **46** 4261 (1991)

Strained layer superlattice GaAs/GaAsP





D. Luh et al, SLAC, PESP2002

QE 1% and Polarization 85%

SVT ASSOCIATES

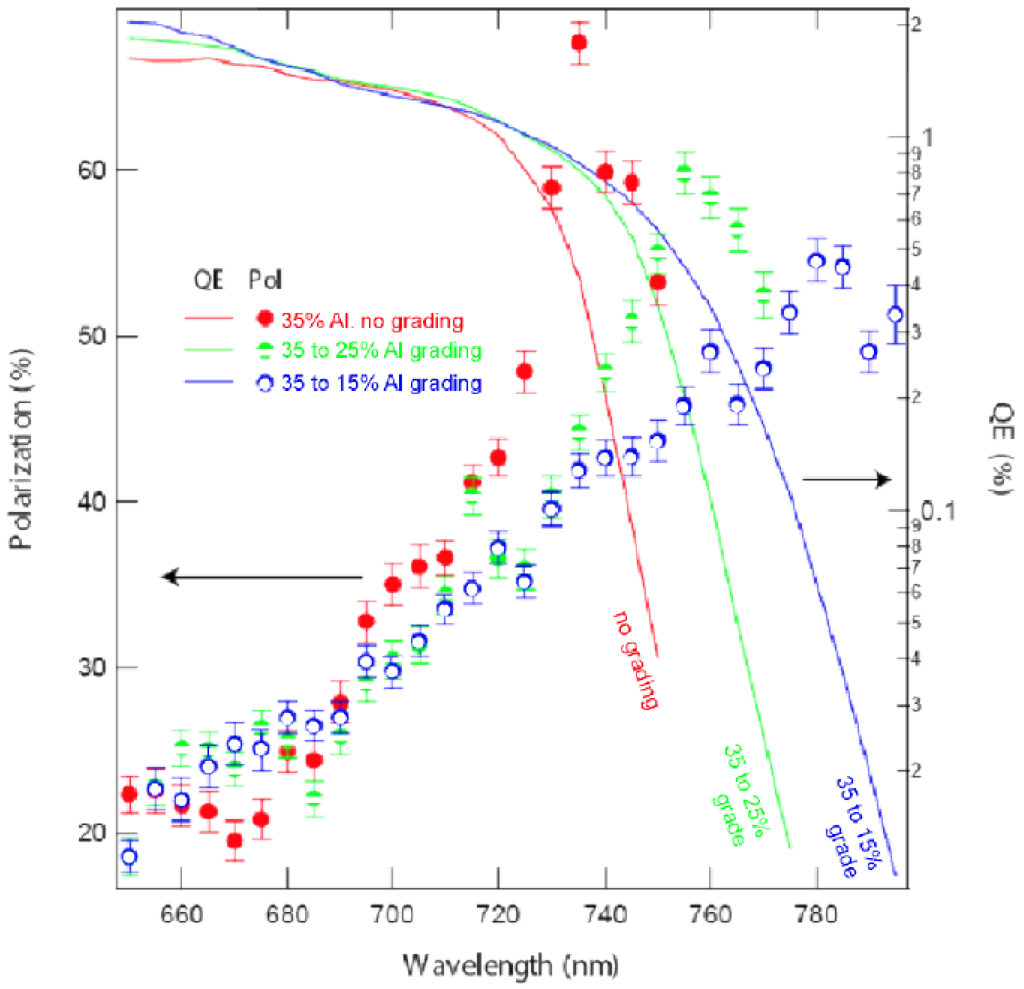
From Aaron Moy, SVT Assoc and SLAC, PESP2002

Innovation through SBIR program

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

Variations

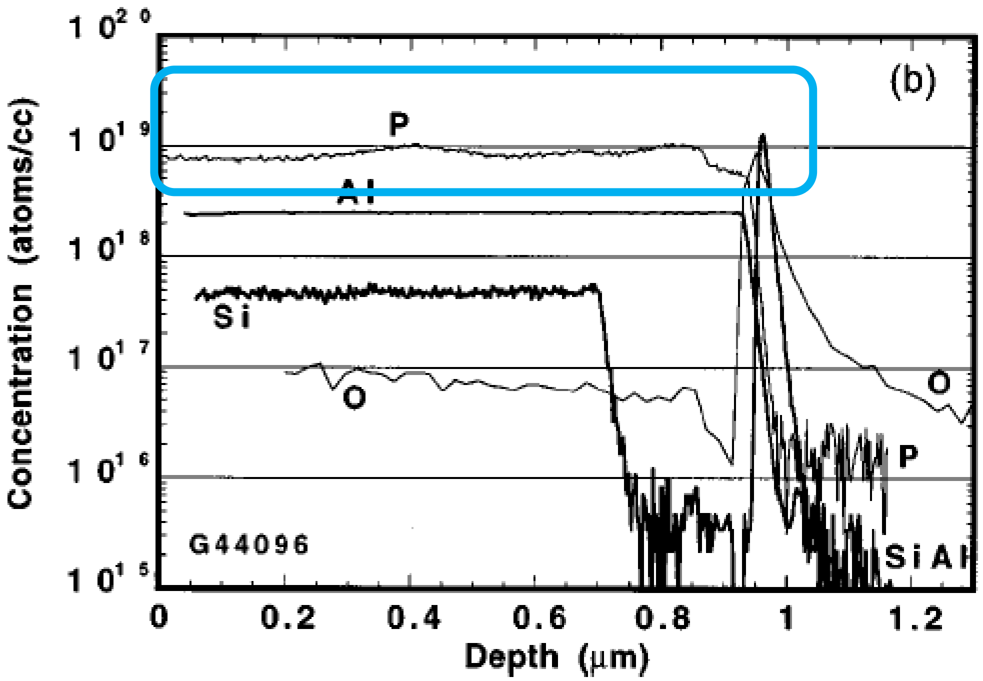
- Quantum Well thickness
- Barrier thickness
- Strain layer concentration
- Number of periods



AlGaAs/GaAs, A. Moy 2009

Technical Challenges of Growing GaAs/GaAsP using GSMBE

- GSMBE (Gas source MBE) uses crackers for AsH_3 (arsine) and PH_3 (phosphine)
  - Both gasses Toxic, Flammable
  - Phosphorus grows on MBE walls
    - Generates phosphine gas & phosphoric acid when venting
    - Absorbs water and has high water vapor pressure when pumped back down
    - Residue cannot be scraped off - ignites
      - Careful degassing can solve this
  - Phosphine residue can cause high background in subsequent samples

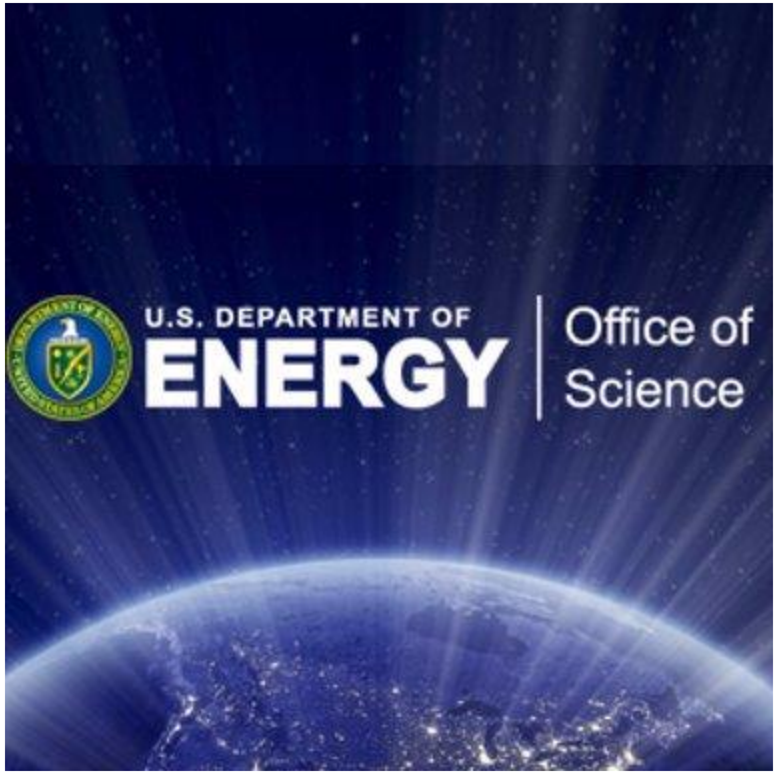


SIMS of AlGaAs grown after Phosphorus contamination

W.E.Hoke and P.J. Lemonias JVSTB **17** 1999, p. 2009.

SBIR research program lifetime

- SBIR Program Goals include
  - Stimulate technological innovation
  - **Use small business to meet Federal R/R&D needs**
- SBIR Phases
  - Phase I explores the feasibility of innovative concepts with awards up to $250,000 and 12 months.
  - Phase II is the principal R&D effort, with awards up to $1,600,000 and 2 years.
  - *Phase III: pursue commercial applications of their R&D with non-SBIR/STTR funding.*
    - Market for high polarization photocathode material is small
    - Commercialization not (yet?) financially viable



Main Goal: New growth method to restore photocathode supply

- DOE Funding Opportunity 20-2310
  - CBE (Chemical Beam Epitaxy)
    - Jefferson Lab:
      - Marcy Stutzman
    - University of California Santa Barbara
      - Chris Palmstrøm and Aaron Engel

- Investigate Chemical Beam Epitaxy for growing high polarization, strained superlattice photocathodes

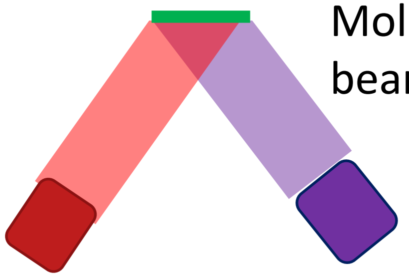
MBE, GSMBE, CBE and MOCVD

MBE

Gas Source Molecular Beam Epitaxy

elemental As, P, Ga

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



Molecular beams

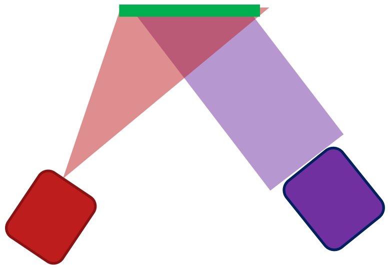
GSMBE

Gas Source Molecular Beam Epitaxy

AsH_3, PH_3, elemental Gallium

Used at SVT

Molecular and gas sources



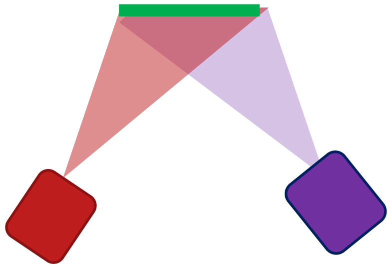
CBE

Chemical Beam Epitaxy

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

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

Low pressure gas sources



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

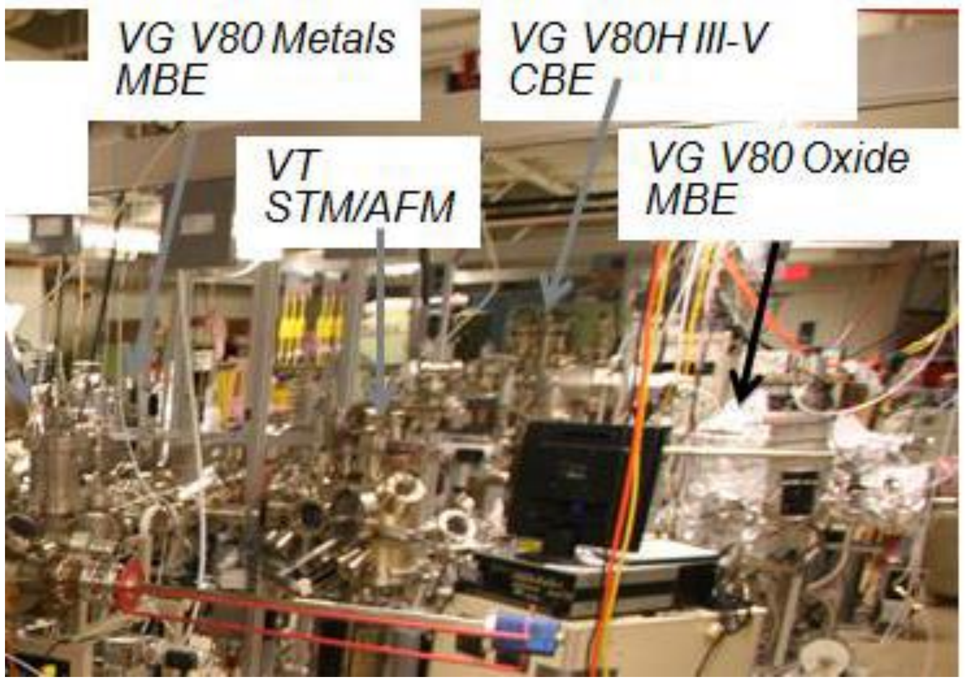
Gas sources

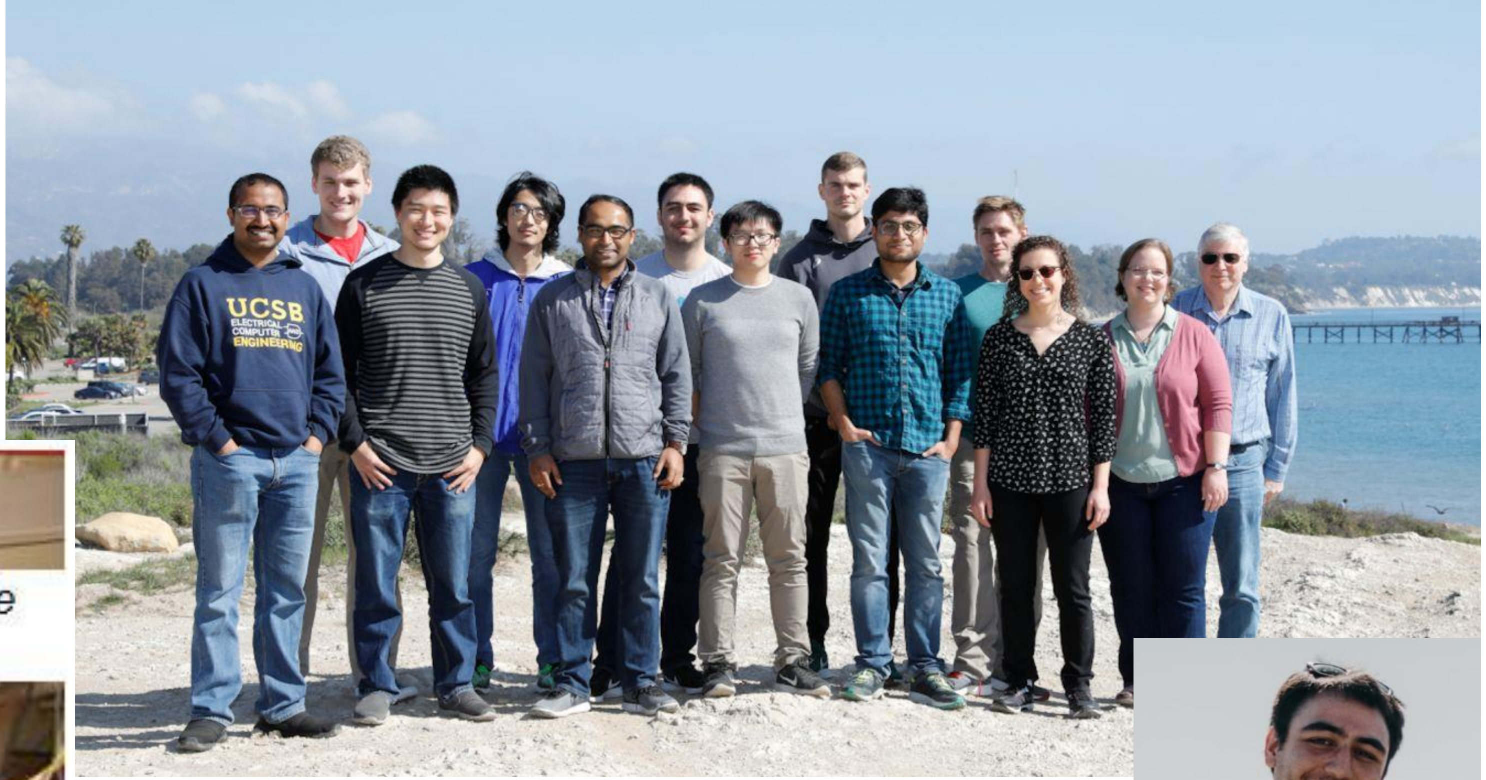
CBE: Photocathode progress

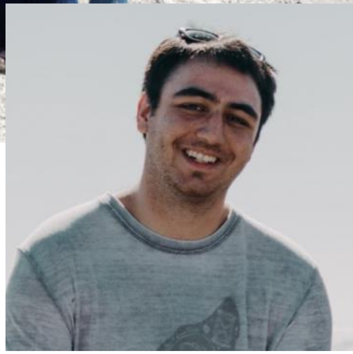
Chris Palmstrøm Group, UCSB

- Aaron Engel, graduate student

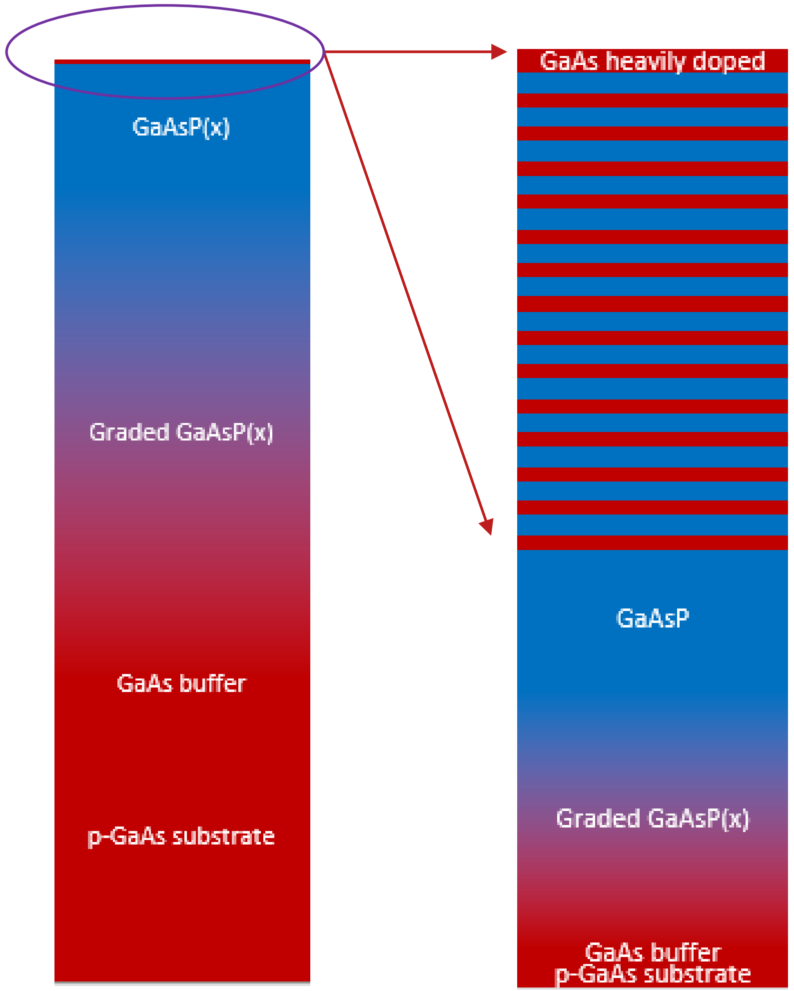
- Chemical Beam Epitaxy System







Wafer growth



To scale

Superlattice scaled up

- ➢ Epitaxial Buffer Layer grown on GaAs
- ➢ Graded GaAs to $GaAs_{(1-x)}P_x$
- ➢ $GaAs_{(1-x)}P_x$ layer
- ➢ Superlattice
- ➢ Heavily doped top layer

Parameters to vary

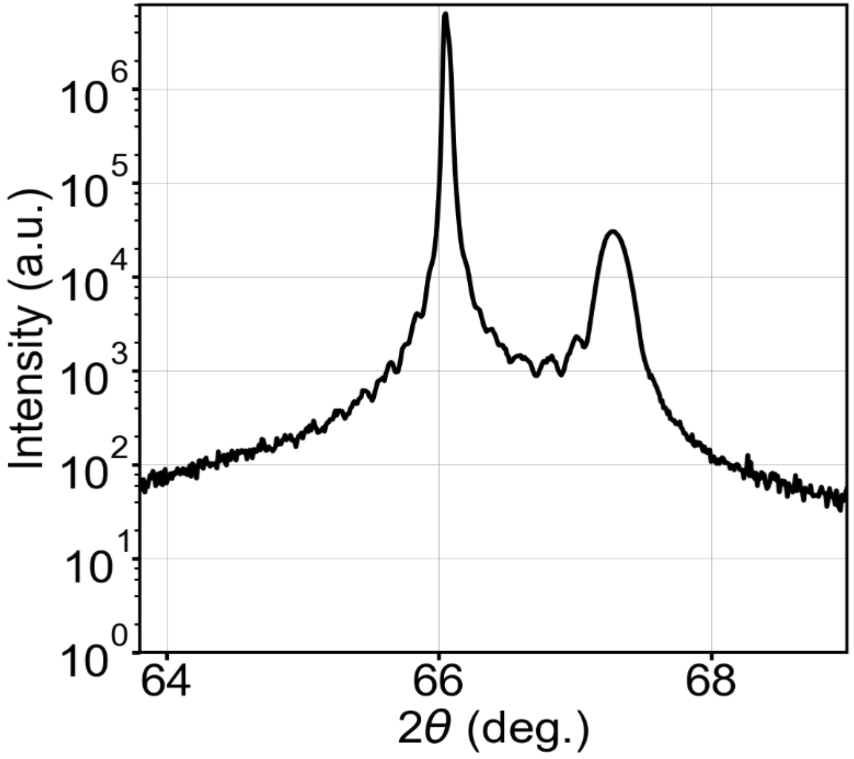
- Substrate Temperature
- Source Temperature/Pressures
- Time
- Grading profile
- Underlying crystal orientation
- Superlattice layer thickness

CBE: Strained Layer growth

- Start with $GaAs_xP_{(1-x)}$ on GaAs
  - Temperature
  - gas pressures
- Testing
  - SIMS: Depth profile
  - XRD: Interface quality

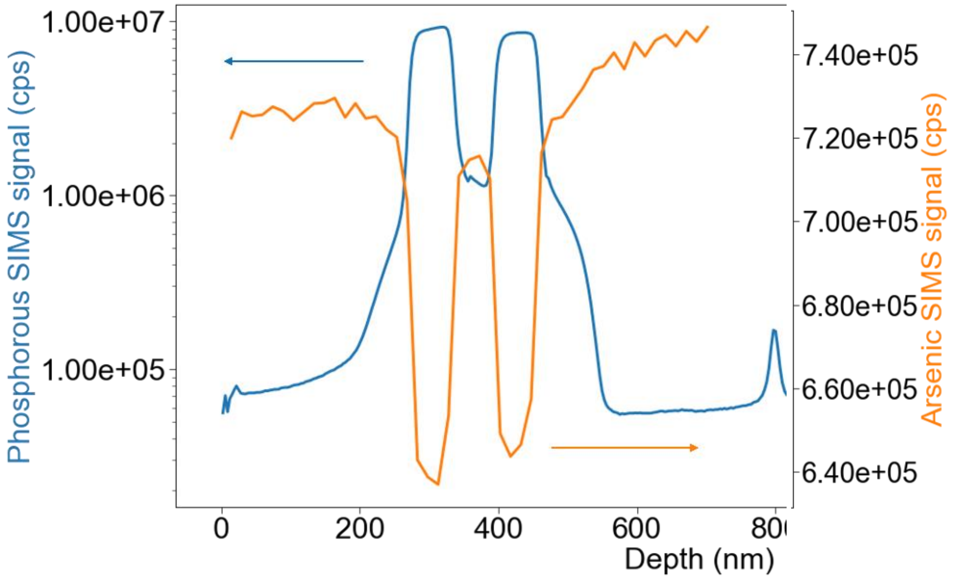
X-Ray Diffraction:
1 micron $GaAs_{0.75}P_{0.25}$ on GaAs

Testing analysis tools
for interface quality



SIMS:
Composition
vs. Depth

GaAs:Be 250 nm
$GaAs_{.83}P_{.17}$:Be 50 nm
GaAs:Be 50 nm
$GaAs_{.83}P_{.17}$:Be 50 nm
GaAs:Be 4 µm
GaAs:Zn >10^{18}



CBE: Graded dopant layer growth

- Computerized control developed for GaAs->GaAsP graded layer
  - Smoothly varying Phosphorous content

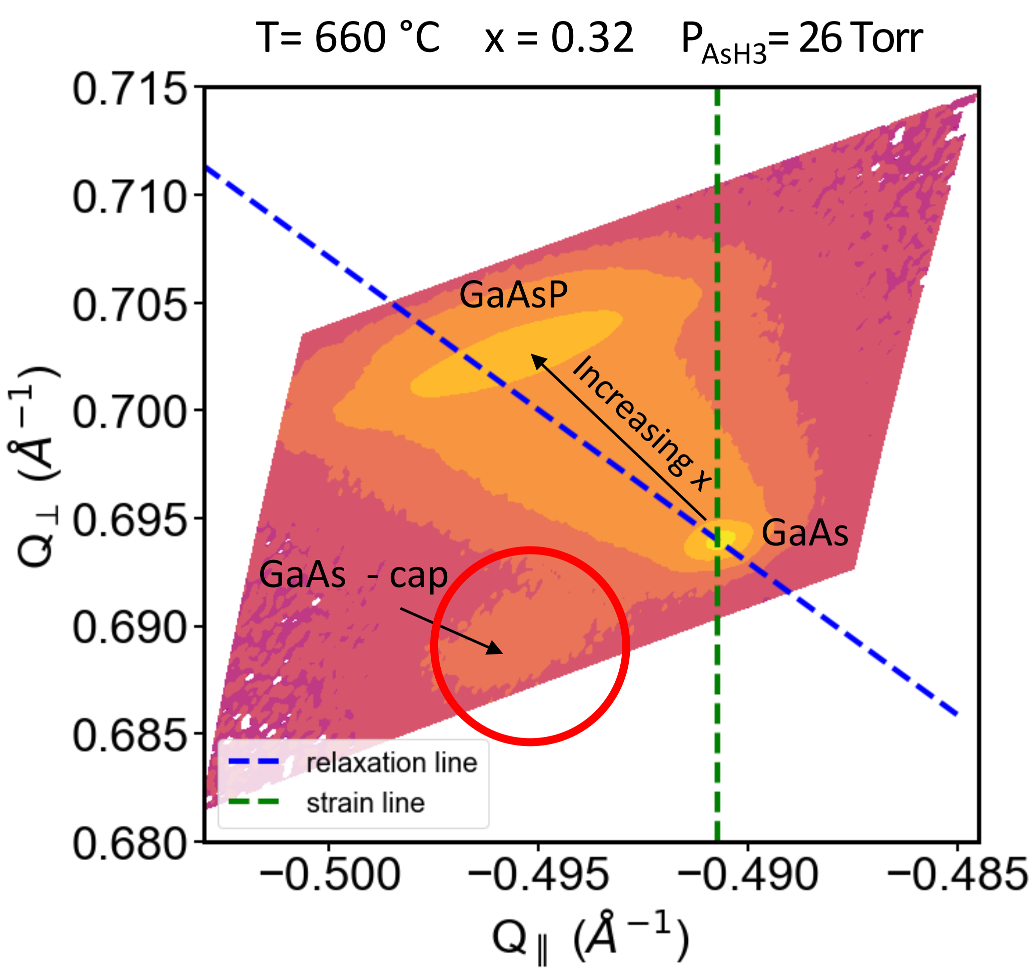
GaAs cap(5-10 nm)

GaAsP uniform conc. (1-2 µm)

$GaAs_{1-x}P_x$ graded buffer(2.5 µm)

p-GaAs substrate

- X-ray Reciprocal space mapping
  - Plot of lattice spacing during growth
  - Graded Layer with minimal strain
  - GaAs layer (5-10 nm) strained: lattice constant that of GaAsP



X-ray reciprocal space map for single 5-10 nm GaAs layer on GaAsPx

CBE: Photocathode progress

Next Steps

- Triethylgallium and phosphine create high vapor pressure background
  - Move to elemental Ga source?
  - Upgrade sample bonding from indium to gallium
- Grow photocathode material to test & test at JLab

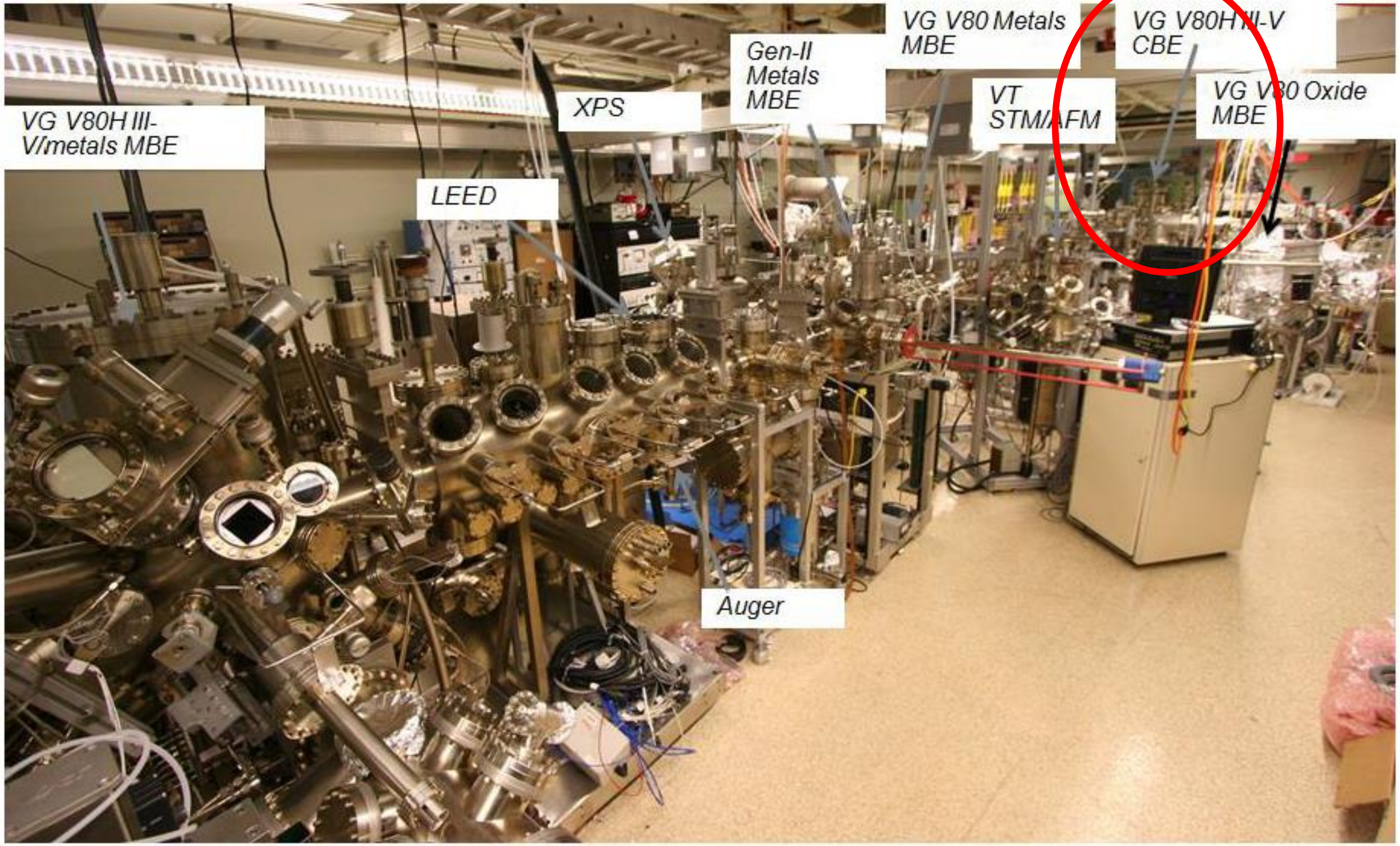


Figure 2 Semiconductor deposition system at Chris Palmstrom's lab at UCSB. The CBE system for the growth of this material is shown at the back and labelled "VG V80H III-V CBE".

Budget Status

- FY20 budget request/received
  - $276.2k / **$129.2k**
  - $93k unloaded / $113.3 loaded to UCSB (vs. $150k UCSB request)
  - Project scope reduced and delayed
- FY21 budget request/received
  - $276.2k / **$276.2k**
  - $150k unloaded / $187 loaded to UCSB
    - Graduate student
    - Supervisor
    - Materials and equipment use fees
  - JLab remainder
    - Design upgraded MicroMott polarimeter
    - Supplies for photocathode tests

	FY20	FY21	Totals
a) Funds allocated	$126,200	$276,200	$402,400
b) Actual costs to date	$110,414	0	$110,414

Project Goals

Tasks Year 1	2020 Q1	2020 Q2	2020 Q3	2020 Q4	2021 Q1	2021 Q2	2021 Q3	2021 Q4
• JLab: Replace MicroMott Polarimeter CEM								
• JLab: Train Student to use MicroMott (COVID delay)			x	x	x			
• JLab: Design upgrade for MicroMott	x	x	x	x	x			
• JLab: Build MicroMott Upgrade	x	x	x	x	x	x	x	x
• JLab: Polarization and QE measurements				x	x			
• JLab: High voltage gun tests								
• UCSB: Calibration runs	x							
• UCSB: Begin growing graded layers	x	x	x					
• UCSB: Grow superlattice layers to characterize thickness and interface	x	x						
• UCSB: Characterize the interfaces and composition at UCSB: SIMS and XRD								
• UCSB: Send initial material to JLab for testing				x				
• UCSB: Optimize for uniformity across wafer								
• UCSB: Grow and deliver superlattice photocathodes suitable for use at CEBAF								
• UCSB: Investigate DBR growth if extra time							x	x

Green: done
Blue: planned
x: delayed or eliminated

Conclusion

- Project milestone delays and scope reduction due to funding gap
- Graded layer grown successfully
  - Potentially reverting to solid source for gallium, same growth process same as SVT used
  - Good morphology and no unwanted strain in graded layer
- Superlattice interfaces characterized
  - Sharp definition seen in SIMS and XRD analysis
- Current work in progress to grow graded layer and superlattice for first test sample
- Anticipate receiving several high quality photocathodes by end of year

Questions?

backup

Manouchehr's instructions

PI Meeting Presentation Guidelines:

Each presentation should include the following information:

- Description of the project and the current status;
- Main goal of the project for which you received the FY 2020- 121 Accelerator R&D award , and/or Lab Data call for AI/ML award.
- A table showing annual budget and the total received to date (see below);
- A table showing major deliverables and schedule;
- Summary of expenditures by fiscal year (FY):
- There will be no written report or follow up actions required for this meeting.
- All talks will be posted on PI Exchange meeting page on NP website.
- **35 min talks should allow 7 min for Q/A and 30 min talks 5 min for Q/A**

	FY20	FY21	Totals
a) Funds allocated			
b) Actual costs to date			

1

M. Farkhondeh, 2021 NP Accelerator R&D and AI/ML PI Meeting, Nov 30, 2021