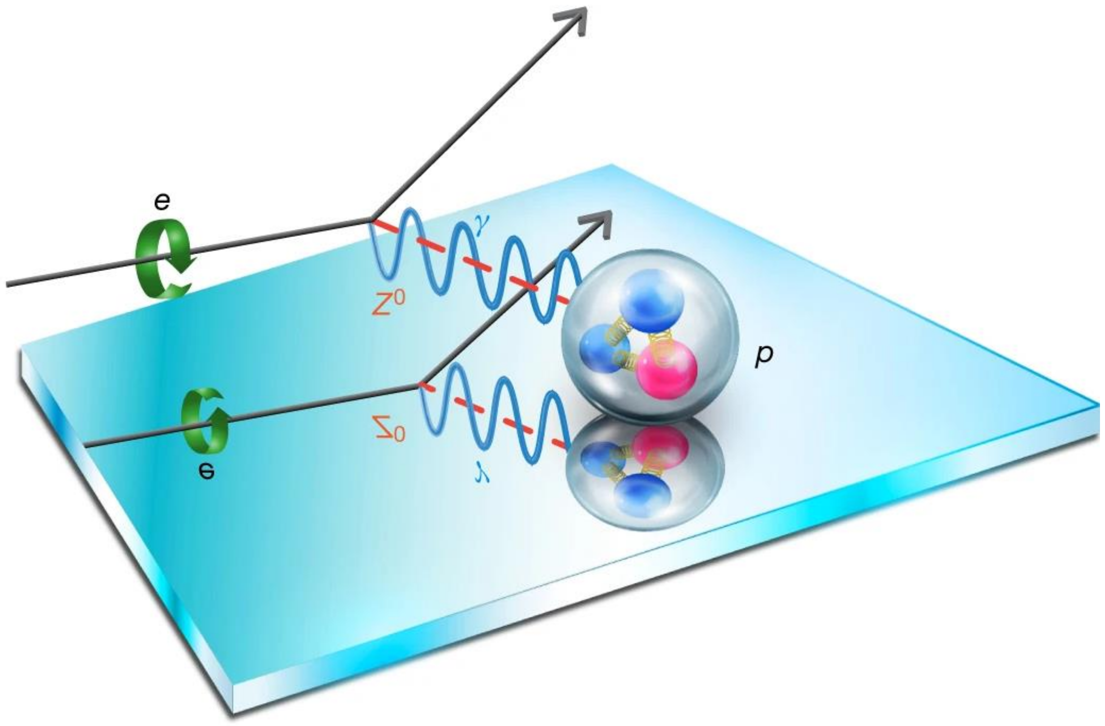
High Polarization Photocathode Research

Jefferson Lab research projects for high polarization photocathode development



From Nature, May 2018
Jefferson Lab Parity Violation
using high polarization photocathode electron sources

Marcy Stutzman
Center for Injectors and Sources

March 9, 2023

Motivation

2015 DOE NP Long Range Plan:

Polarized electron beams essential

SCIENCE HIGHLIGHTS AT THE ELECTRON ION COLLIDER

The EIC, with high energy and high luminosity polarized beams, will unite and extend the scientific programs at CEBAF and RHIC in dramatic and fundamentally important ways, as illustrated in the following subsections by highlights of relevant theoretical calculations and simulations under realistic experimental conditions.

2021 Jefferson Lab

Accelerator Advisory Committee Recommendations

Topic 23: Polarized Positrons Upgrade at CEBAF:

Recommendation

Continue the excellent work

Topic 22: Superlattice photocathode R&D:

Recommendation

R30: Develop a long-term plan for superlattice photocathodes to maintain the intellectual property and develop a production capability for the wider community

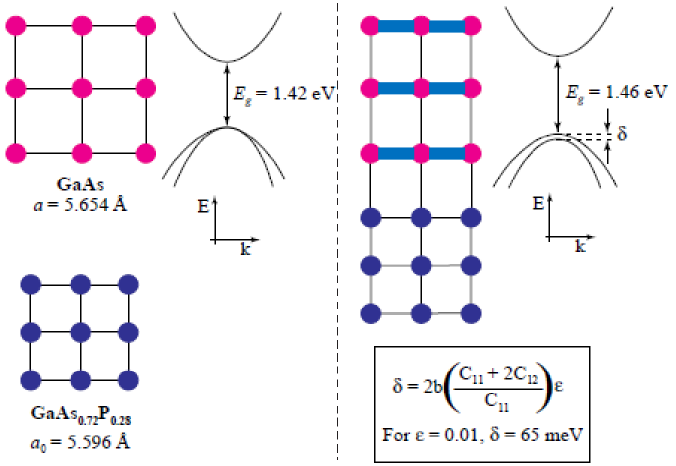
Jefferson Lab Perspective

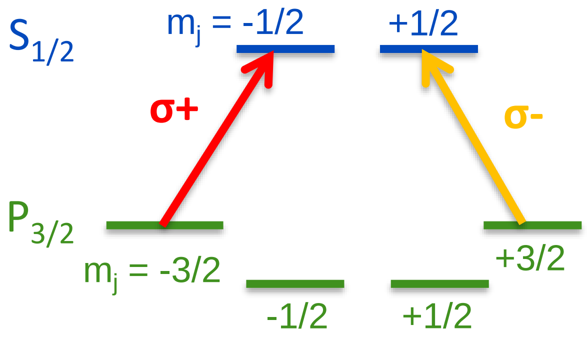
- Run CEBAF 12 GeV & Moller FY25-FY28
- CEBAF upgrades: 22 GeV CEBAF/e+ in out years
- EIC needs reliable high-P material
- Demonstrate leadership to our community
    - MESA under construction
    - Super KEK-B upgrade
    - ILC

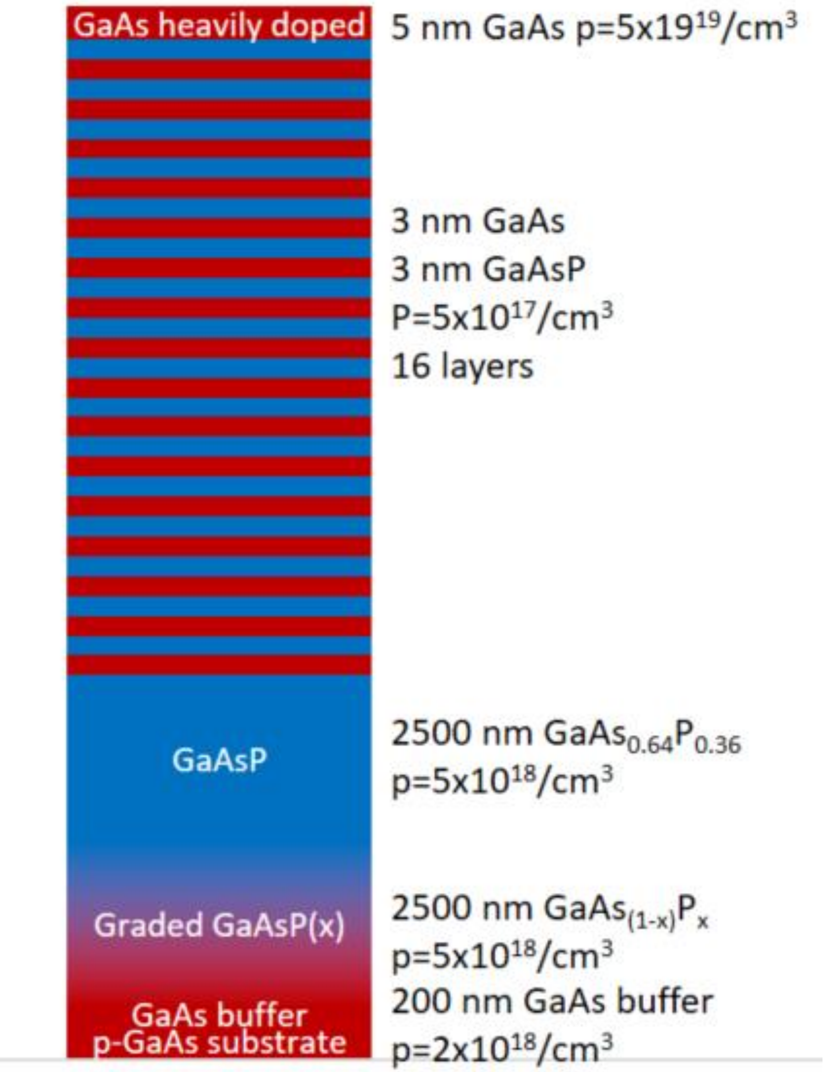
All Require High Polarization Photocathodes

Strained Superlattice Photocathodes

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







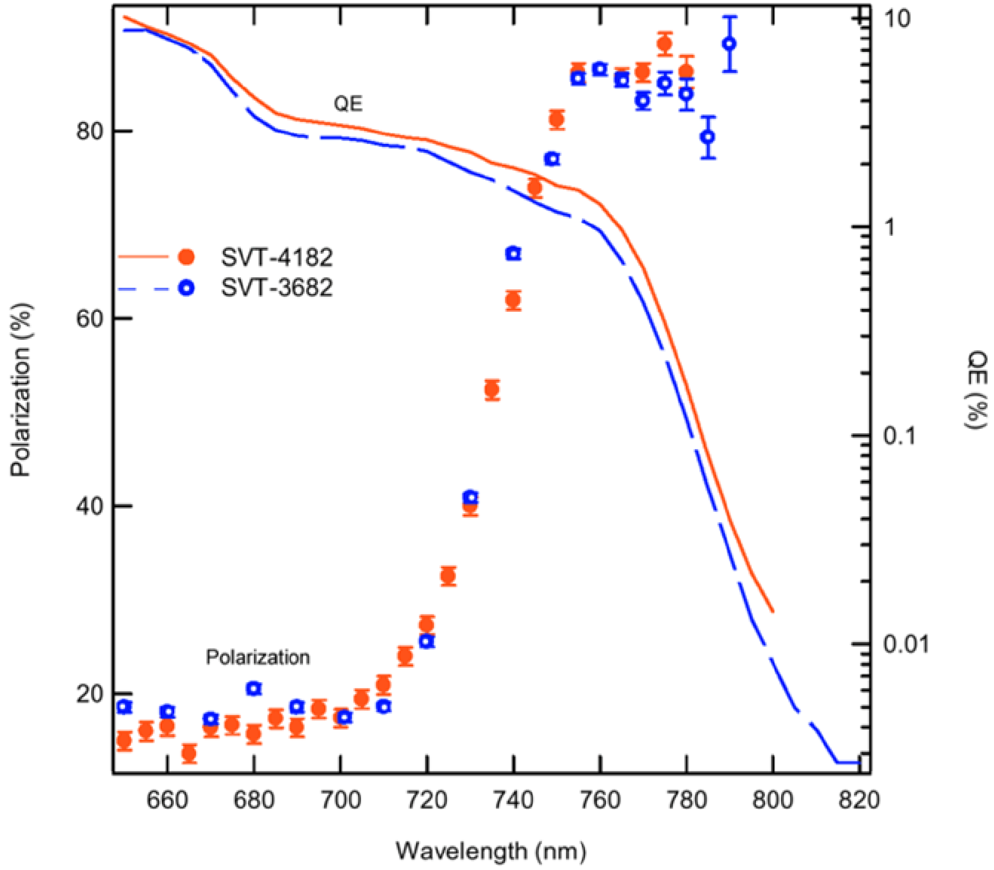
Strained Superlattice Photocathode Development

- 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 Compositions
  - **GaAs/GaAsP**
  - GaAsSb
  - AlGaAs/GaAs
  - *Distributed Bragg Reflector*

Variations

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

- SVT ended commercial fabrication ~2015



A. Moy, SVT Associates 2009

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High Polarization Photocathode Research Projects

MOCVD

(Metal Organic Chemical Vapor Deposition)

- JLab: M. Poelker and *(M. Stutzman)*
- BNL: E. Wang
- ODU/RIT: S. Marsillac, *(B. Belfore)*, G. Blume

CBE/MBE (Chemical/Molecular Beam Epitaxy)

- JLab: M. Stutzman
- UCSB: C. Palmstrøm, A. Engel

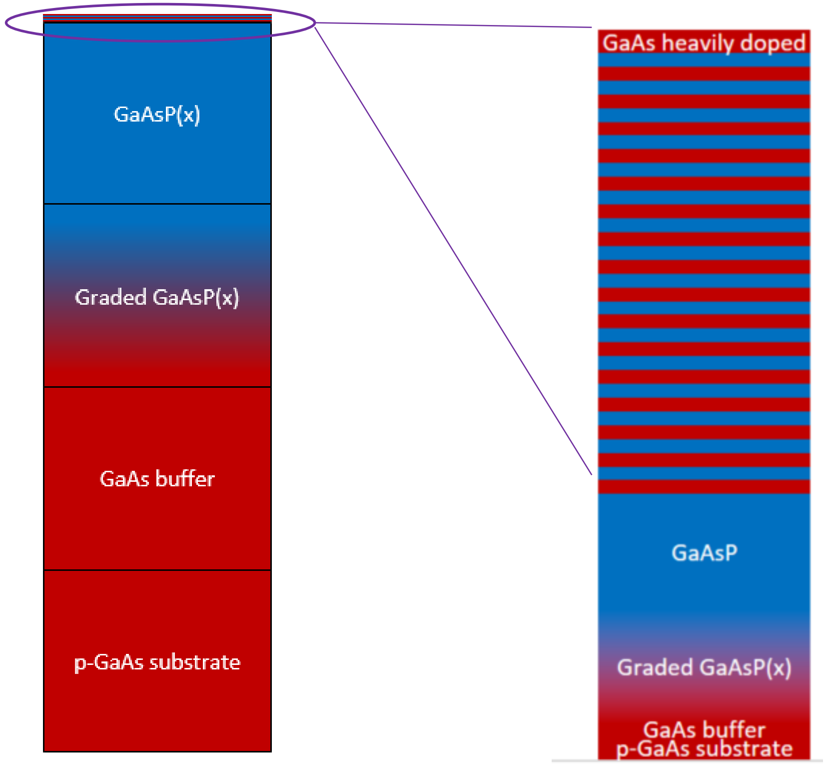
Nanostructured Photocathodes

- JLab: S. Zhang
- ODU: A. Rahman, H. Elsayed-Ali

MOCVD: JLab, ODU, BNL and RIT research project

MOCVD cathode growth

- Metal organic chemical vapor deposition
- Growth rate: 3 – 8 μm/hour
- Growth pressure: >100 mbar



Rochester Institute of Technology
MOCVD growth system

- Fast Growth
- Near-commercial growth facility
- Phosphorus less problematic

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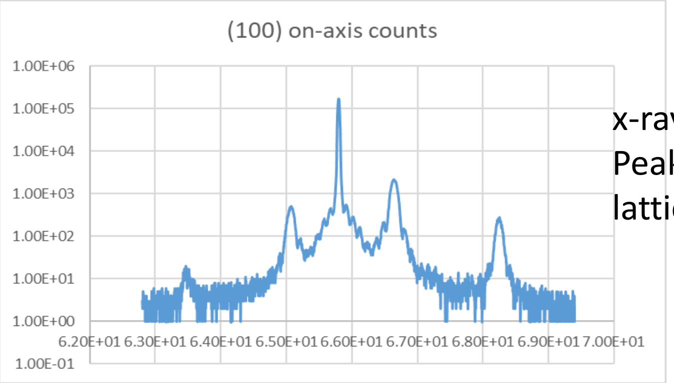
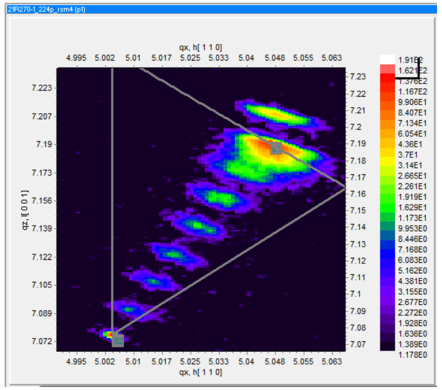
MOCVD SSL characterization and Results

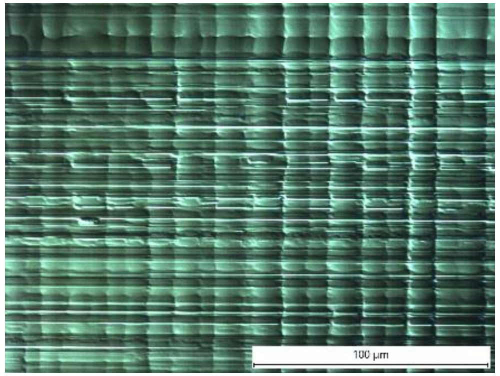


x-ray diffraction:
Peaks for different lattice constants

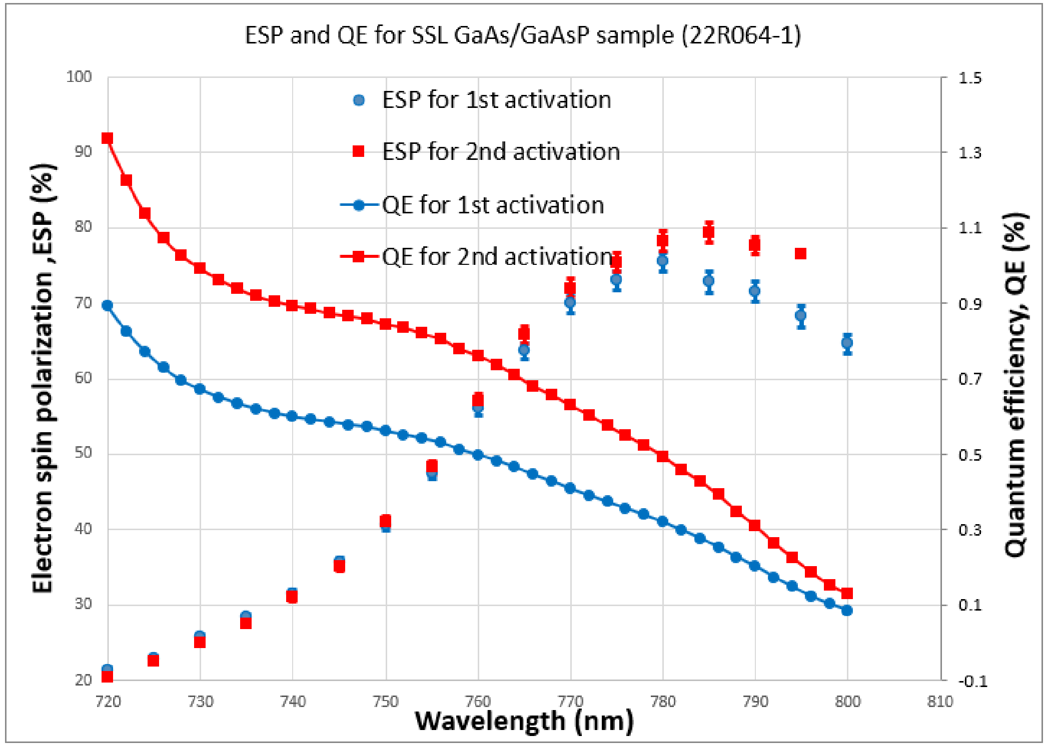


Reciprocal Space Map
Lattice constant through buffer layer

Microscopy:
Strain Relaxation



Early Result:
Good Polarization
Reasonable QE



Pol ~ 80%
QE ~ 0.4%
λ_{peak} ~ 785 nm

Grown at RIT: Ben Belfore.
Characterized in
BNL MiniMott: Wei Liu

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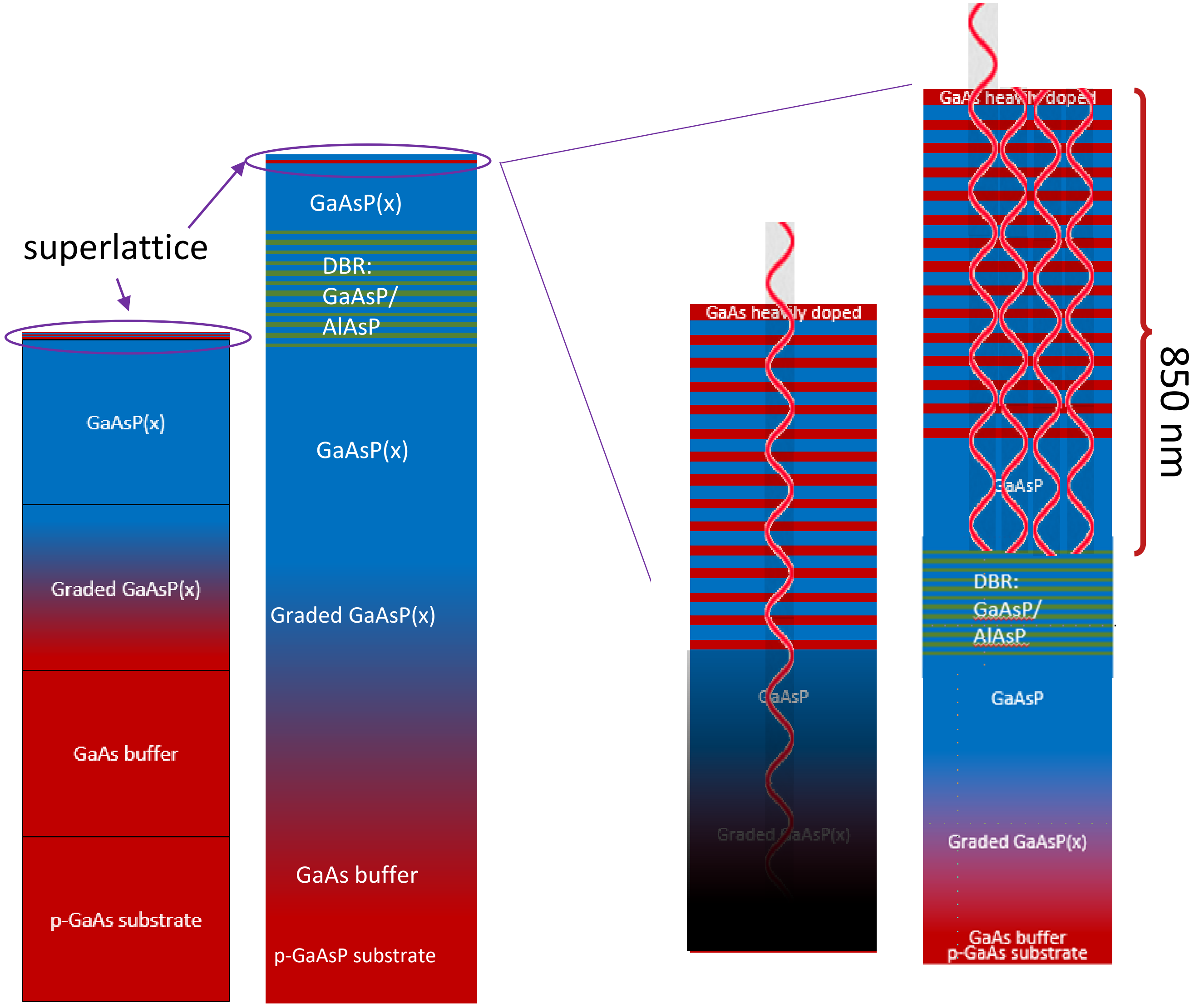
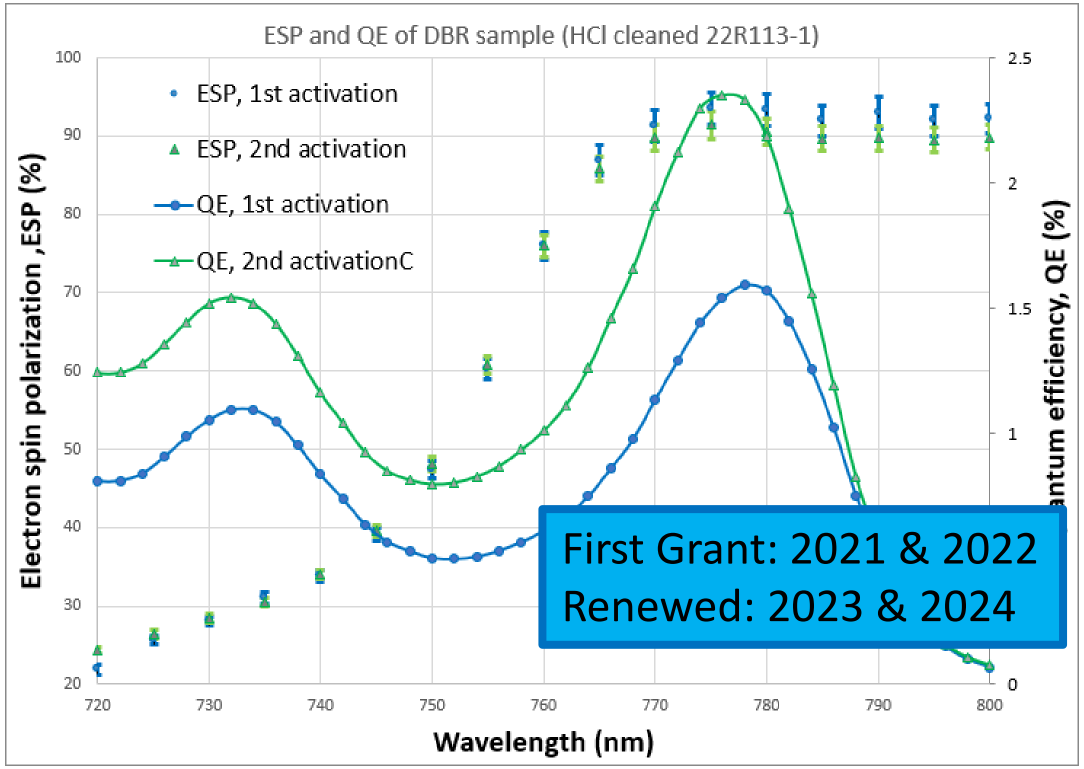
QE Enhancement: Distributed Bragg Reflector





Best DBR:
Excellent Polarization
Good QE (6% from SVT)

Pol ~ 92%
QE ~ 2.3%
λ_{peak} ~ 785 nm

BNL microMott, measurements by Wei Liu

Record-level quantum efficiency from a high polarization strained GaAs/GaAsP superlattice photocathode with distributed Bragg reflector
Appl. Phys. Lett. **109**, 252104 (2016); https://doi.org/10.1063/1.4972180
Wei Liu, Yiqiao Chen, Wentao Lu, Aaron Moy, Matthew Poelker, Marcy Stutzman, Shukui Zhang

CBE/MBE Photocathode Growth at UCSB

U California
Santa Barbara

Semiconductor Deposition System

- CBE and MBE growth
- ARPES, XPS, STM, LEED, Auger analysis
- Collaborators for growing GaAs/GaAsP SSL

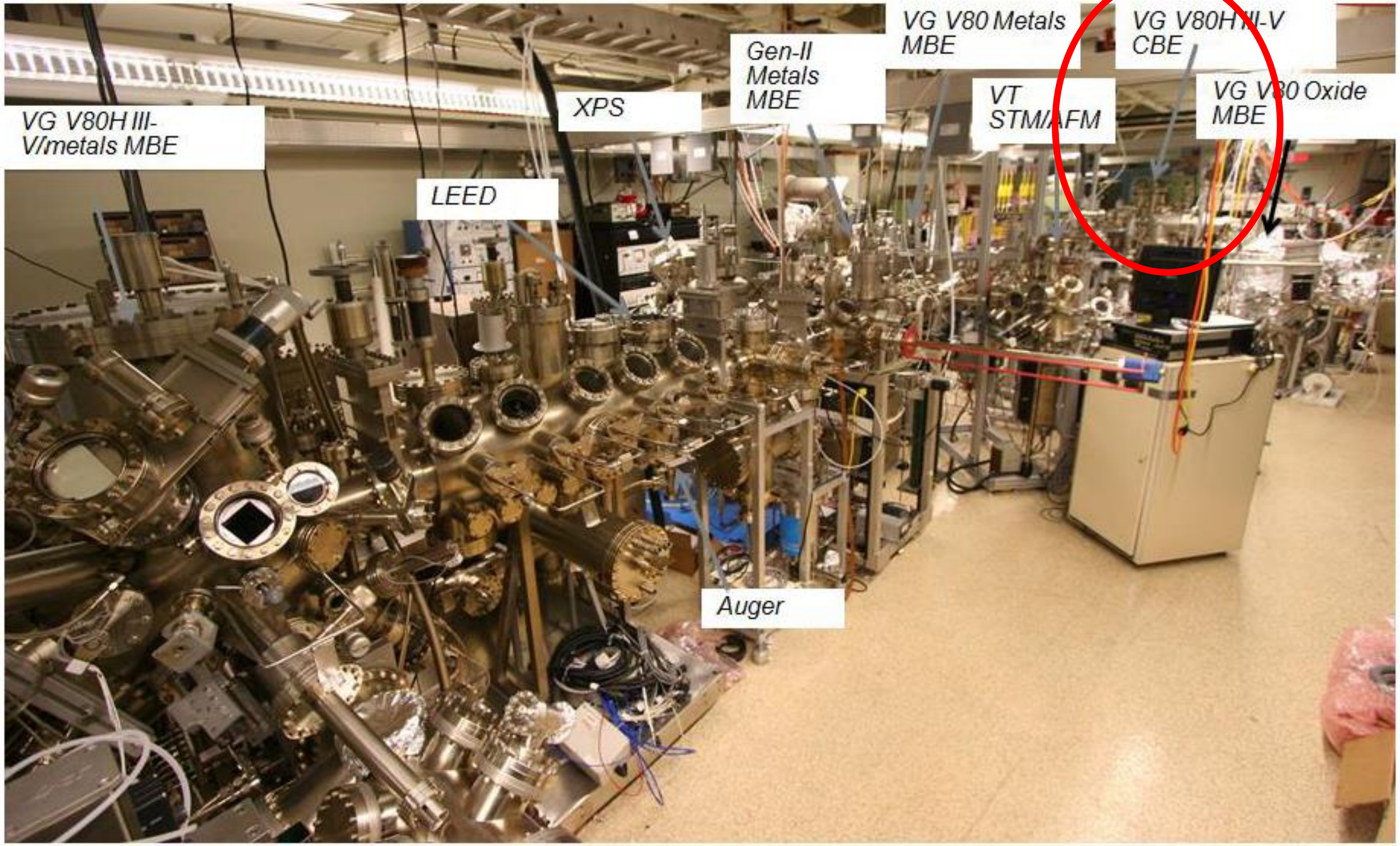
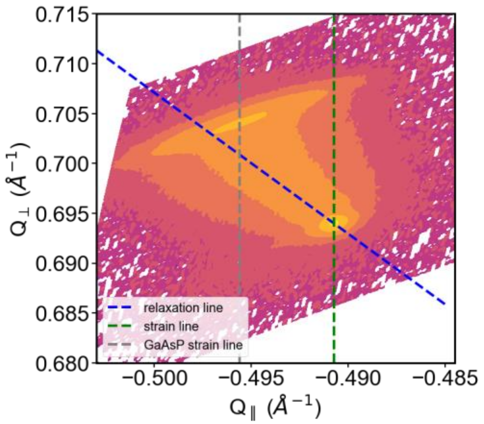
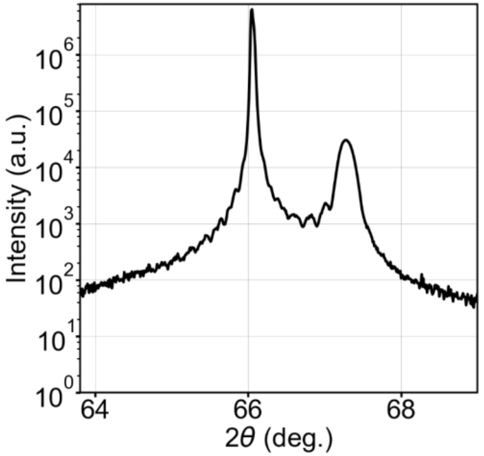


Figure 2 Semiconductor deposition system at Chris Palmstrom's lab at UCSB. The CBE system for the growth of this material is shown at the back and labelled "VG V80H III-V CBE".

CBE & MBE GaAs/GaAsP

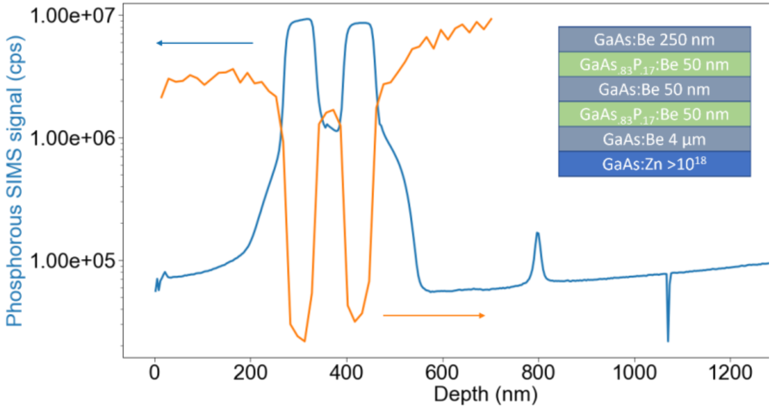


X-ray Reciprocal space mapping



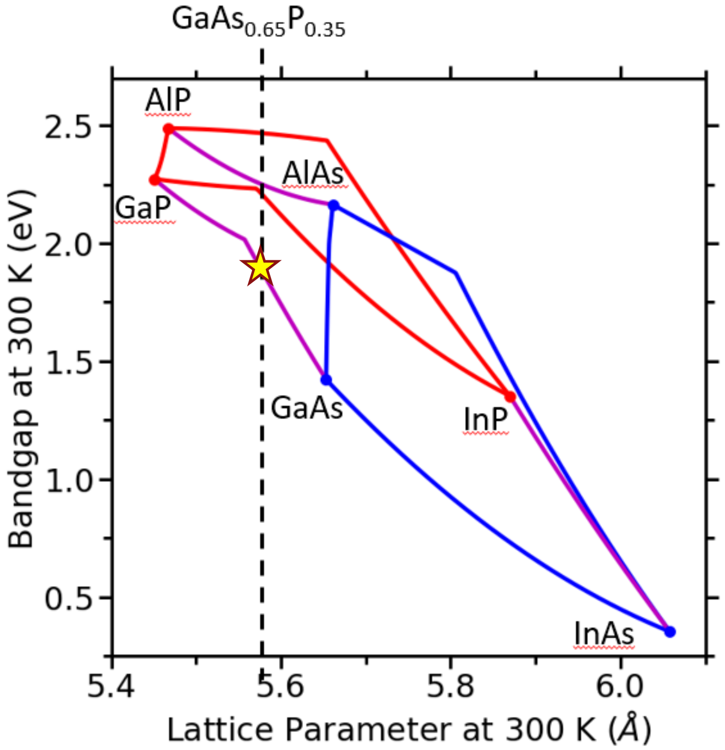
XRD Pendellösung fringes: crystal spacing

SIMS profile: thickness and interfaces



Drawbacks to GaAsP in MBE and CBE

- UHV chamber pressures required
- Triethyl-gallium -> high vapor pressure byproducts
- Extensive cleaning procedures
- GaAs and GaAsP optimal growth temperatures different
- Arsenic:Phosphorus ratio is fixed
  - GaAsxP(1-x) must sit on purple line
  - Changing band gap also changes strain in GaAs layer



Allowed band gaps and lattice constants for III-V semiconductor alloys

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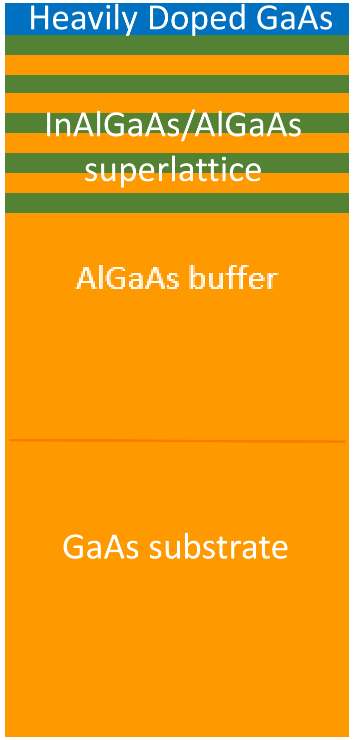
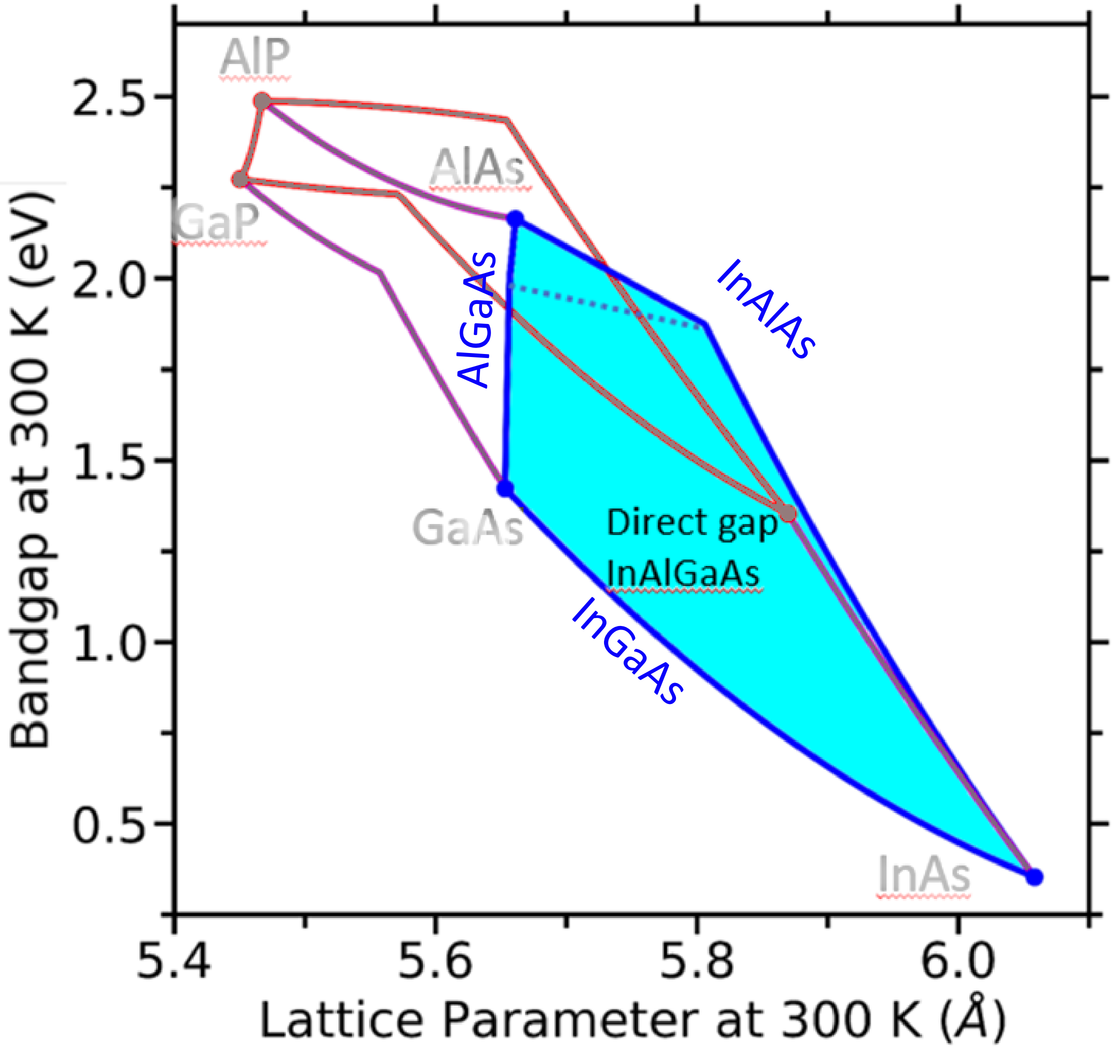
Benefits of InAlGaAs/AlGaAs



- Lattice constant of AlGaAs well matched to GaAs
  - No thick graded layer necessary
  - No lateral undulations from virtual substrate
- Better growth temperature match
- Easily tunable DBRs
  - AlAs/AlGaAs for DBR
  - well characterized optical constants
  - abrupt interfaces
- Wavelength tuning
  - Vary Ratio of Al in superlattice layers
  - Tunes emission wavelength independent of strain
  - Tunes valance band and conduction band offsets



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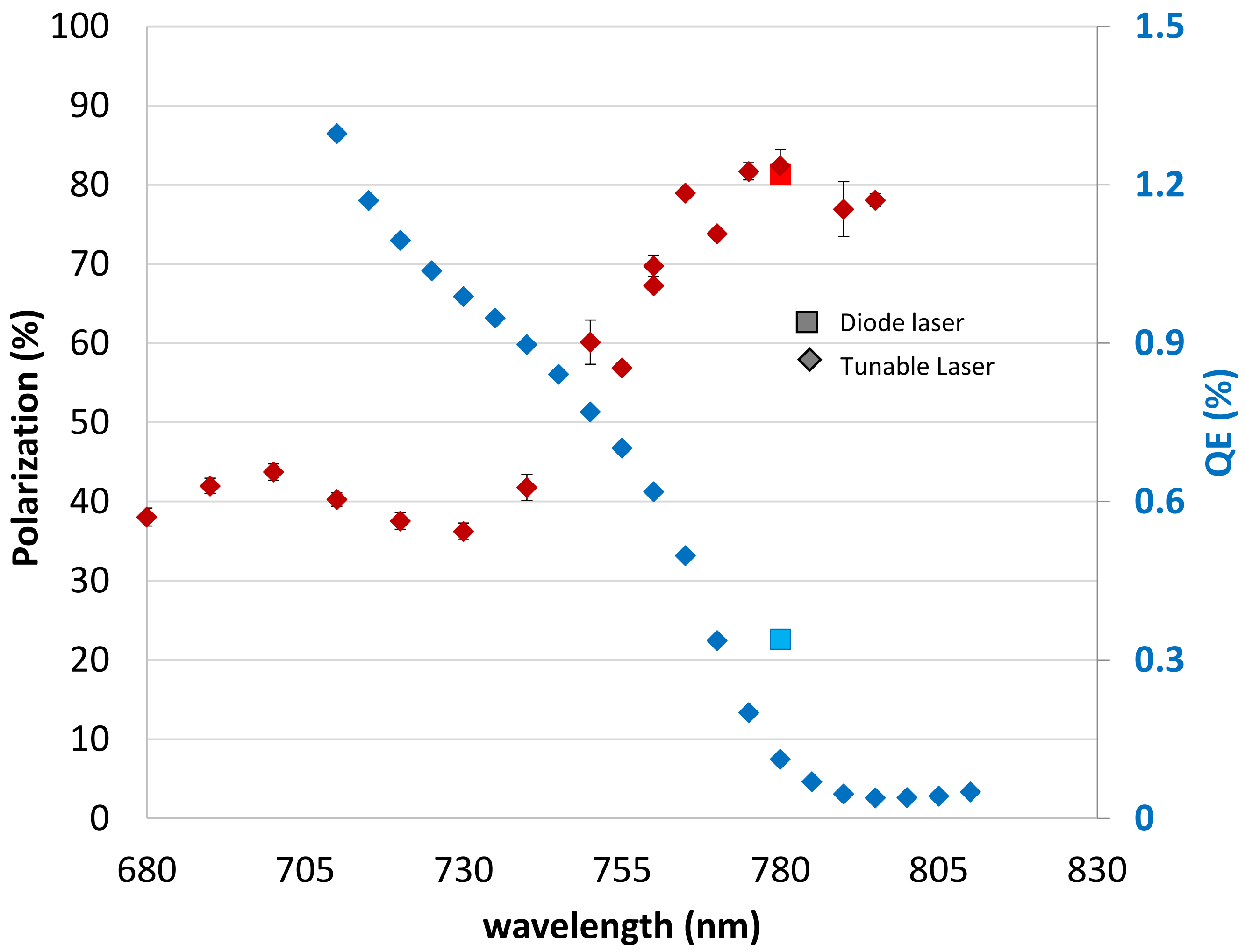
MBE grown InGaAs/InAlGaAs Superlattice



First Result:
Good Polarization = 82%
Reasonable QE = 0.3% at 780 nm

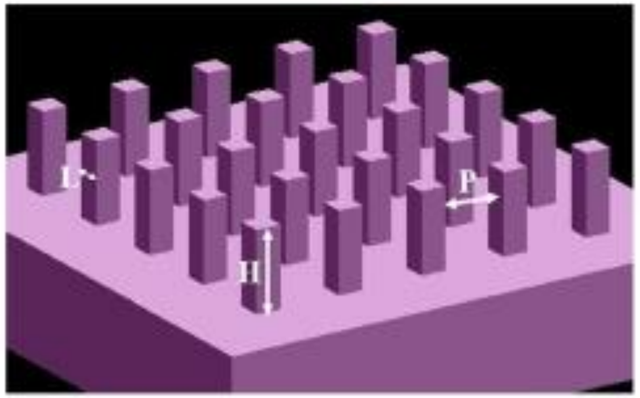
microMott measurements JLab

FOA project with UCSB

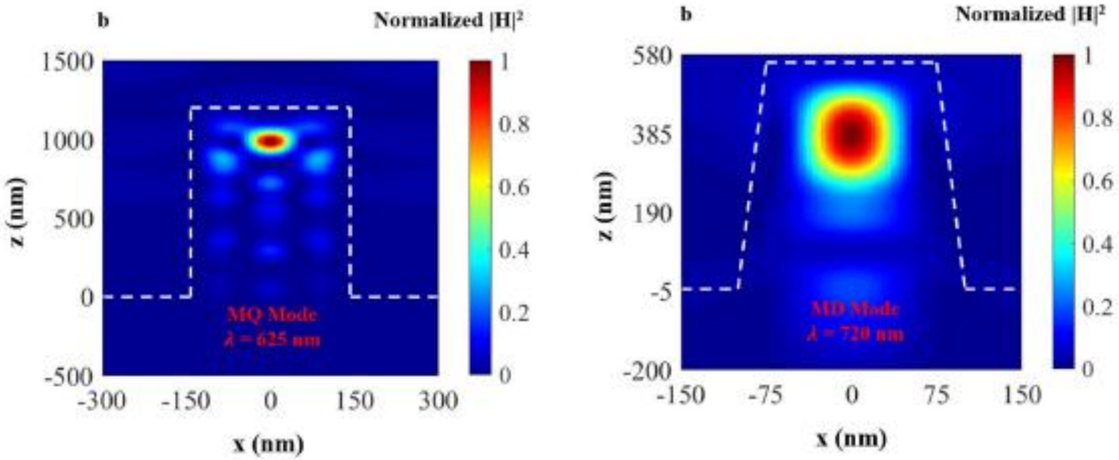
- Zero-cost extension ongoing through June 2023
  - Grant extension not approved
- Various InGaAs/InAlGaAs samples awaiting testing
  - JLab MicroMott being repaired
- UCSB work
  - GaAs/GaAsP chamber work
  - InAlGaAs/AlGaAs: waiting for results

Nano-structured Semiconductor Photocathodes

- Objectives
  - Model nanopillar arrays to enhance photoemission
    - Mie resonances enhance effect of light in photoemission
  - Test nanopillar structures for use
    - Study QE, lifetime



- Modeling Progress
  - Modeled different shaped nanostructures
    - Shape: cylinder, rectangle, trapezoid
    - Optimization: Height vs width vs spacing
  - Published Results
    - "Quantum efficiency enhancement in simulated nanostructured negative electron affinity GaAs photocathodes" Md. Aziz Ar Rahman, S. Zhang, H. Elsayed-Ali, Journal of Applied Physics 133, 023105 (2023)



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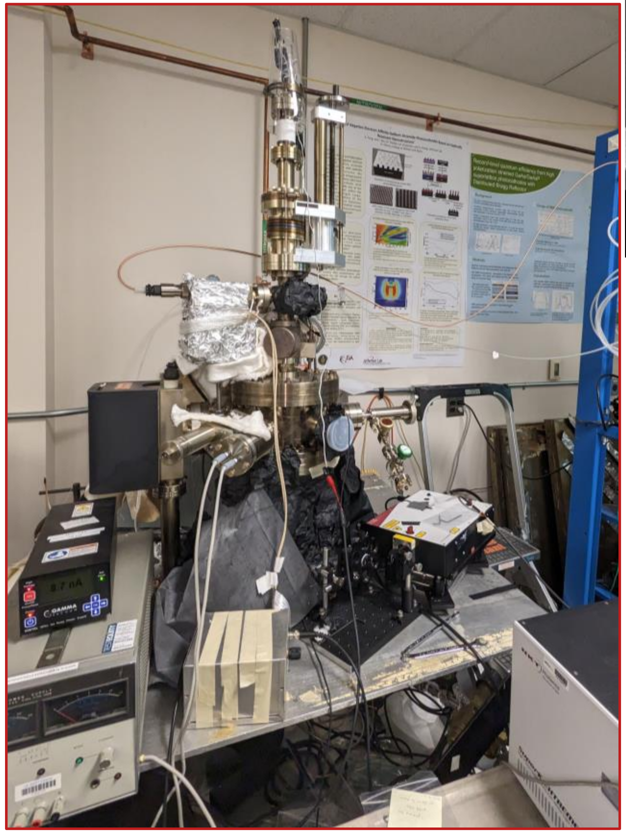
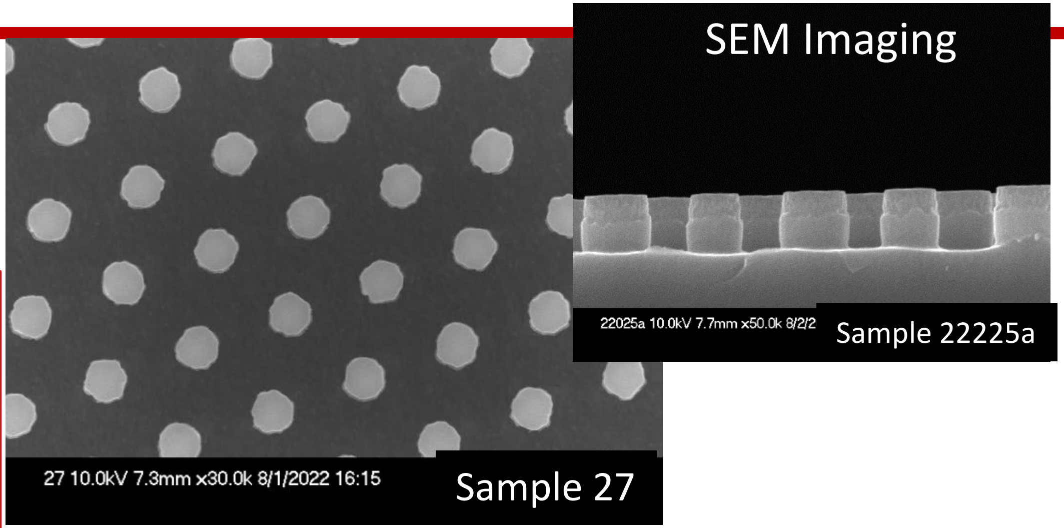
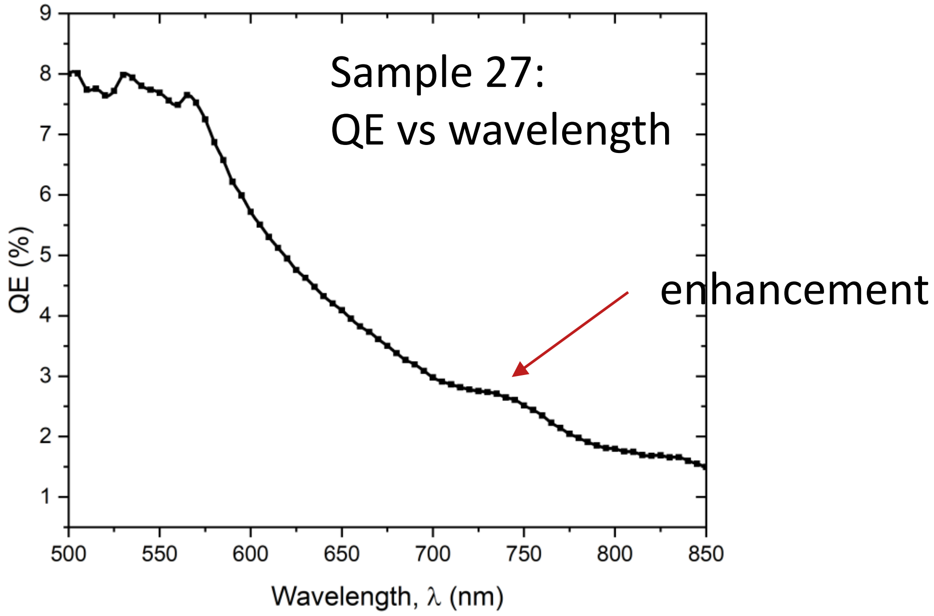
Nano-structured Photocathode Progress

- Experimental Measurements
  - Measurements on existing nanopillar structures
    - Topology:SEM/AFM for geometry & shape
    - QE and Lifetime evaluation
- Plans
  - Simulate & study new structures
  - Explore polarization effects
  - Improve test equipment
  - Collaborate to fabricate new samples







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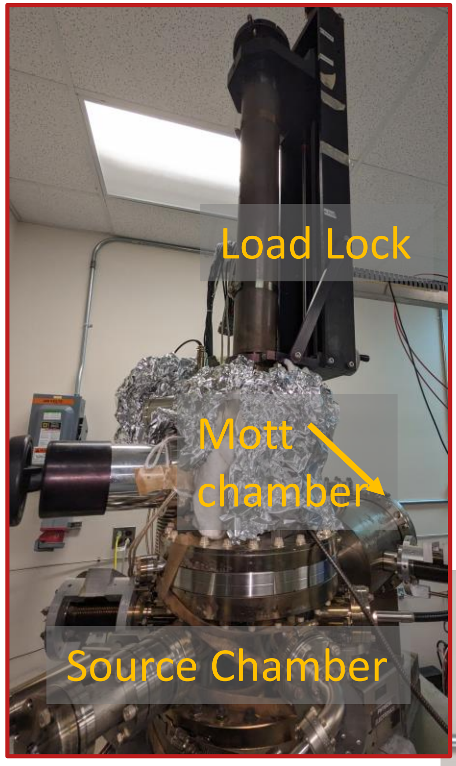
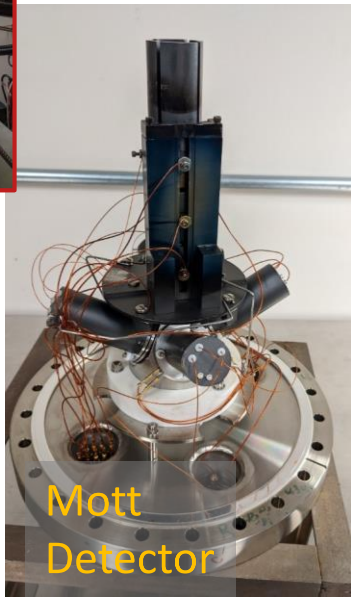
JLab microMott Polarimeter



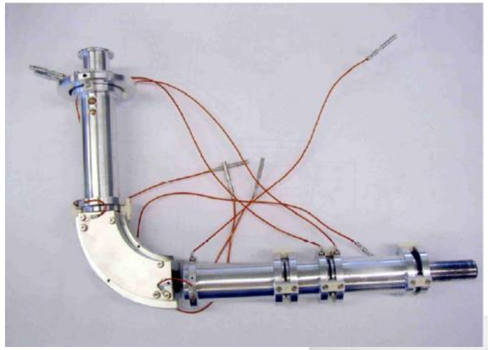
- Designed by Tim Gay, Univ. Nebraska Lincoln
- Successful operation for years
- Requires regular maintenance
  - Software: custom made by students & physicists
  - Delicate connections, occasional shorts
  - Uses stalk from Horizontal Gun



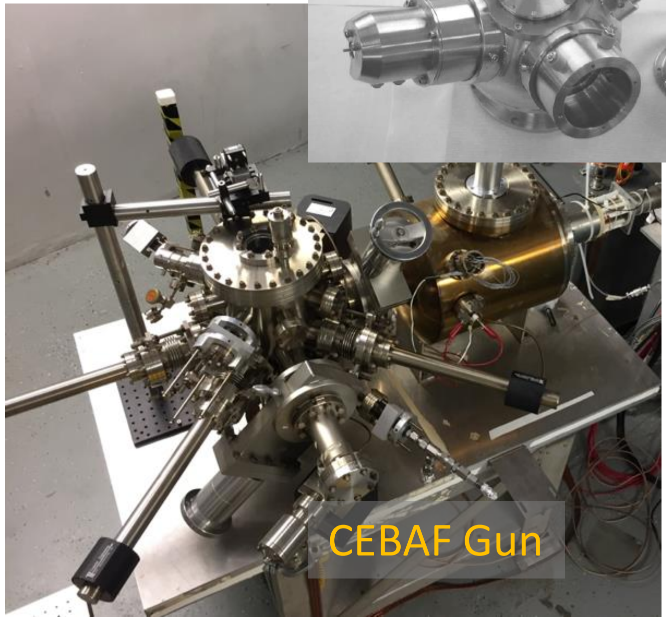
Paths for upgrade

- Load lock with puck?
  - Compatible with High Voltage Guns
- Commercial miniMott?
  - More robust electron optics and detector mounting
  - Commercial software & tech support
- Optics upgrade: Pockels cell?

** Cannot measure high voltage lifetimes*



Commercial miniMott

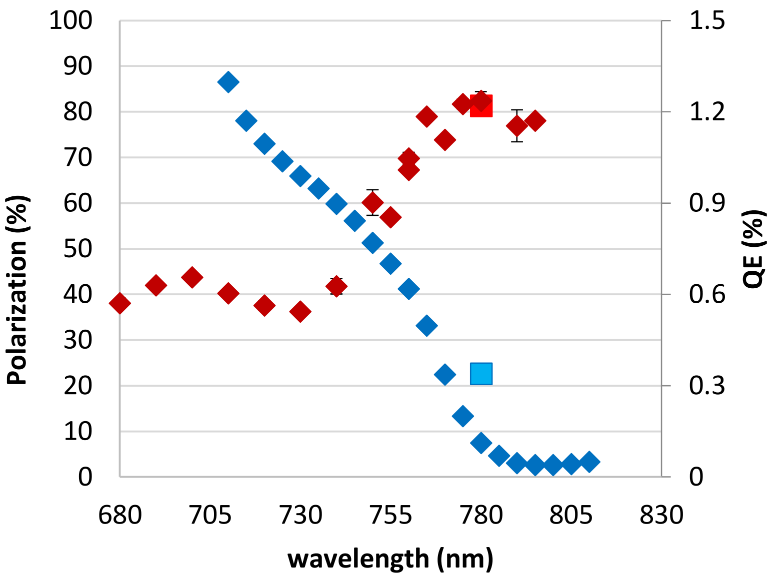


SuperK laser

SuperK Source

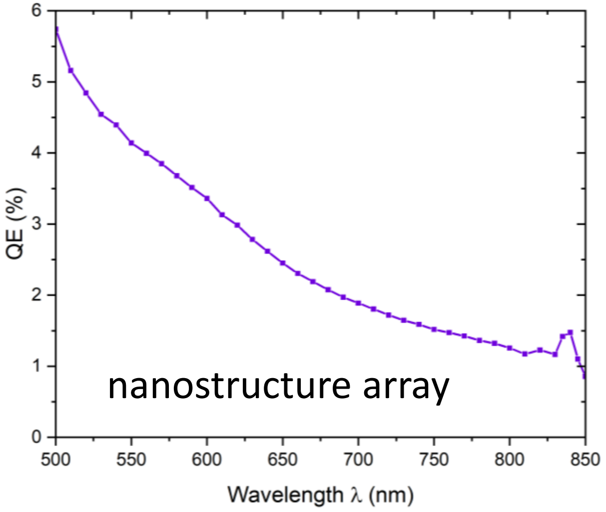
SuperK Filter

- NKT SuperK Laser
  - White light source + fiber optic + filter
  - Allows one system for 400-820 nm
  - Second filter allows two optics alignments on two chambers



strained superlattice

Spectral Responses



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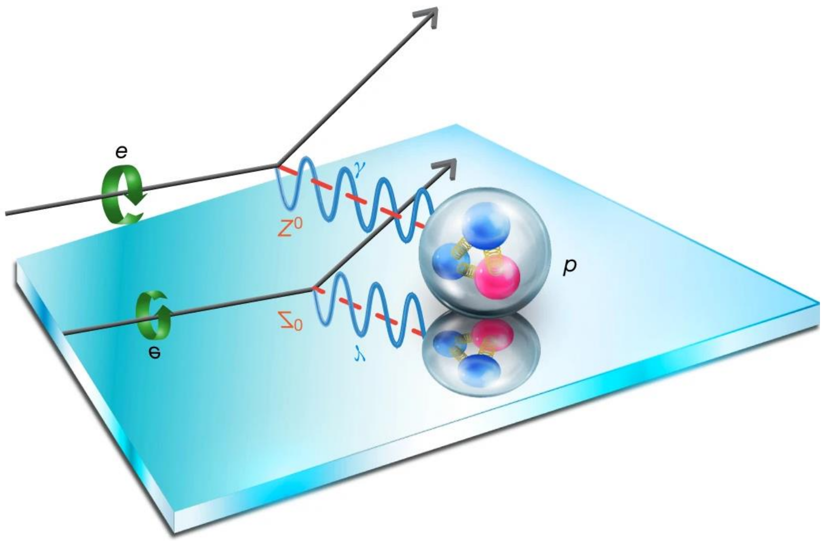
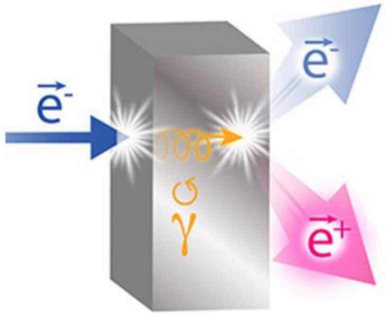
Conclusions

- Developing and Characterizing high polarization photocathodes for
  - Run CEBAF 12 GeV & Moller FY25-FY28
  - CEBAF upgrades: 22 GeV CEBAF/e+ in out years
  - Developing EIC polarized beam source
  - Demonstrate leadership to our community
    - MESA
    - Super KEK-B upgrade
    - ILC



- Three collaborations
  - ODU, RIT and BNL: MOCVD GaAs/GaAsP
  - UCSB: CBE or MBE, GaAs/GaAsP OR InGaAs/InAlGaAs
  - ODU: Nanostructured Photocathodes

- Photocathode characterization with microMott polarimeter
  - Aging, requires more maintenance than optimal
  - Potential upgrades to improve characterization capacity
  - SuperK laser enables wavelength scans, shared between systems



Polarized Positrons