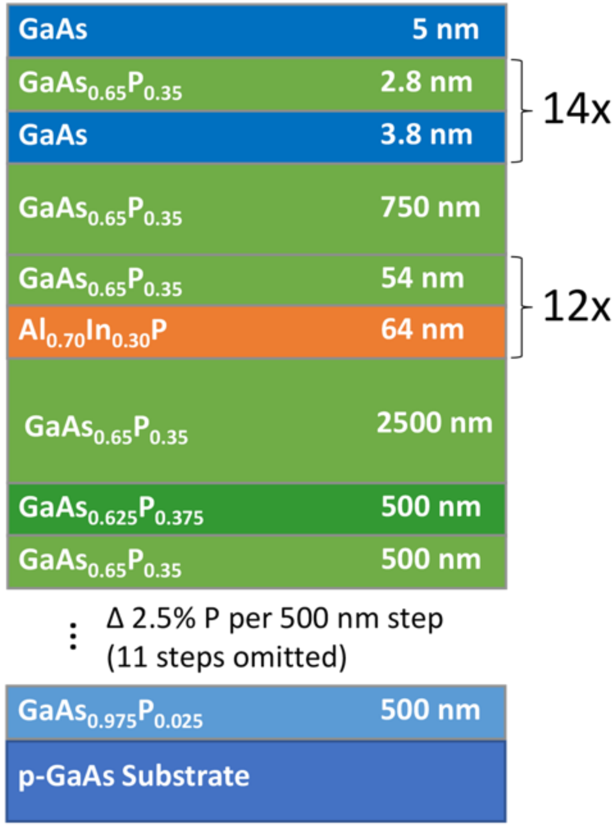
Enhancing the Design of Photocathodes with 90% polarization and QE > 1% for DOE NP

Nuclear Physics Accelerator R&D

PI Exchange Meeting

December 7 2023



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Jefferson Lab · Old Dominion University · Brookhaven National Laboratory · U.S. Department of Energy Office of Science · JSA

Project Main Goal

The overarching long-term goal of this proposal is to develop the capacity to fabricate the next generation of high polarization strained superlattice photocathodes with the best process possible and provide them to JLab and BNL. To achieve this goal, while ensuring no disruption of the current tasks at both JLab and BNL, this project will achieve the following 3 objectives:

- Fabricate state-of-the-art photocathodes using MOCVD and develop knowledge of fabrication parameters
- Enhance the design of 2 structures of photocathodes (strained-superlattice and strained-superlattice with distributed Bragg reflector) to assess paths to the next generation of photocathodes
- Provide a supply of state-of-the-art photocathodes to both BNL and JLab

Project Description and Status

Year 1: Fabrication and Testing of photocathode with GaAs/GaAsP strained superlattice with DBR

- Task 1.1. Calibration runs
  - 1.1.1. Calibration of $In_{0.30}Al_{0.70}P$
  - 1.1.2. Calibration of $GaAs_{0.65}P_{0.35}$ / $In_{0.30}Al_{0.70}P$ DBR
- Task 1.2. Device Fabrication runs
- Task 1.3. Sample Evaluation (P/QE)

Year 2: Fabrication and Testing of enhanced photocathode with GaAs/GaAsP strained superlattice with DBR

- Task 2.1. Superlattice Enhancement
- Task 2.2. Modified superlattice photocathode evaluation (P/QE)
- Task 2.3. Modification of the dopant used and lifetime testing inside a photogun operating at high voltage
- Task 2.4. Sample Evaluation (P/QE)

Major deliverables and schedule

Tasks Year 1	Q1	Q2	Q3	Q4
Report on Calibration of $In_{0.30}Al_{0.70}P$	X			
Report on $GaAs_{0.65}P_{0.35}$ /$In_{0.30}Al_{0.70}P$ DBR fabrication		X		
4 wafers photocathodes with various DBR			X	
Strained superlattice/DBR Photocathodes Evaluation			X	X

Tasks Year 2	Q1	Q2	Q3	Q4
Report on Superlattice enhancement	X	X		
3 Wafers with Modified superlattice Photocathodes Evaluation		X	X	
Modification of the dopant used and Lifetime studies		X	X	
Enhanced Strained superlattice/DBR Photocathodes Evaluation			X	X

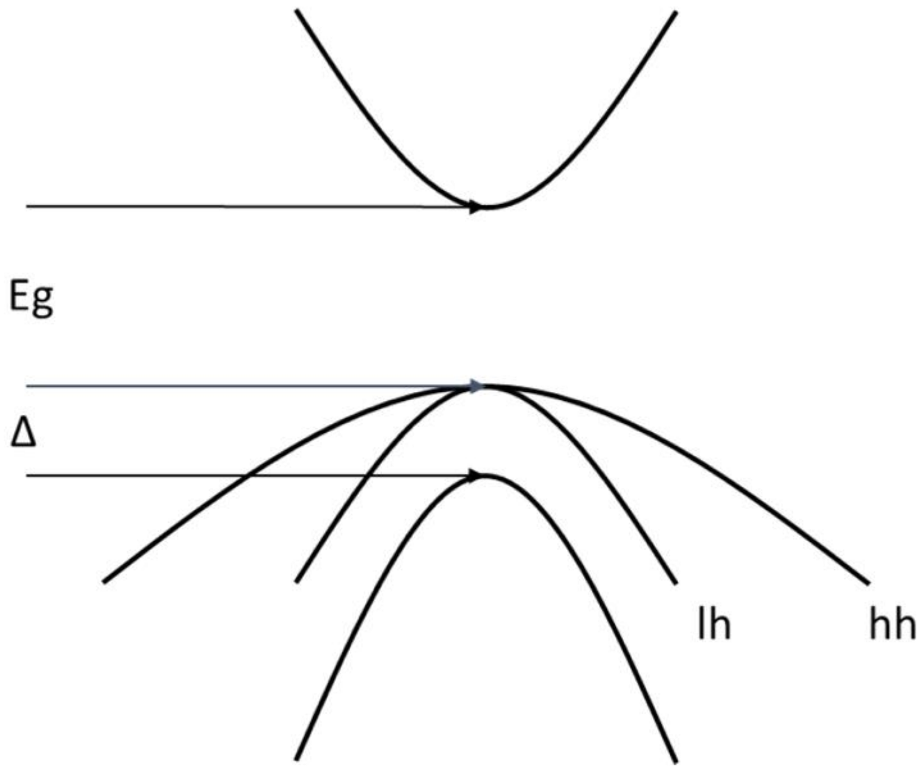
Old Dominion University

Budget

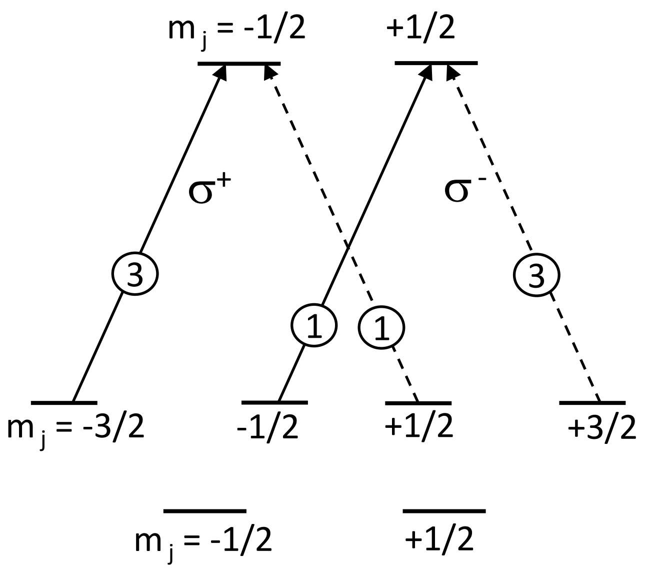
	FY23($k)	FY24($k)	Total($k)
a) Funds allocated	$179,000	$179,000	$358,000
b) Actual costs to date	$126,067	$0	$126,067

- Remaining funds: ~ $230k
  - Salary: $50k
  - Fabrication and Testing: $80k ($40k encumbered)
  - Travel: $10k
  - Tuition: $10k
  - IDC: $80k

Making polarized electron beams with GaAs

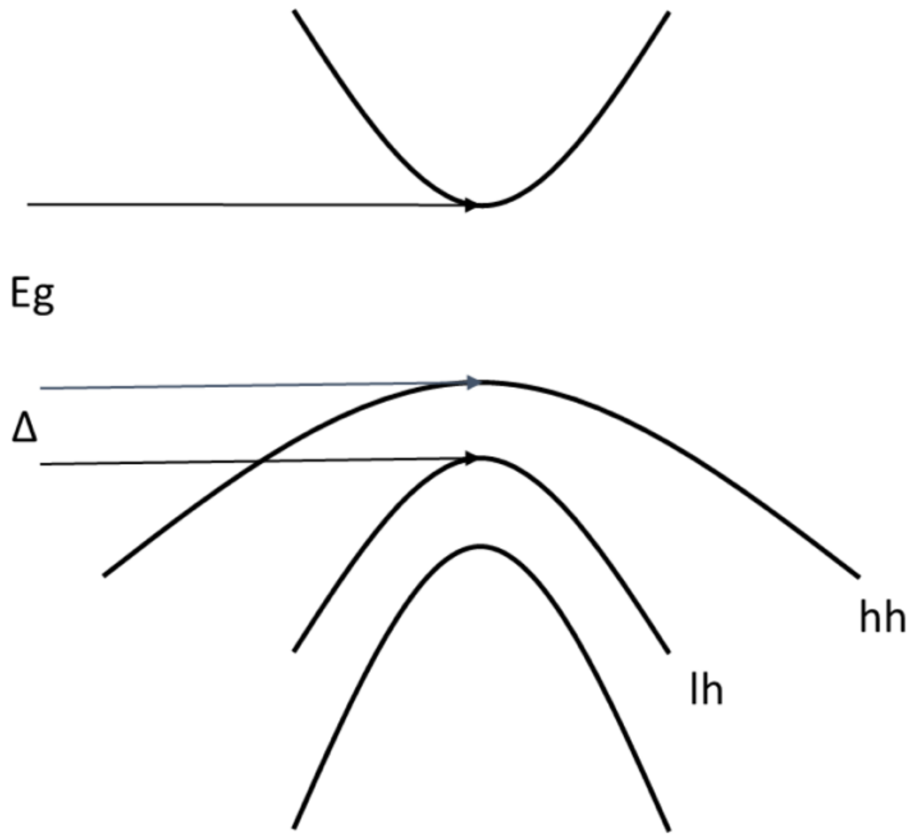


Bulk GaAs – no strain

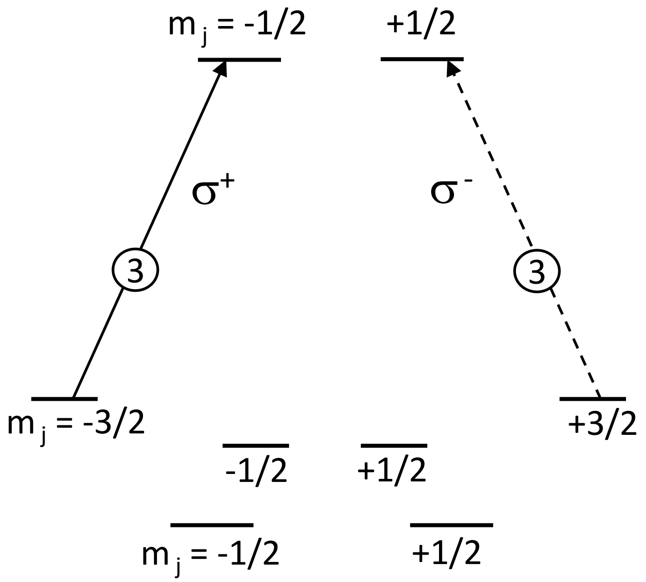


Maximum Polarization 50%

Making polarized electron beams with GaAs

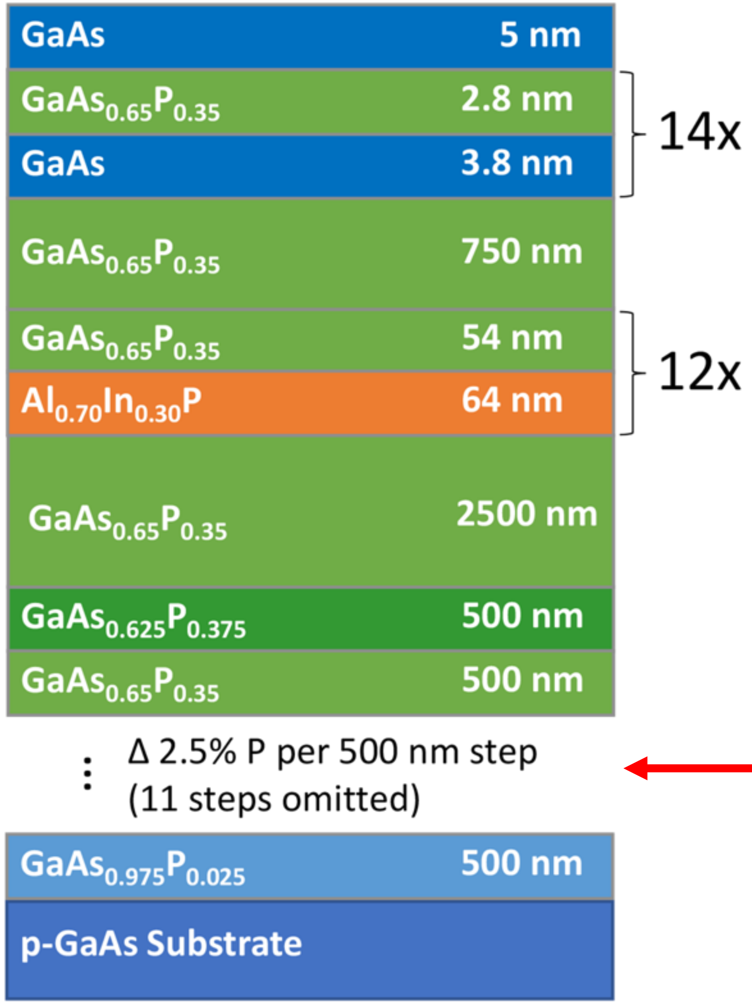


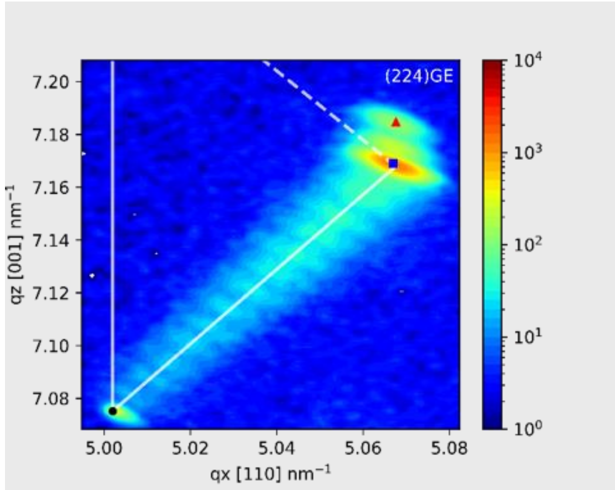
Strained GaAs

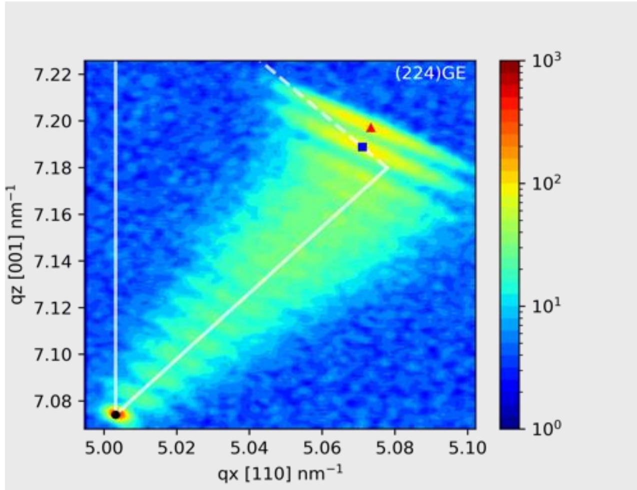


Maximum Polarization 100%

Device Structure: Strained Superlattice with Distributed Bragg Reflector

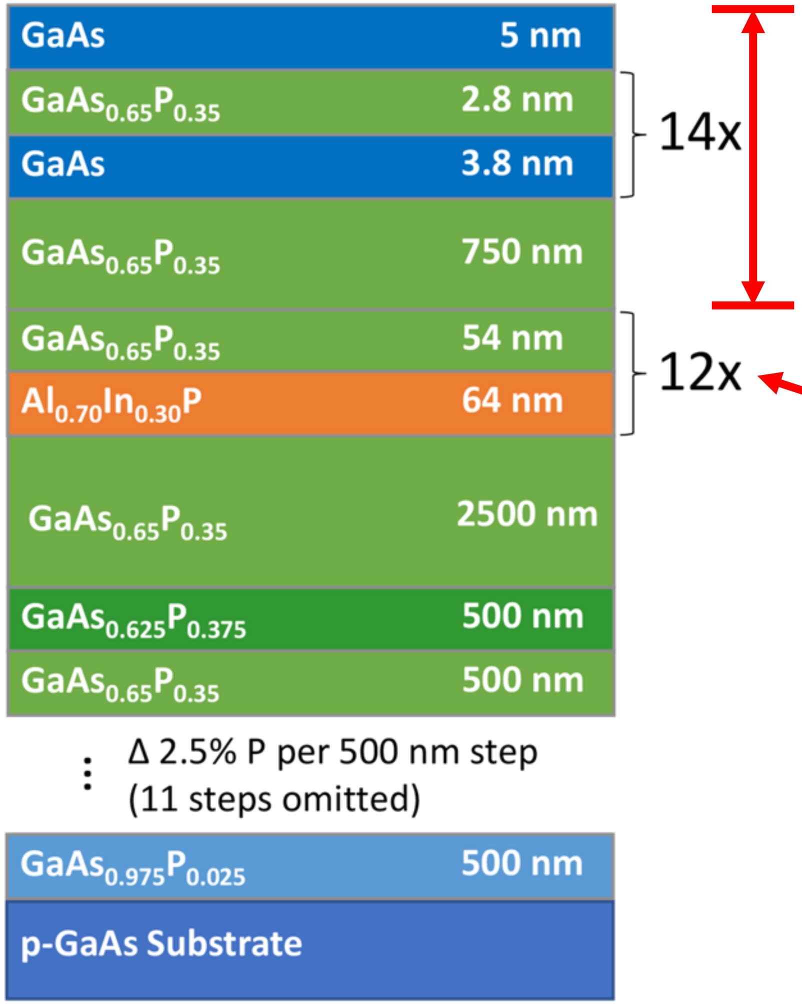






Metamorphic grading: starting with GaAs, ending with $GaAs_{0.65}P_{0.35}$ to create a relaxed layer upon which thick buffer layer is grown

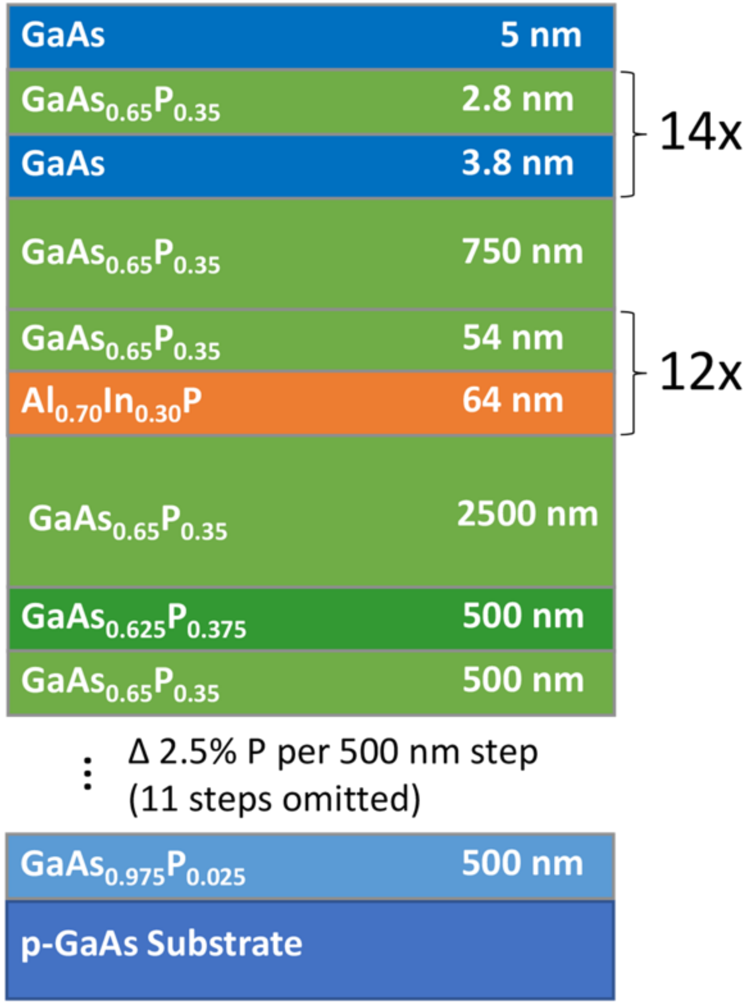
Device Structure: Strained Superlattice with Distributed Bragg Reflector

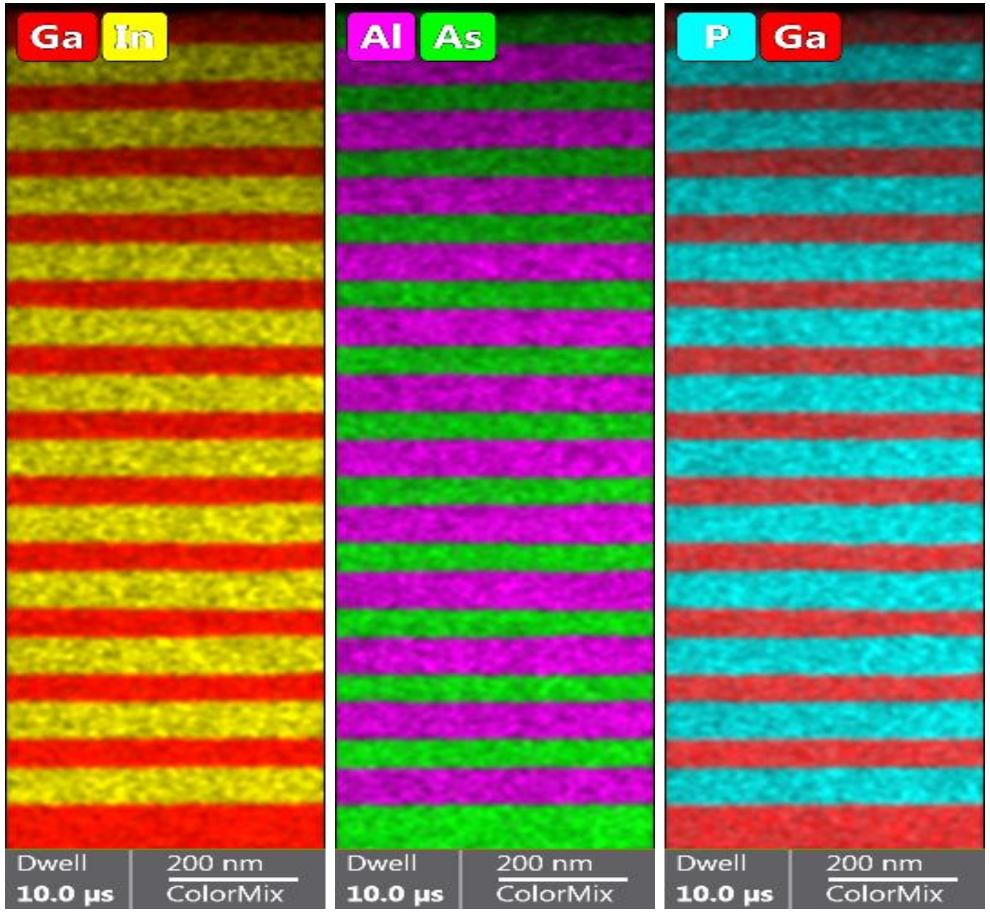


Etalon formed between DBR and top surface: stores light, more light absorbed, higher QE

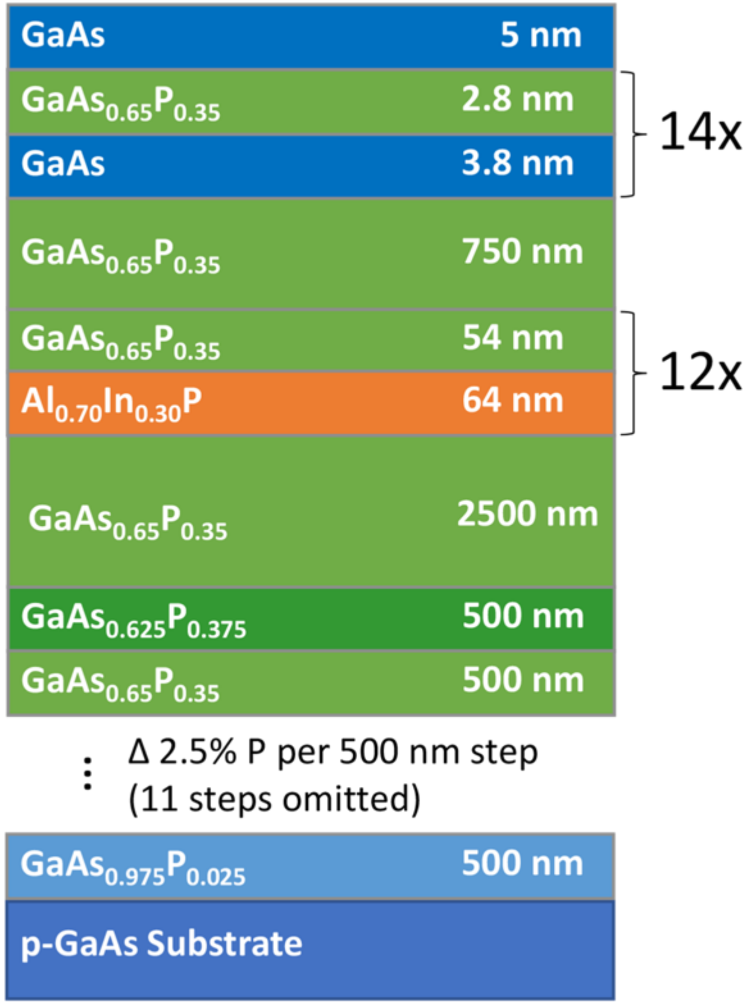
Superlattice which forms the Distributed Bragg Reflector (DBR)

Device Structure: Strained Superlattice with Distributed Bragg Reflector

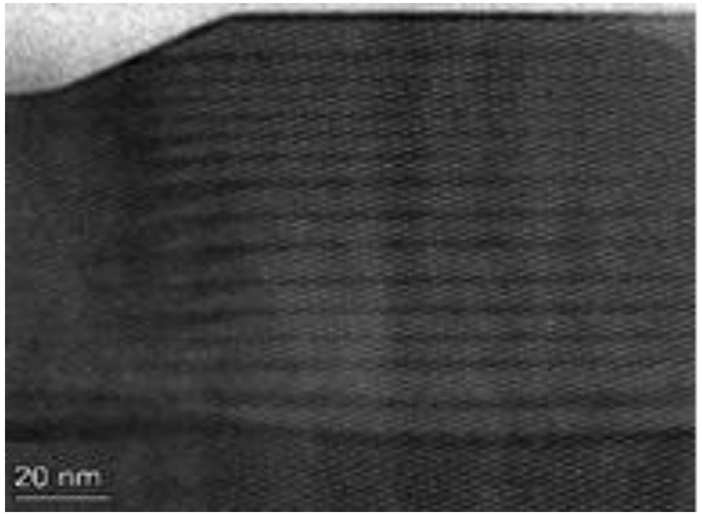


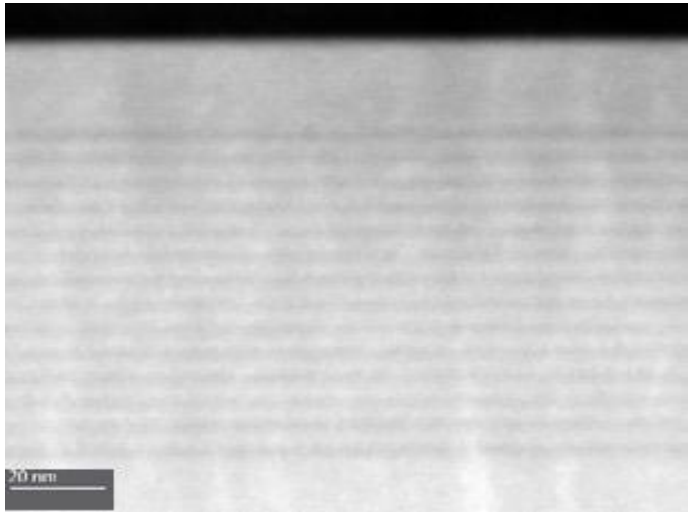


Device Structure: Strained Superlattice with Distributed Bragg Reflector

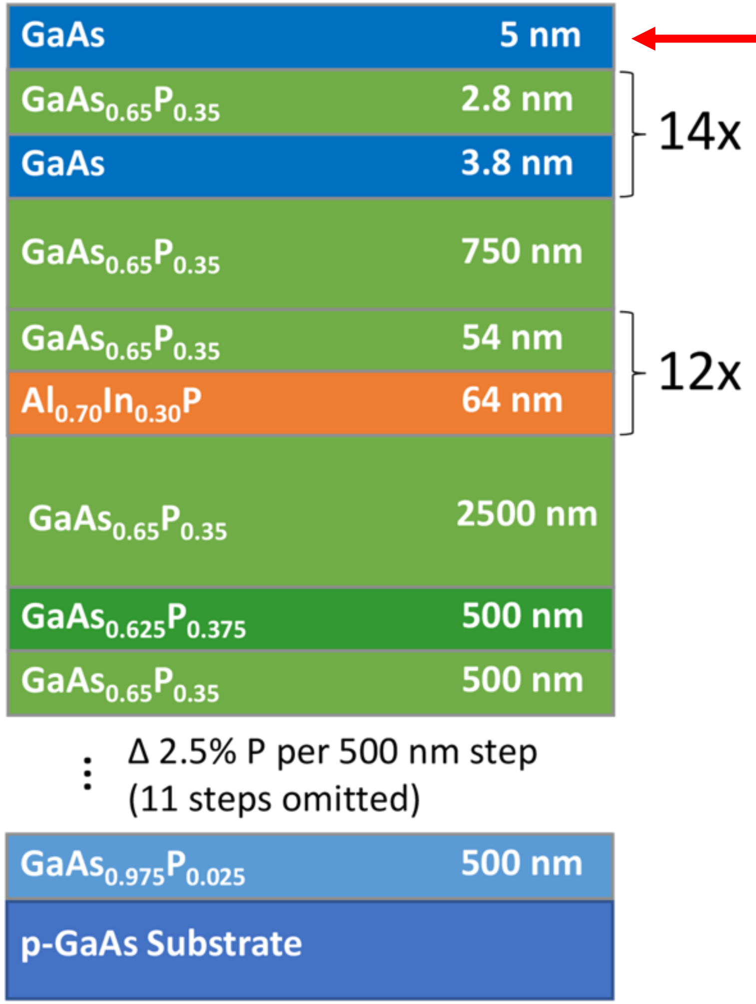


the superlattice - where the polarized electrons come from, many thin layer pairs





Device Structure: Strained Superlattice with Distributed Bragg Reflector

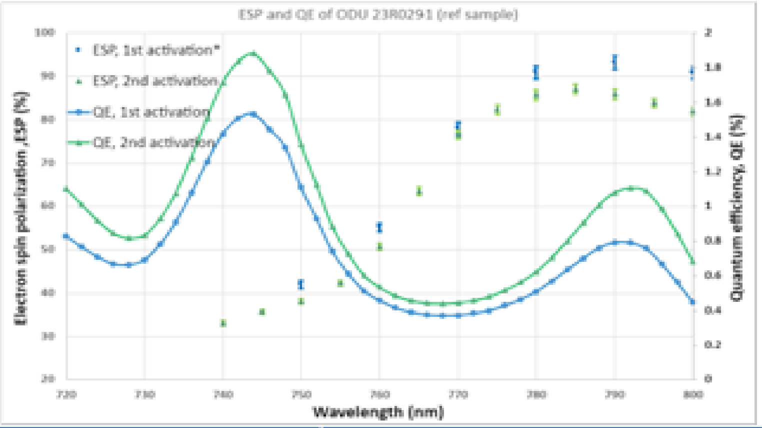


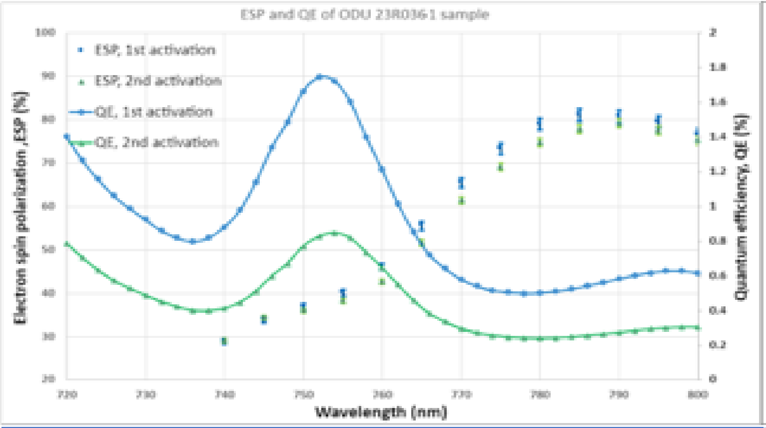
Highly doped surface layer ($5\ 10^{19}\ cm^{-3}$) to reduce surface charge limit (good for EIC)

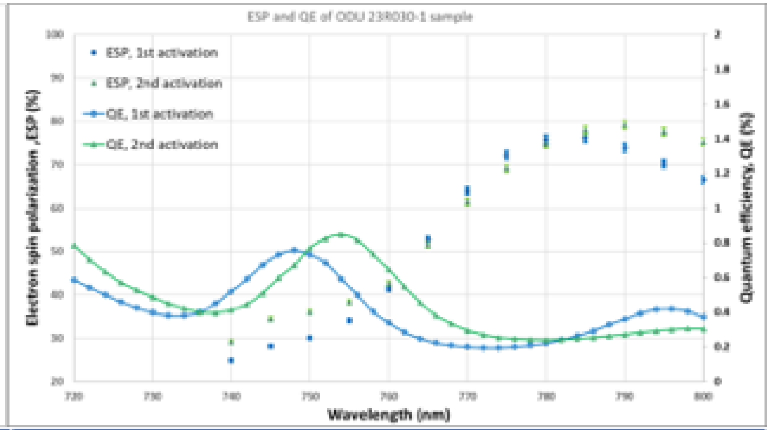
Results on Task 2.3: Modification of the dopant

- Task initially schedule for end of year 2
- However measurement at BNL showed charging issues with our devices
- 3 doping concentration were calibrated (5e19,1e20 and 2.2e20)
- Devices were fabricated and tested

Results on Task 2.3: Modification of the dopant



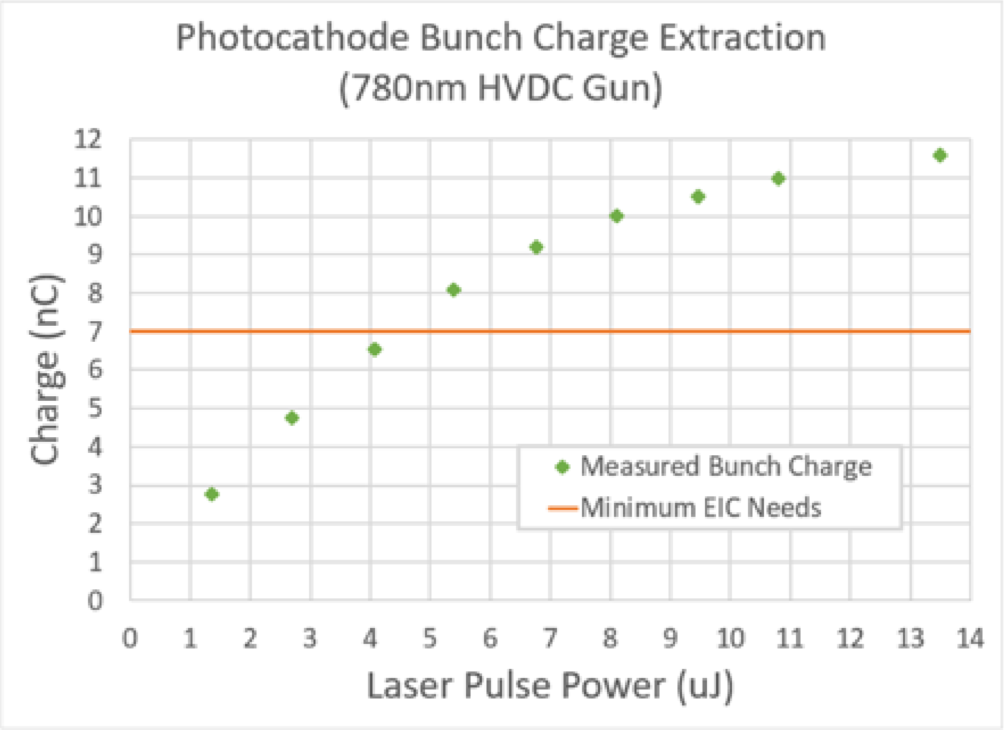




	23R029-1 (reference sample) 5E19 doping		23R036-1 1E20 doping		23R030-1 2.2E20 doping	
	1st Activation	2nd Activation	1st Activation	2nd Activation	1st Activation	2nd Activation
Peak QE	0.79% @ 790 nm	1.10% @ 790 nm	0.63% @ 796nm	0.30% @ 798 nm	0.42% @ 796 nm	0.30% @ 798 nm
Peak Polarization	93.15% @ 790 nm	87.03% @ 785 nm	81.1% @ 785 nm	79.2% @ 785 nm	76.14% @ 785 nm	79.2% @ 790 nm
QE@780nm	0.51%	0.62%	0.50%	0.24%	0.22%	0.24%
Polarization@780nm	91.0%	85.7%	79.0%	74.8%	75.8%	74.8%
Notes:	This sample was capable of 11nC emission		This sample had major degradation during growth that caused poor performance		This sample had minor degradation during growth that caused poor performance	

Results on Task 2.3: Modification of the dopant

- $5\ 10^{19}$ dopant preserves polarization and QE and enables EIC goals
- Higher dopant would likely provide higher bunch charge but provide so far poor polarization and QE
- Test results from BNL's HVDC gun showed sample with doping of $5\ 10^{19}\ cm^{-3}$ achieving 11 nC with the free limit range and 9 nC with an 8 mm diameter laser. This is above the EIC requirement of 7 nC.
- Device was tested for 9 hours at 20µA operation (approximately 20 weeks worth of operation of EIC) with only 10% decay.



5e19 Doping Bunch Charge Test

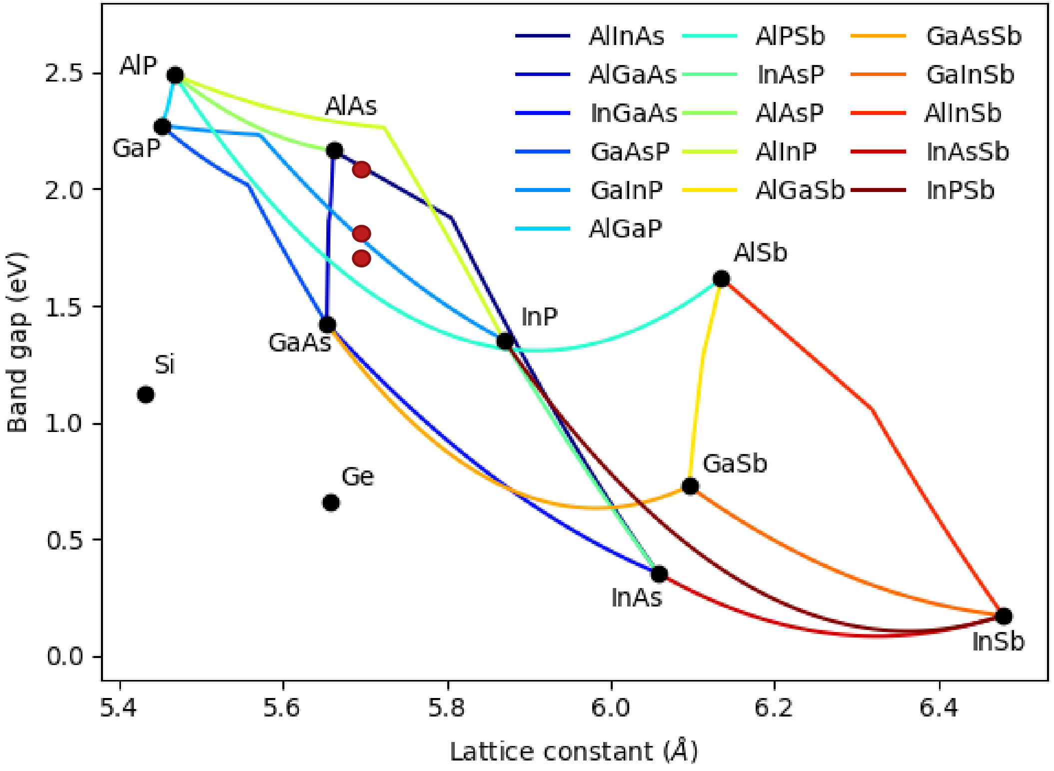
Results on Task 1.1: Calibration of new DBR layer

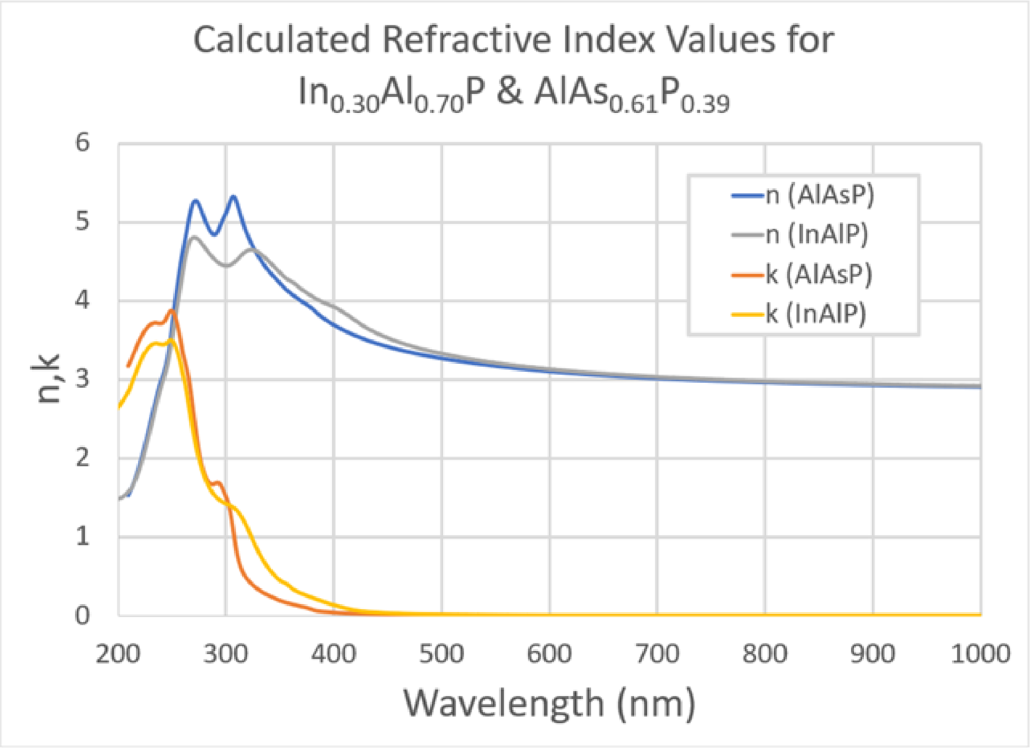
- $AlAs_{0.61}P_{0.39}$ used previously by our team in MBE process to fabricate DBR along with $GaAs_{0.65}P_{0.35}$
- Need to change the material due to $AlAs_{0.61}P_{0.39}$ instability in MOCVD process
- ***Requirement***:
  - Similar refractive index at wavelength of interest
  - Lattice matching to $GaAs_{0.65}P_{0.35}$
  - E_g(Material) > E_g(strained GaAs)
- Refractive Indices were calculated using interband-transition model as defined by:

$$n^2(E) = A_0\left[\left(\frac{2-\sqrt{1+\frac{E}{E_0}}-\sqrt{1-\frac{E}{E_0}}}{\left(\frac{E}{E_0}\right)^2}\right)+\frac{1}{2}\left(\frac{E}{E_0+\Delta_0}\right)^{3/2}\left(\frac{2-\sqrt{1+\frac{E}{E_0+\Delta_0}}-\sqrt{1-\frac{E}{E_0+\Delta_0}}}{\left(\frac{E}{E_0+\Delta_0}\right)^2}\right)\right]+B$$

Results on Task 1.1: Calibration of new DBR layer

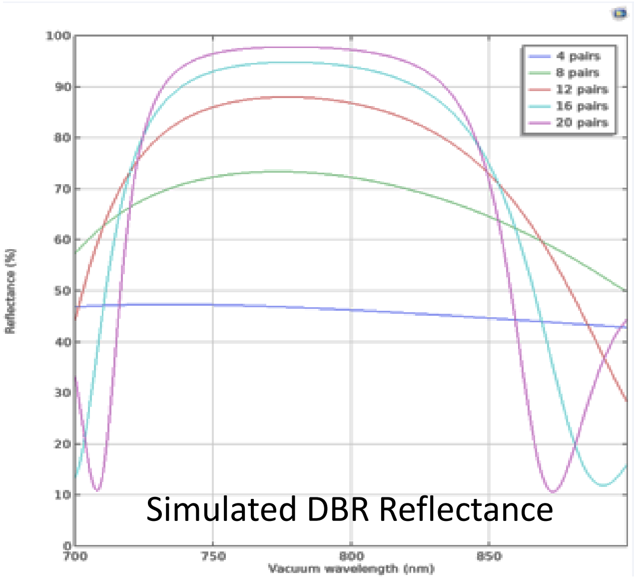
- $In_{0.30}Al_{0.70}P$ is a potential match in terms of lattice constant (left Figure)
- Calculations of refractive index indicate that it is also a good match to $GaAs_{0.65}P_{0.35}$, with optical constants similar to $AlAs_{0.61}P_{0.39}$ (right Figure)

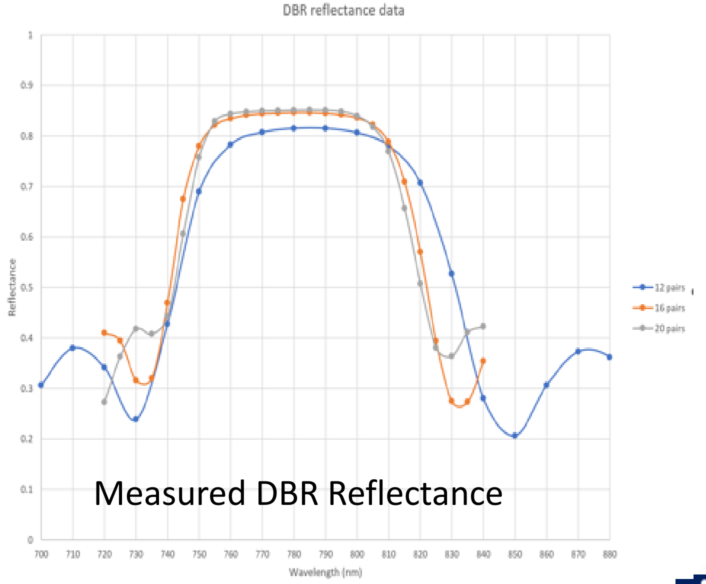




Results on Task 1.2: Fabrication with new DBR layer

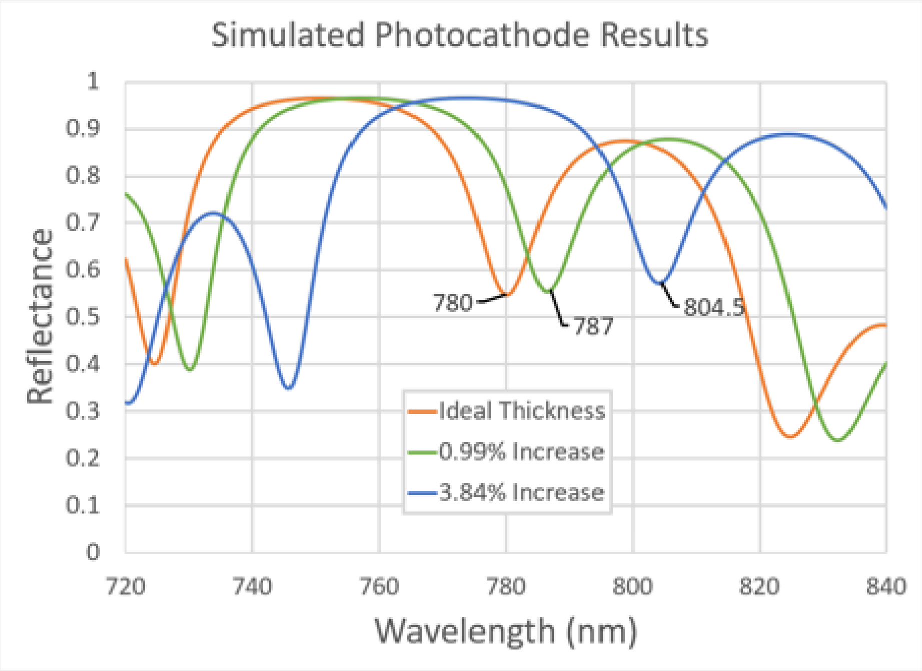
- Using COMSOL and the modeling of the refractive indices, simulations were run to show potential improvements to the device by increasing the number of DBR pairs.
- Modeling (values at 780 nm):
  - 12 pairs = 87% reflectivity
  - 16 pairs = 95% reflectivity
  - 20 pairs = 98% reflectivity
- Simulations were done assuming smooth surface so measured values will not match simulated values due to surface scattering
- Lack of change in reflectance still unexpected





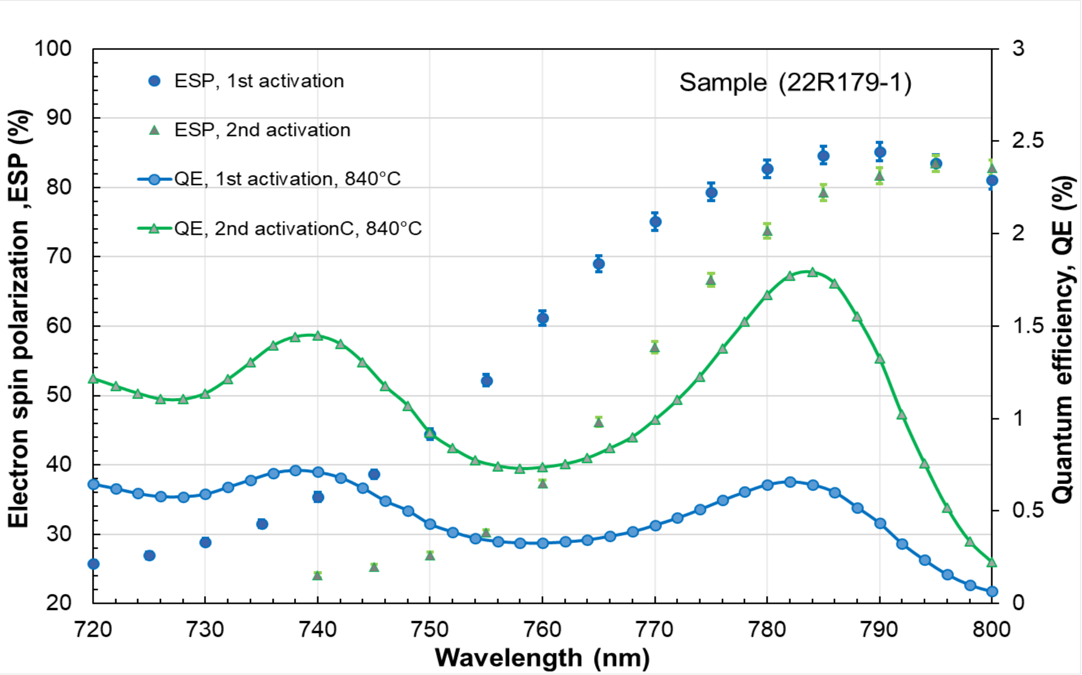
Results on Task 1.2: Fabrication with new DBR layer

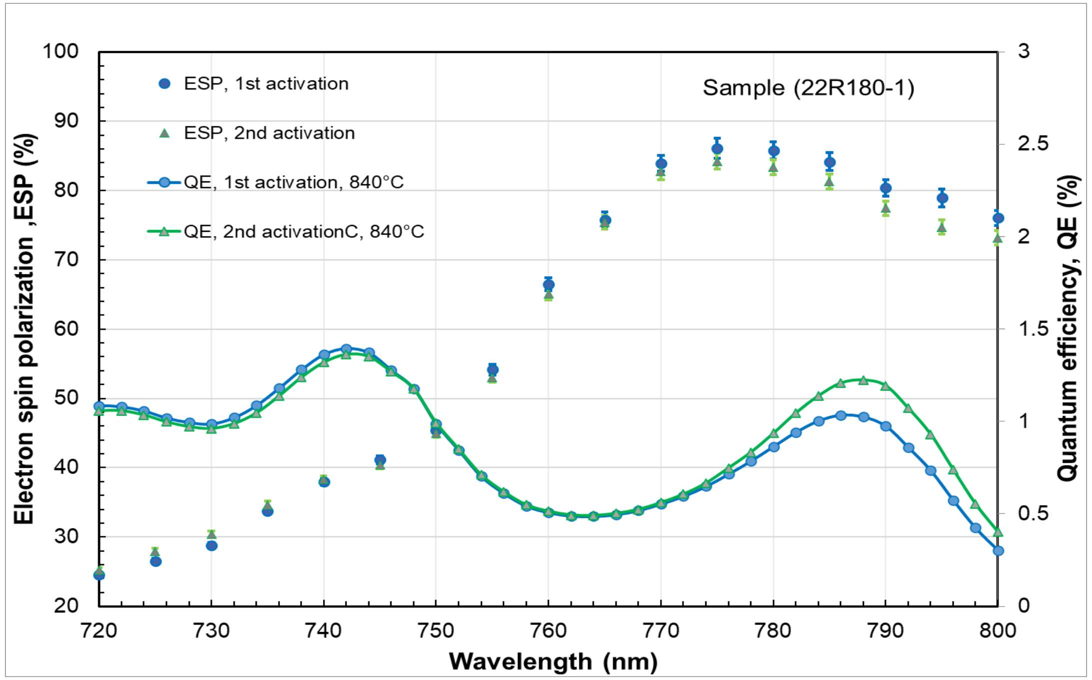
- Measured reflectance across a wafer (Left): variation in peak position
- Could come from composition or thickness
- Simulation as a function of thickness (Right): good match with experimental results for variation in thickness of 4%



Results on Task 1.2: Fabrication with new DBR layer

- To confirm this issue, measurements were compared on different devices
- Measured on two different wafers from two different runs with the same process: apparently lead to different polarization and QE (position and intensity)

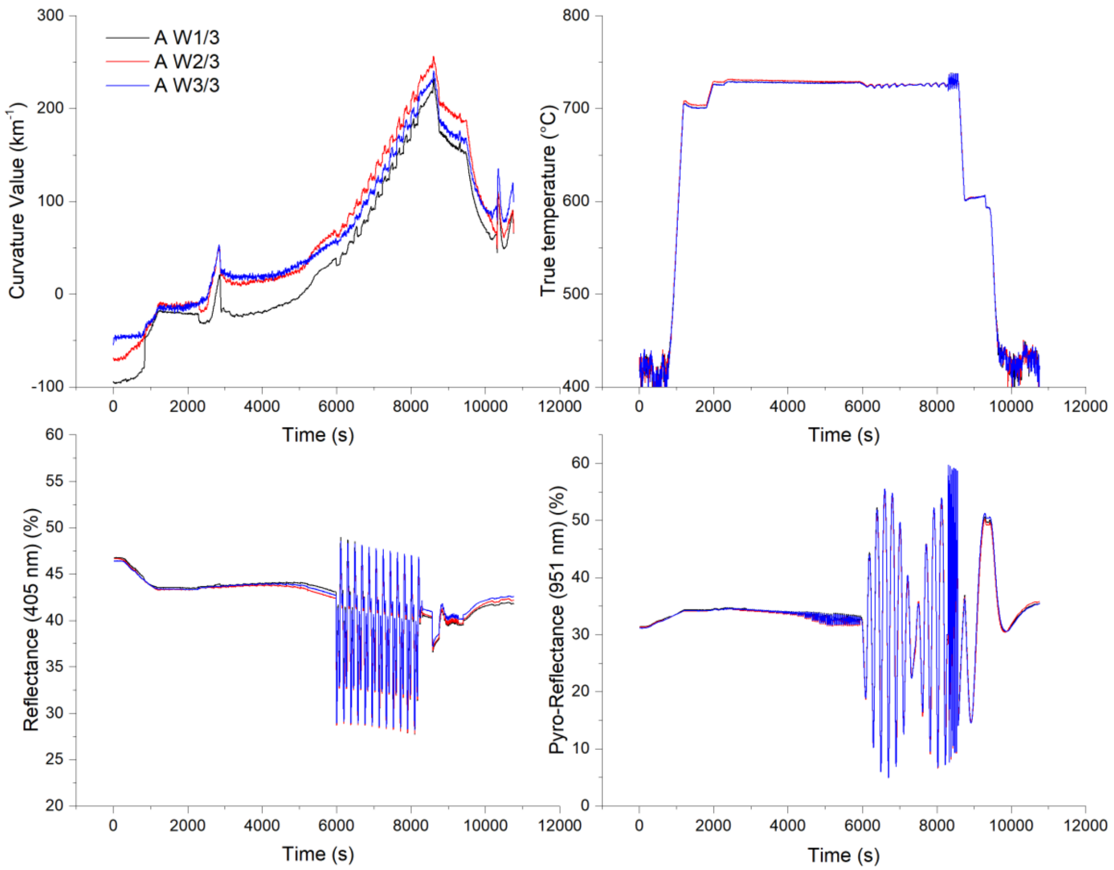




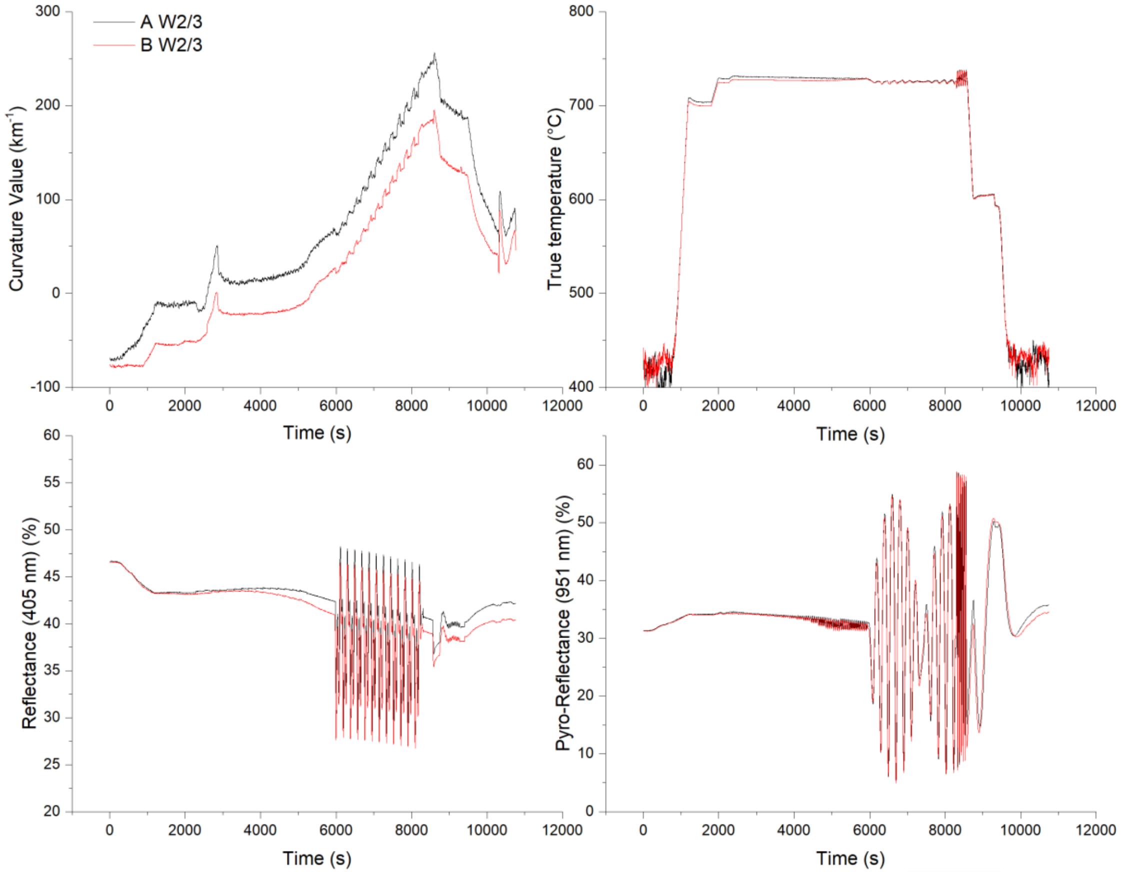
Results on Task 1.2: Fabrication with new DBR layer

Compared in-situ measurement for one run on 3 wafers and from one run to another: NO CHANGE

Inter-run variation



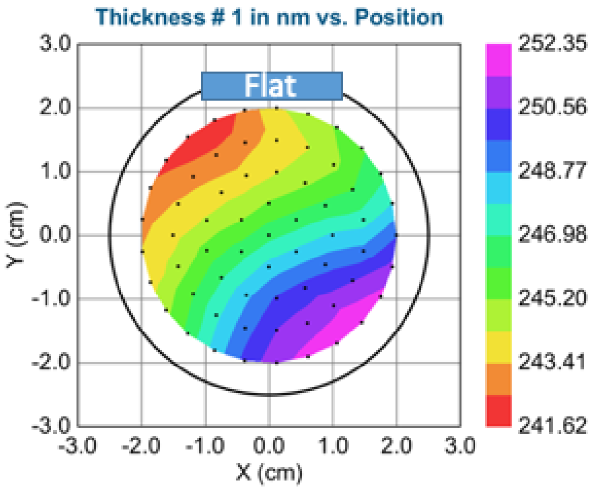
Run-to-run variation



Results on Task 1.2: Fabrication with new DBR layer

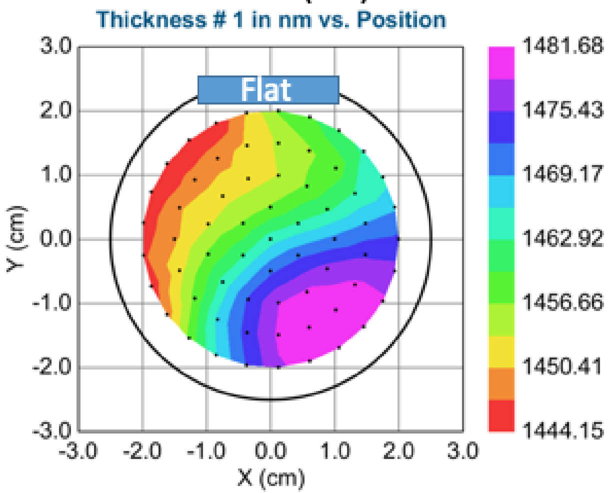
- Temperature calibration within 1^0C across the wafer
- Check Calibration of thickness of various materials: thickness variation within 1%

AlInP (LM GaAs) w/GaAs Cap
Thickness (nm)



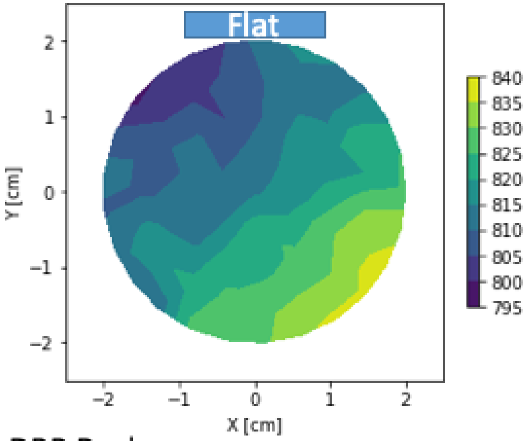
	Average	246 nm
± 1.2%	St.Dev.	2.97 nm
	Min:	241 nm
	Max:	252 nm
± 2.2%	Range:	10.7 nm
	Count:	64

InGaP (LM GaAs)
Thickness (nm)



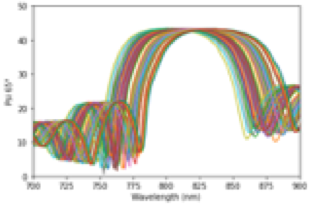
	Average	1462 nm
± 0.8%	St.Dev.	11.7 nm
	Min:	1444 nm
	Max:	1481 nm
± 1.3%	Range:	37.5 nm
	Count:	64

AlGaAs/AlGaAs DBR
Peak (nm)



DBR Peak

	Average	817 nm
± 1.2%	St.Dev.	9.6 nm
	Min:	799 nm
	Max:	836 nm
± 2.3%	Range:	37 nm
	Count:	64



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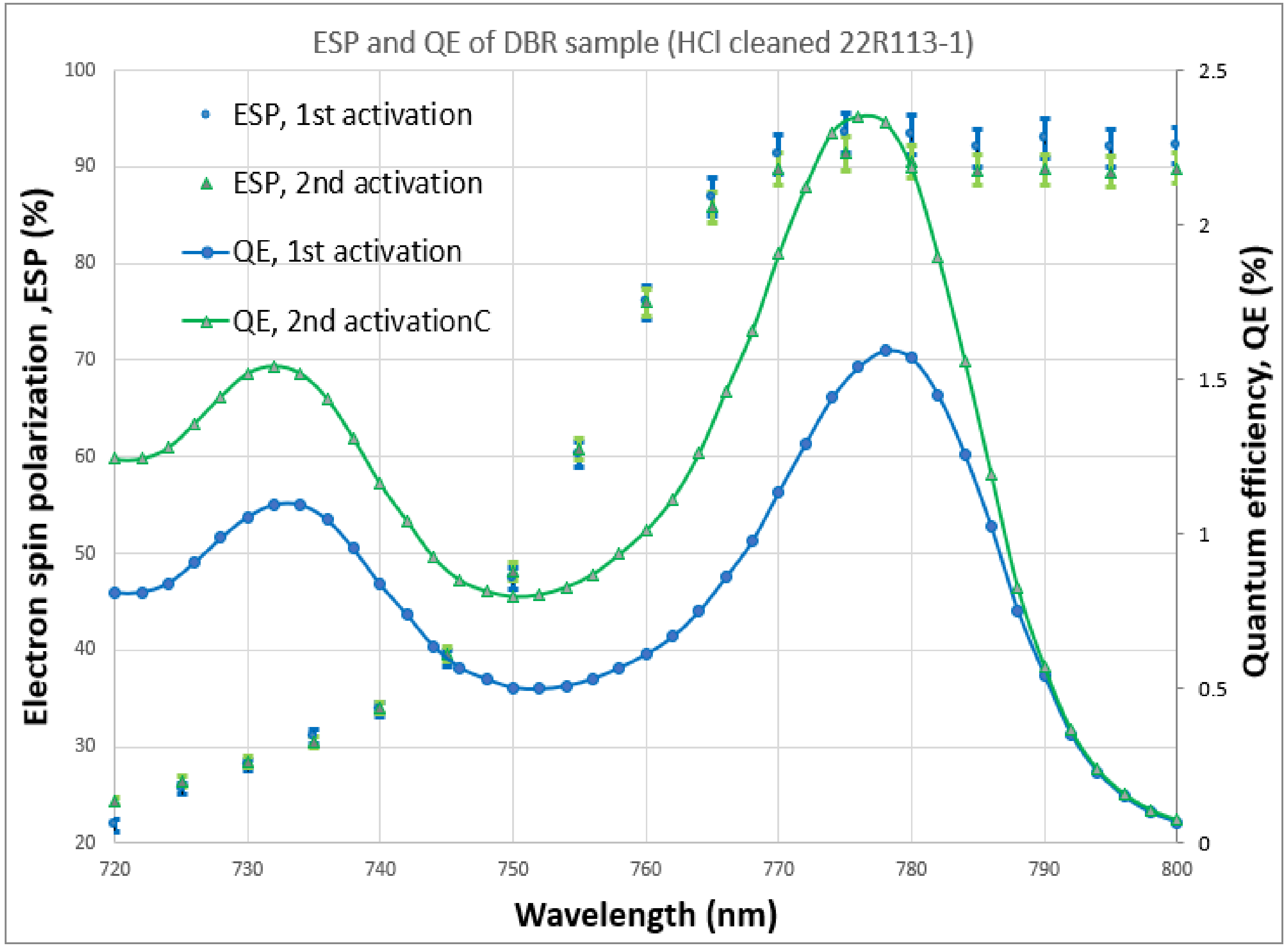
- Problem with thickness control for our specific material across the wafer: Need to modify process parameters!

Best Device



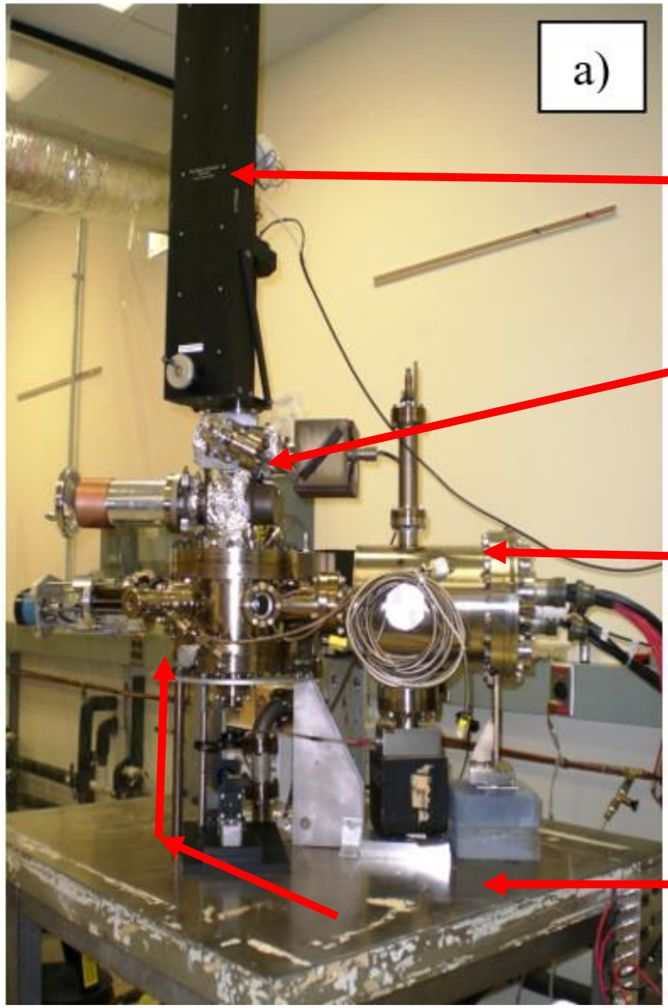
BNL microMott

Pol ~ 92%

QE ~ 2.3%

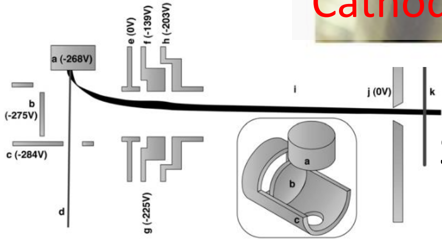
λ_{peak} ~ 785 nm

Jlab MicroMott Polarimeter



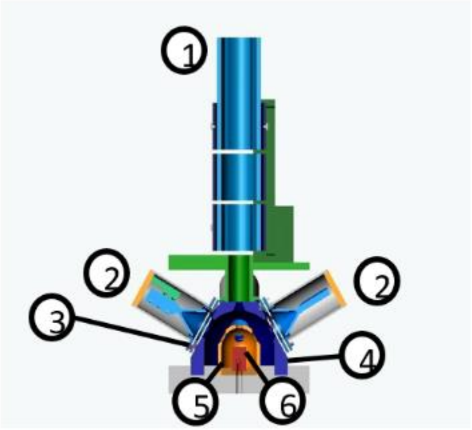
LoadLock Bellows
Wafer on stalk installed, baked and inserted within ~1 day.

Source Chamber
- Photocathode activated Cs, NF3
- Generate beam, measure QE



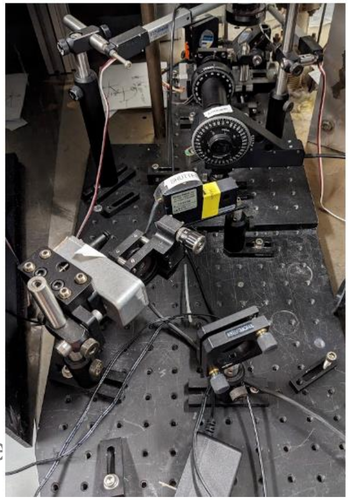
Source layout

Mott Chamber
- Transmit beam toward target at 250eV
- acceleration to 20 kV, scatter on gold, decelerate
- detectors



Mott layout

Optics Path:
- Circular polarization
- SuperK tunable laser now installed



MicroMott repair and refurbishment

- Safety & upgrades
  - JLab wide OSP review
  - Interlocked cathode bias
  - Improved Mott chamber pumping
  - NIM crate DAQ for discriminators, upgraded grounding
- Equipment failure repairs: aging equipment
  - **Source chamber**
    - Leak valve, Cesium & Lens supports, new windows
  - **Mott Chamber**
    - Broken CEM wire repairs (multiple)
    - **CEM Mounting Redesign**
      - CEM design change allowed shorts to ground - repaired
    - **This was root cause of recent functional problems**
- Busy CEBAF injector upgrade schedule 2021-2023

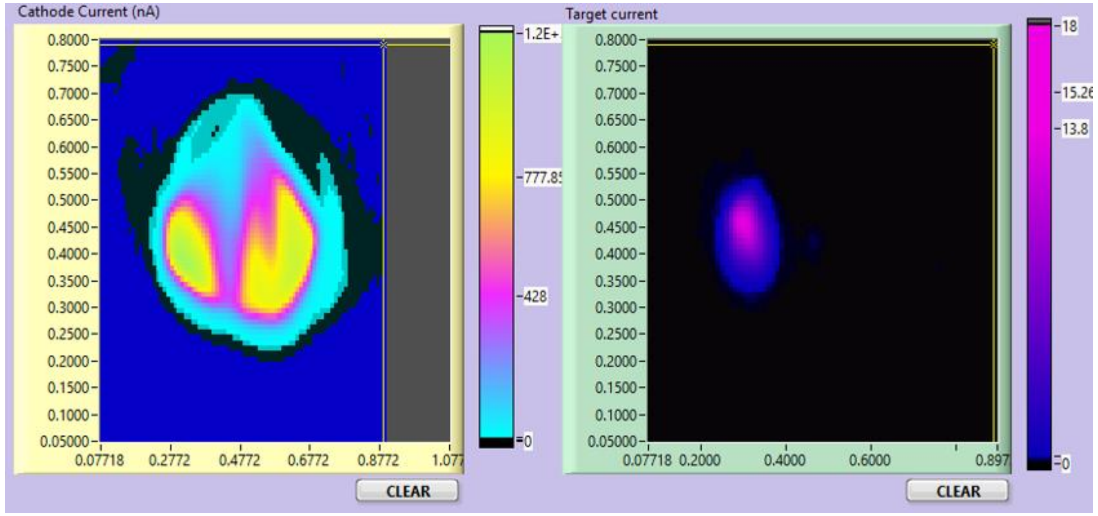
CEM Detector. 15 mm opening

Contact from redesigned metallization caused shorts

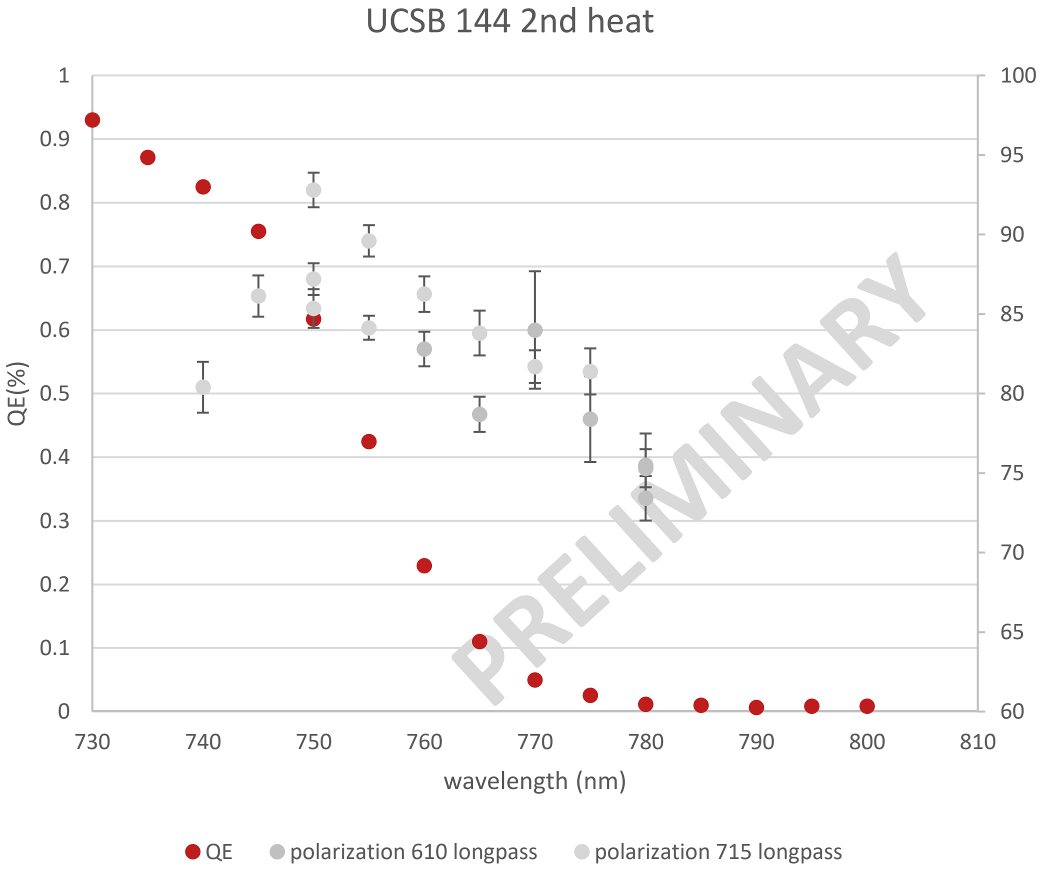
QE and Polarization vs. wavelength measurement

- SuperK laser installed for wavelength scans
- Good cathode lifetime
- Transmission to target reproducible
- Measurements underway on UCSB samples
  - ready for ODU samples when scheduling allows

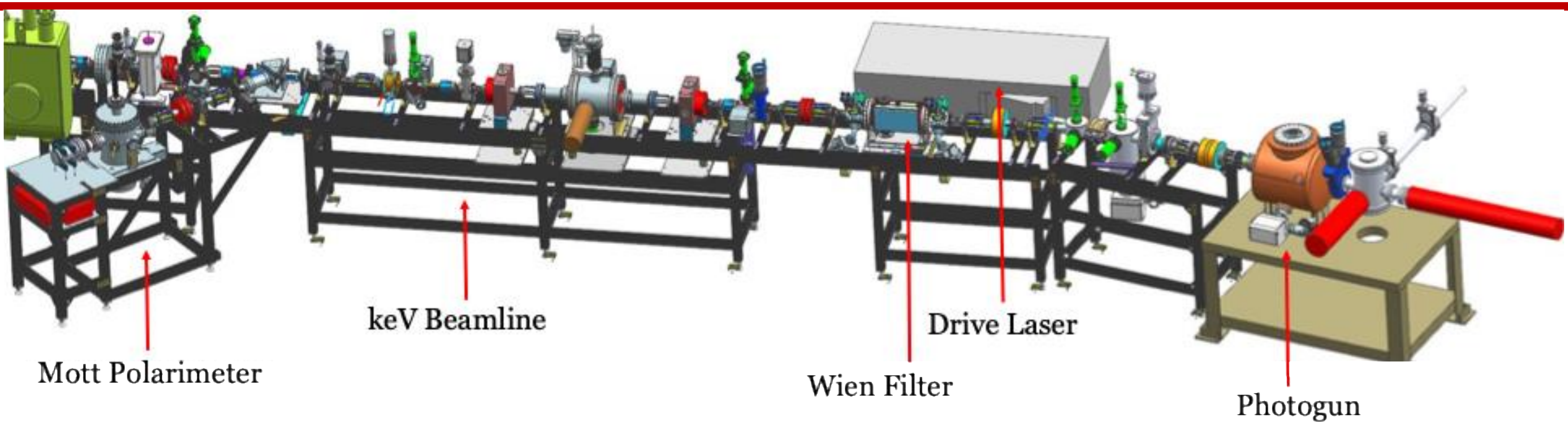
Laser scan of cathode surface



Cathode current   Target current



UITF keV beamline

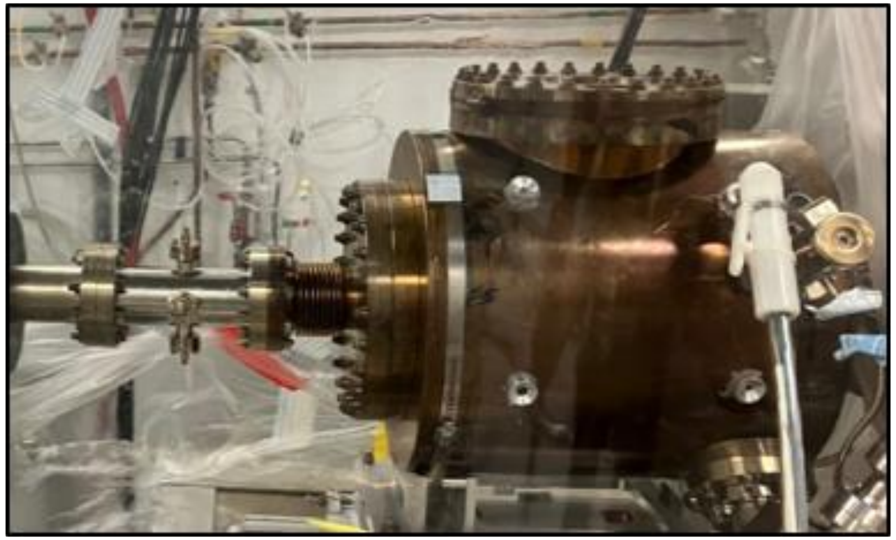


UITF Drive Laser:

- Option #1 – High power 780 nm diode laser for photocathode lifetime studies
- Option #2 – Low power tunable (630 – 840 nm) SuperK laser for POL and QE wavelength scans
- Pockels cells and insertable waveplate for fast and slow laser polarization reversal

UITF photogun:

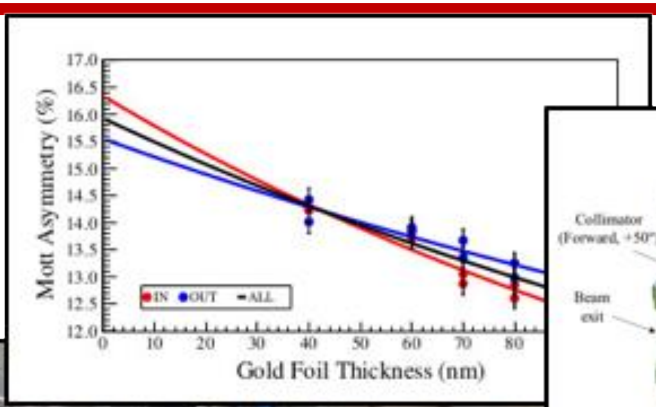
- Inverted Tee-shape Nb electrode
- Kr processed to 200 kV
- Biased anode to reduce ion back-bombardment
- Load up to 4 GaAs samples at once

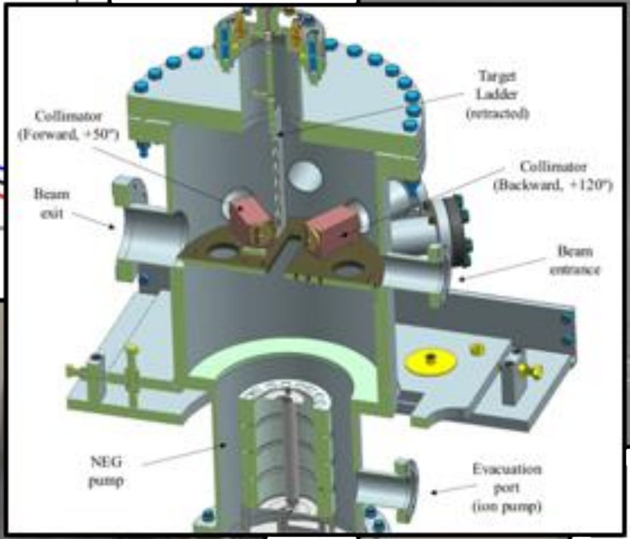


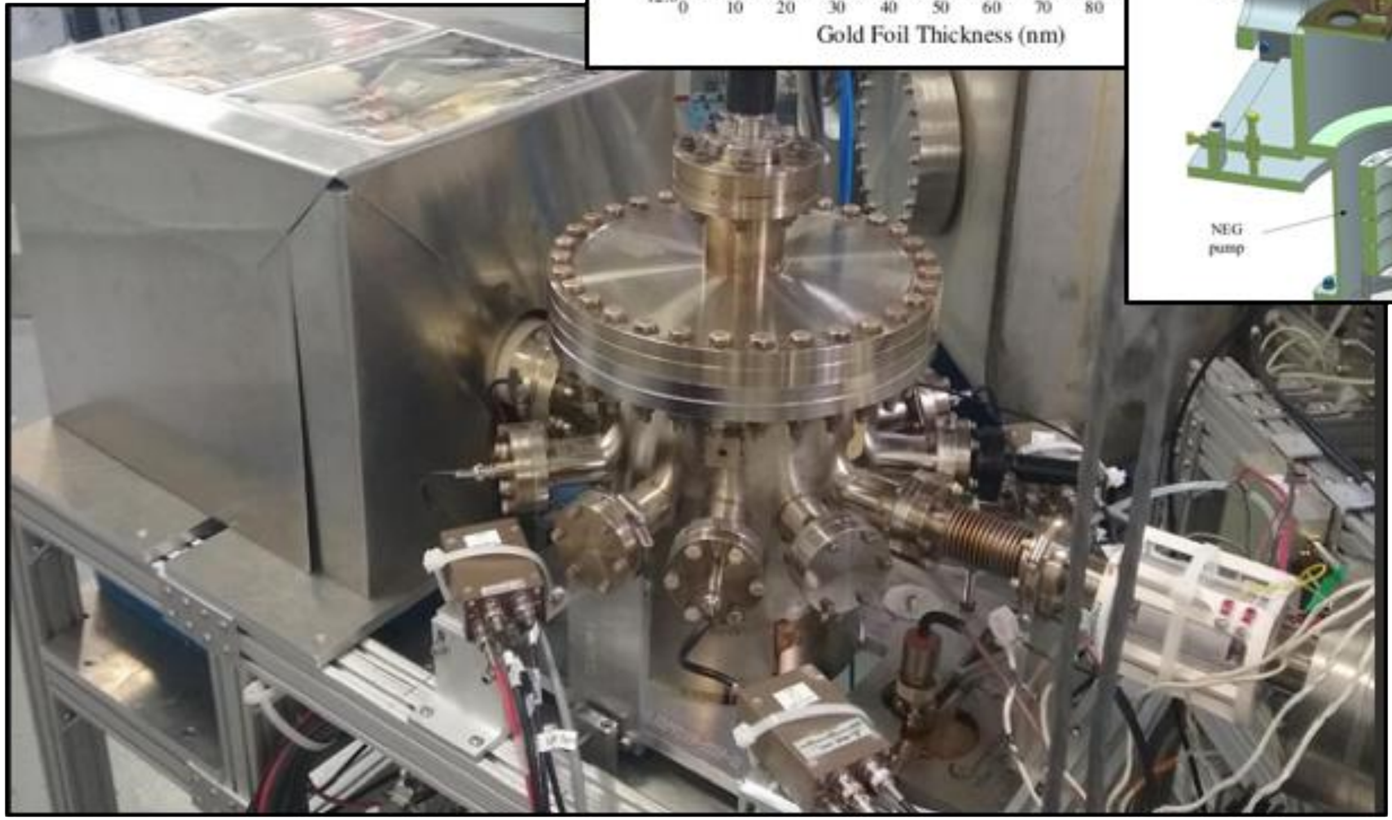
Polarimetry measurements

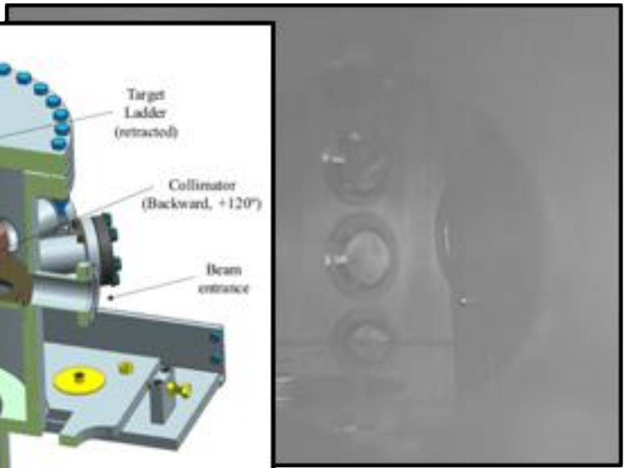
Mott Polarimeter:

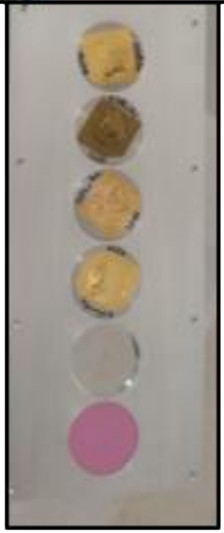
- 4 thin gold targets used
- Detectors at 120 degrees
- Asymmetry measured for each target and extrapolated to "zero-thickness"

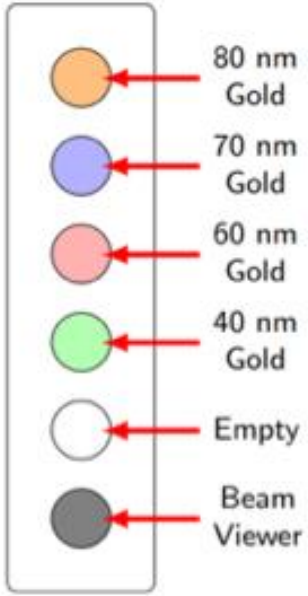








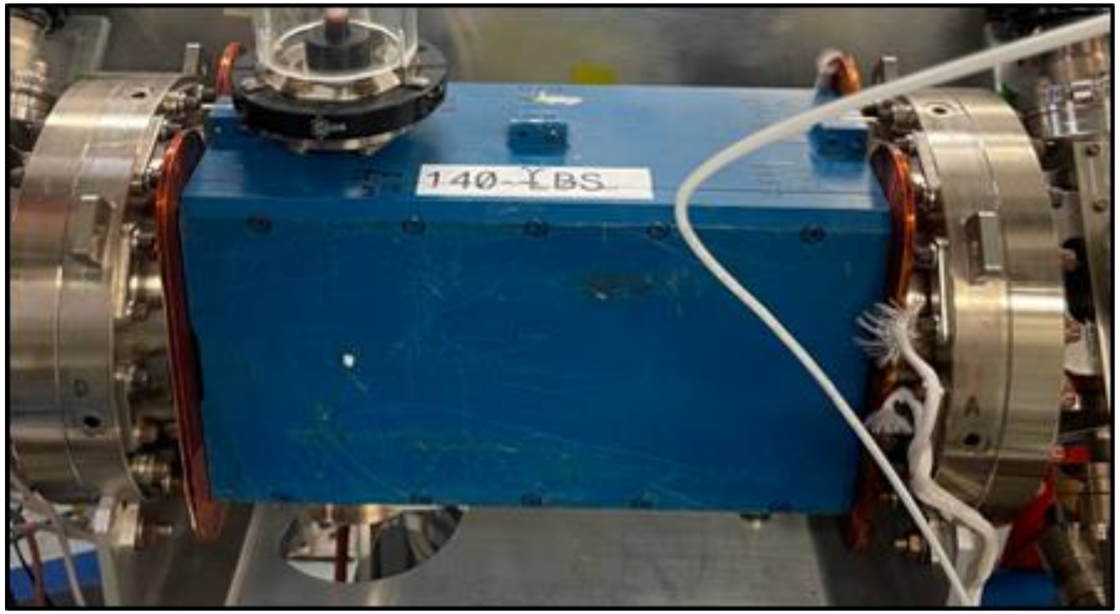


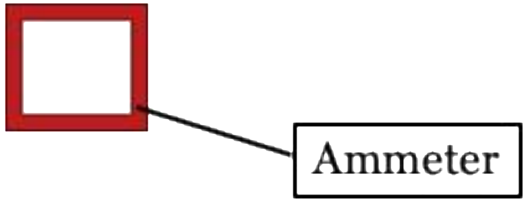


Spin Manipulation and QE measurements

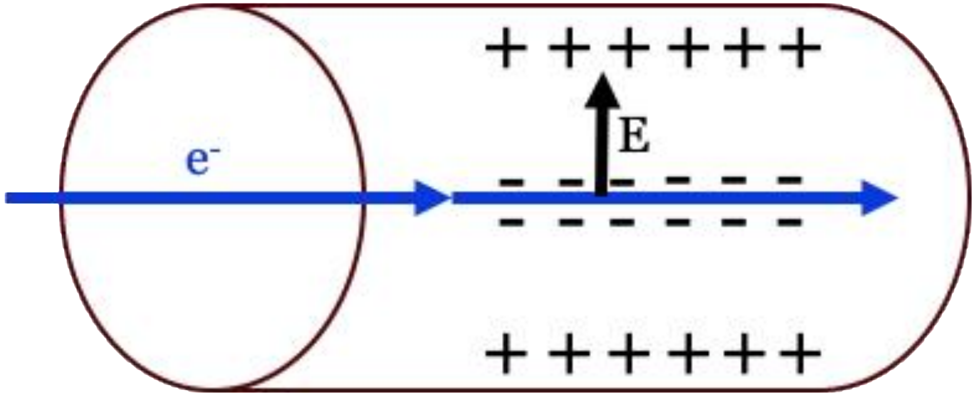
Wien Filter:

- Mott Polarimetry requires transverse polarization
- Wien filters rotate polarization vector





Destructive Method – Faraday Cup



Non-destructive Method – BCM Cavity

- Current corresponds to electric and magnetic fields generated in the cavity

QE measurements:

- Insertable Faraday Cup
- Beam Current Monitor (BCM) Cavity

Conclusion

- Spin polarized electron sources were fabricated successfully via MOCVD
- Study on doping concentration of the top layer:
  - 11 nC with the free limit range
  - 9 nC with an 8 mm diameter laser
- Study on DBR:
  - Enhancement of reflectivity with additional pairs (as expected)
  - Non uniformity across the wafer but uniformity on single spot on various wafers and run to run
  - Uniformity for many materials
  - Need to modify process parameters to reach uniformity with our materials
- Best Device
  - Polarization: 92%
  - QE: 2.3%

Back up slides

MOCVD growth parameters

- Key Precursors
  - Trimethyl Gallium ($Ga(CH_3)_3$)
  - Arsine (AsH_3) and Phosphine (PH_3)
  - Diethyl Zinc ($Zn(CH_3CH_3)_2$)
  - Carbon Tetrachloride (CCl_4)
  - Lower diffusivity of carbon in GaAsP should improve lifetime of device surface
- Substrate: 2” GaAs wafers on axis in the 110 direction
- Growth rate range: 3-8 μm/hr
- Temperature: 650-750^{o}C

MOCVD system at Rochester Institute of Technology

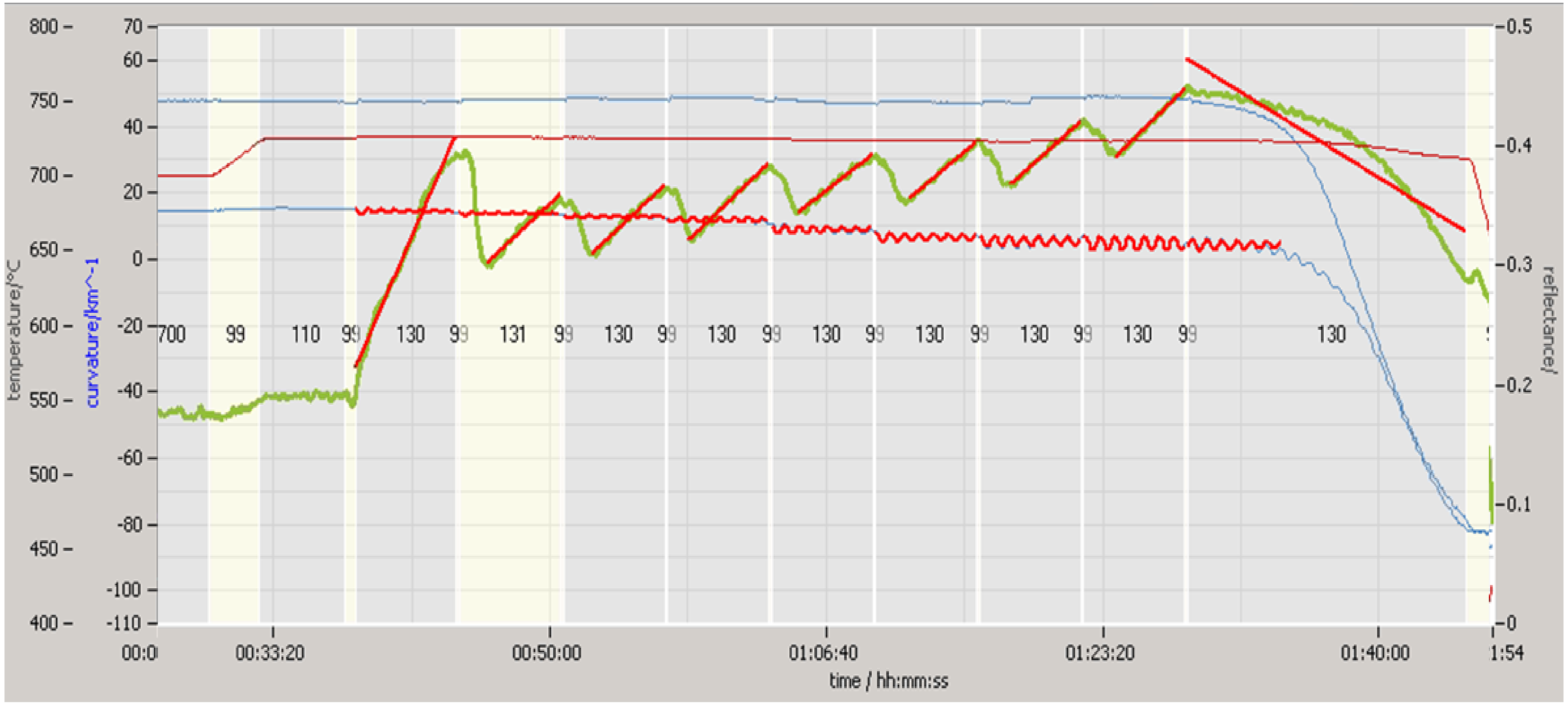
Tools Used

- Telemetry: in-situ measurement
  - Pyrometry
  - Curvature
  - Reflectivity

Temperature

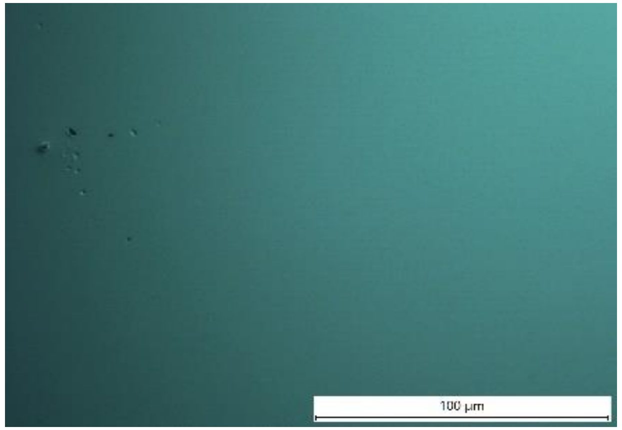
Reflectivity

Curvature

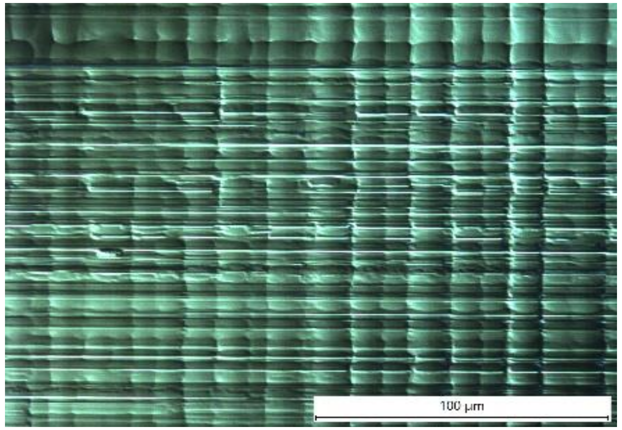


Tools Used

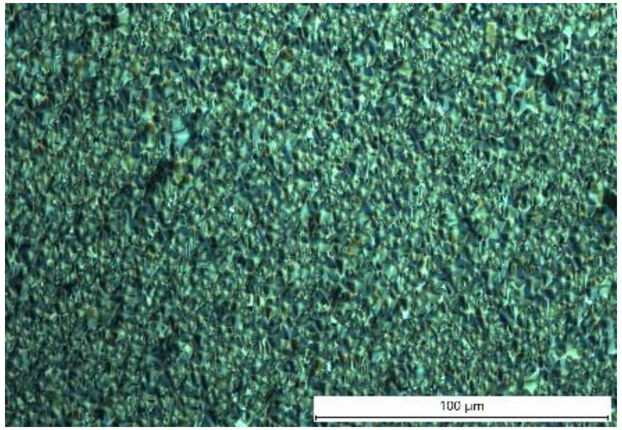
- Nomarski Microscopy : ex-situ measurement
  - Differential interference contrast (DIC) microscopy
  - Surface topography



$GaAs_{0.95}P_{0.05}$ minimal strain so minimal surface features



Textured photocathode, good, there's uniform strain

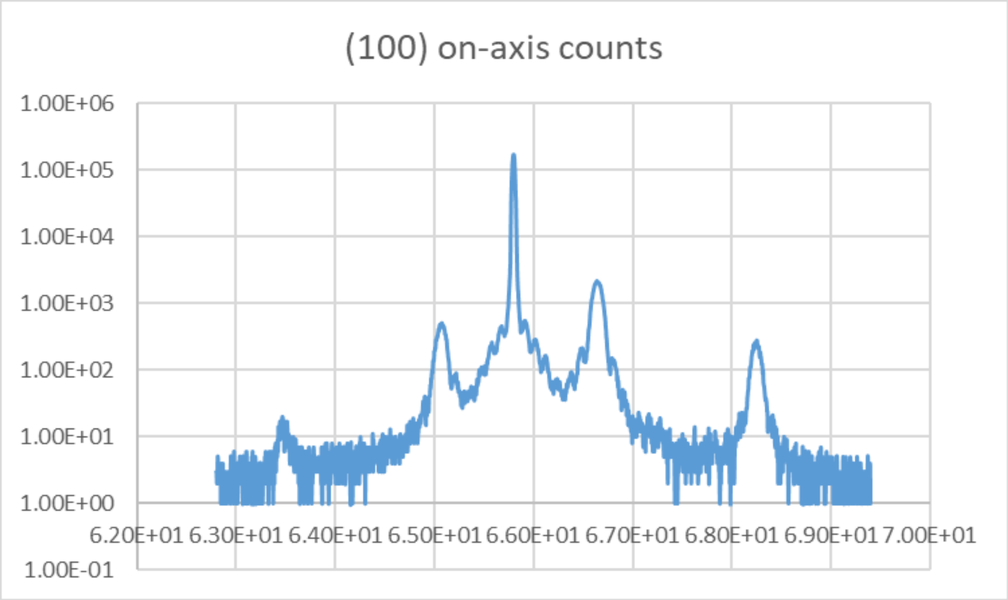


poorly relaxed growth

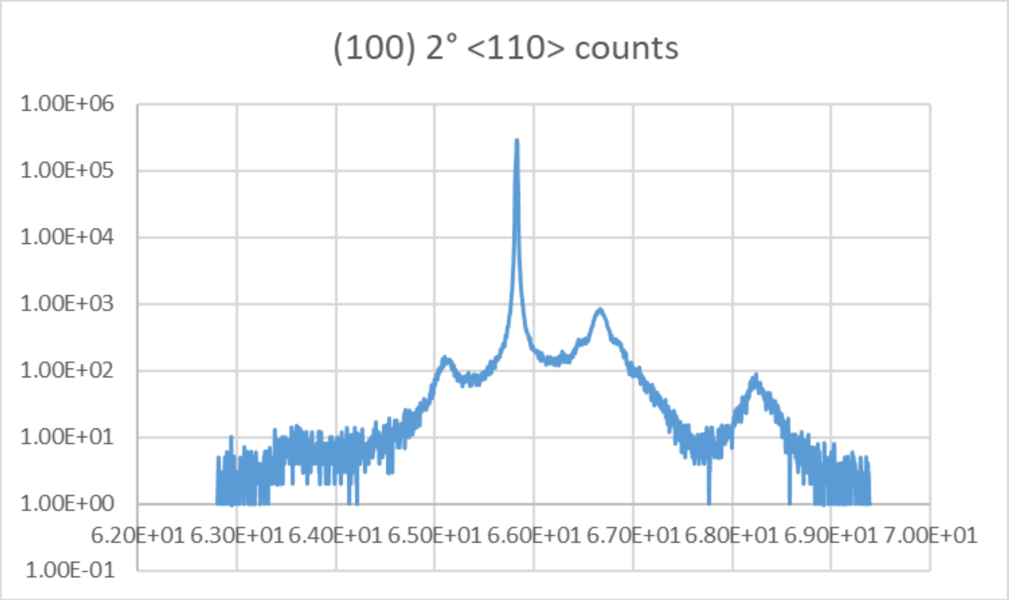
Tools Used

- X-ray Diffraction : ex-situ measurement
  - Used to measure material strain and composition
  - destructive and constructive interference that occurs when X-rays impinge on sample

$GaAs/GaAs_{0.65}P_{0.35}$ superlattice samples grown on different substrates:



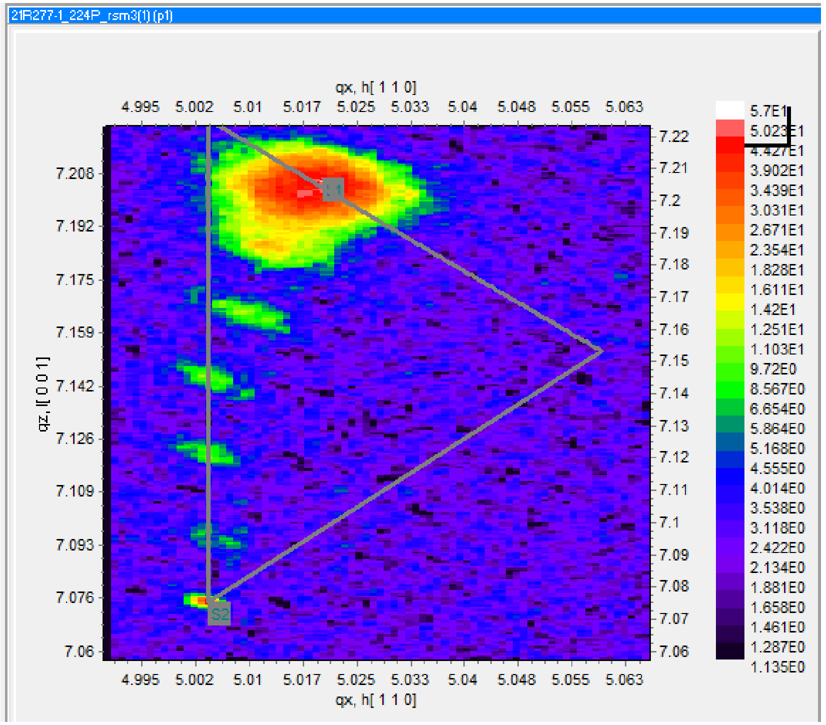
(100) substrate, on-axis



(100) substrate, 2 degree offcut in the (110) direction

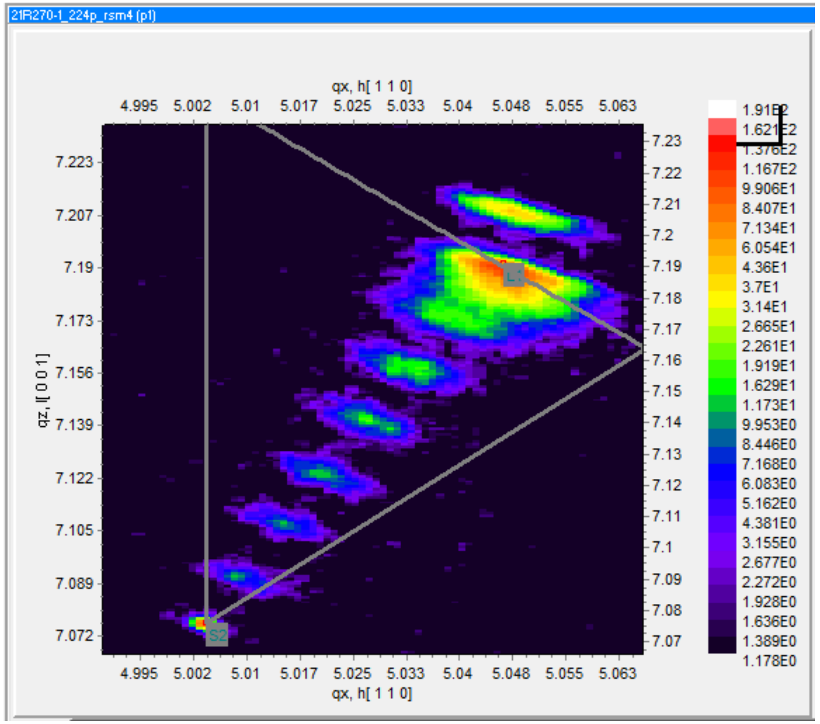
Tools Used

- X-ray Diffraction : ex-situ measurement
  - Reciprocal phase space mapping
  - Shows relaxation of deposited films, key to determining quality of the deposited metamorphic grading



3µm/hr 730ºC Growth Temp

Close to vertical line: more strain

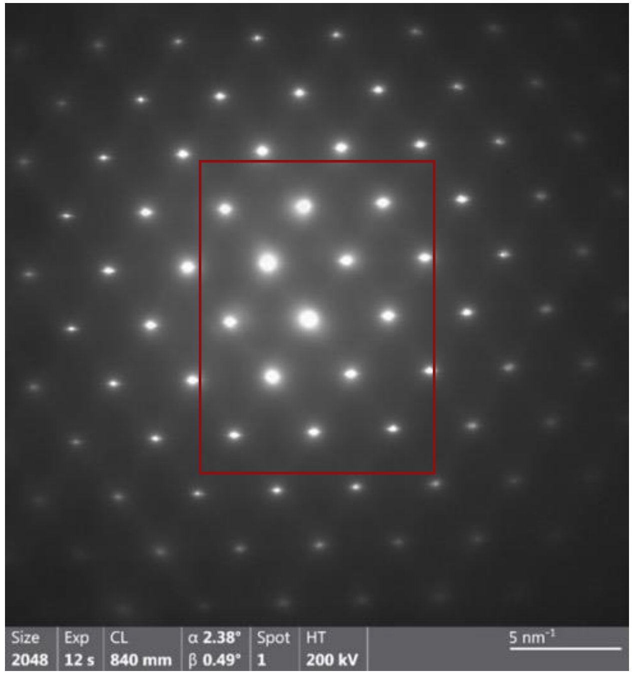


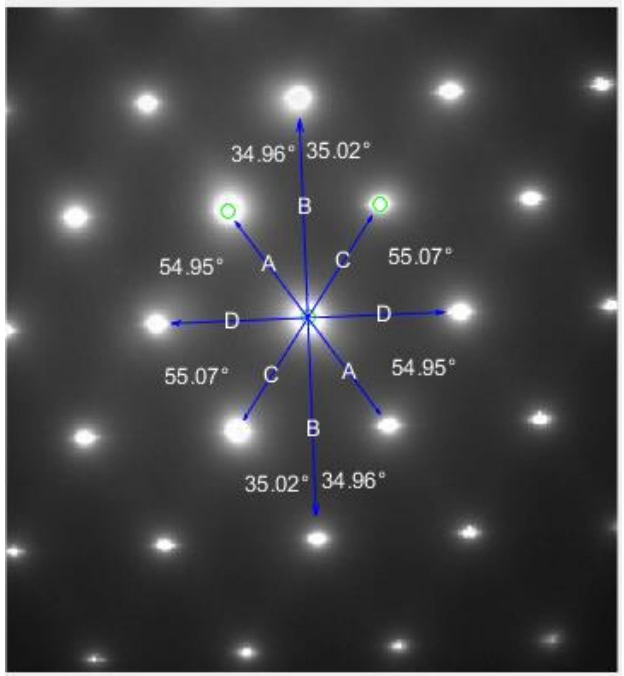
10µm/hr 730ºC Growth Temp

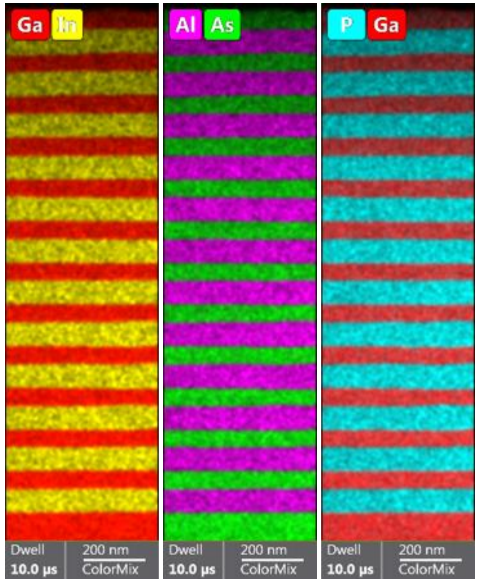
Close to diagonal line: less strain

Tools Used

- Transmission Electron Microscopy : ex-situ measurement
  - TEM micrographs (Images)
  - Selected Area Electron Diffraction (SAED)
  - Energy Dispersive X-Ray Spectroscopy (EDS)

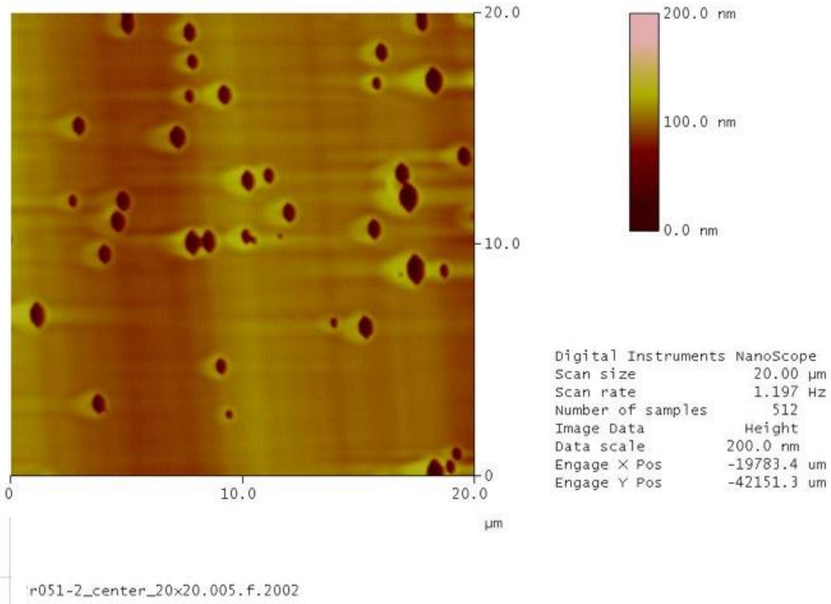


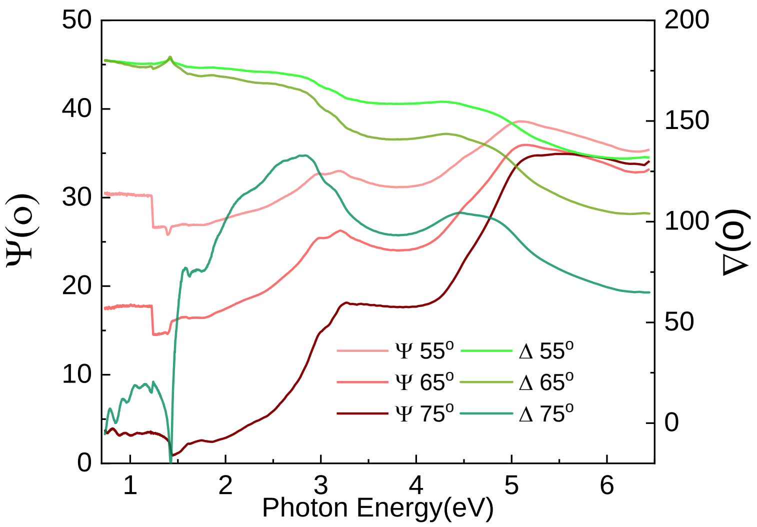


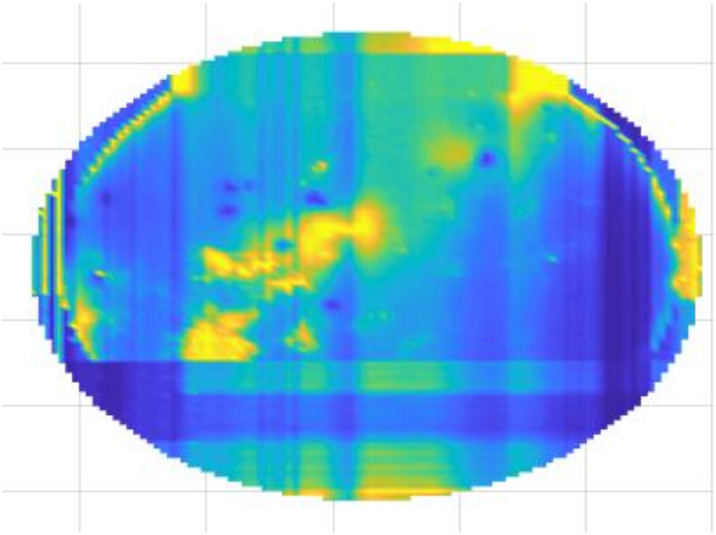


Tools Used

- Ellipsometry (optical method, layer thickness)
- Photoluminescence (PL) mapping (uniformity)
- Hall Effect (measure dopant concentration)
- Atomic Force Microscopy (surface defects)





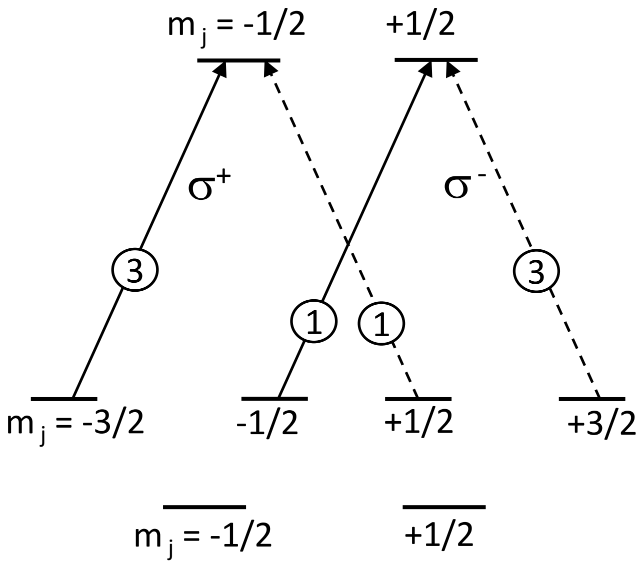


Results: Metamorphic Grading

- High-quality strain relaxation of underlying layers is key to getting intended GaAs strain in the emitting region
- Necessary because of growing on lattice mismatched substrate
- RSM used to characterize extent of relaxation in metamorphic layers
- Key parameters changed:
  - Growth Rate
  - Growth Temperature
  - Arsine/Phosphine Ratio

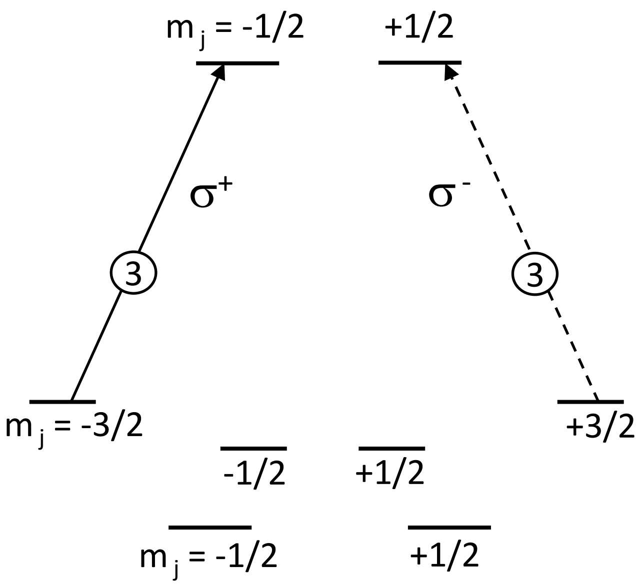
Making polarized electron beams with GaAs

Bulk GaAs – no strain



Maximum Polarization 50%

Strained GaAs



Maximum Polarization 100%

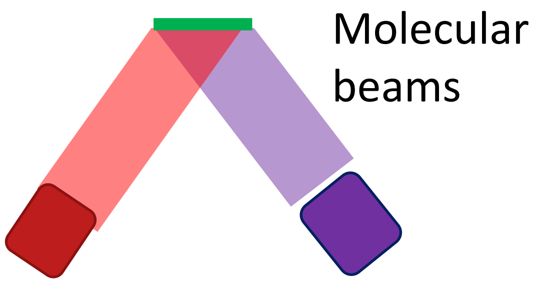
MBE, GSMBE, CBE and MOCVD (aka MOVPE)

MBE

Gas Source Molecular Beam Epitaxy

elemental As, P, Ga

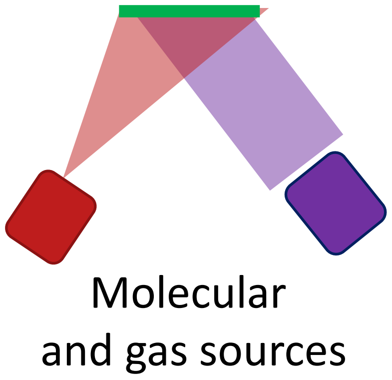
- Pressure ~10^{-8} mbar
- Growth rates ~ 1 µm/hr
- Very precise control



GSMBE

Gas Source Molecular Beam Epitaxy

AsH_3, PH_3, elemental Gallium

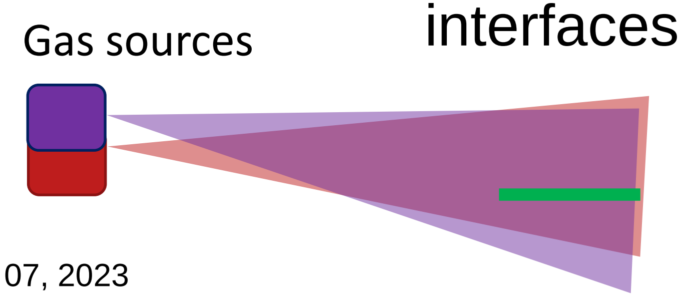


CBE

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 (metal organic vapor phase epitaxy)

AsH_3, PH_3, trimethylgallium (TMGa)

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