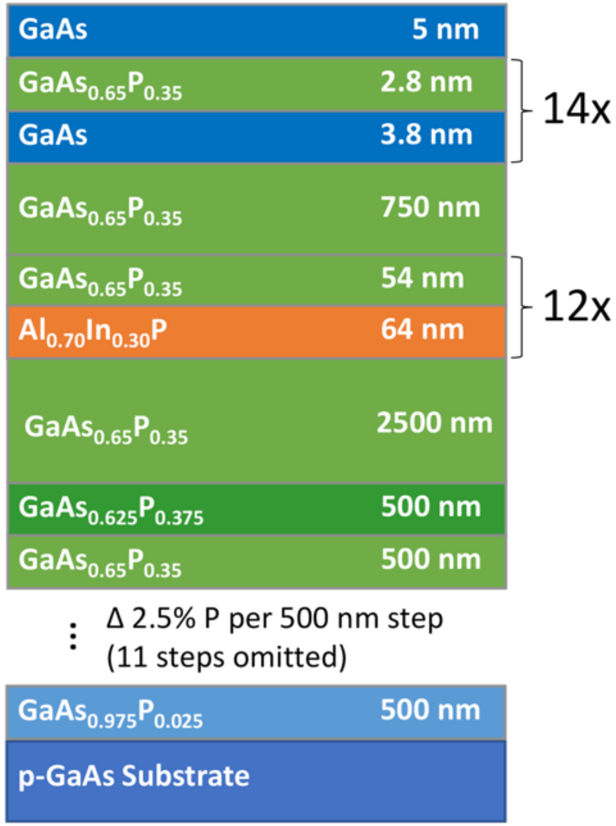
# Enhancing the Design of Photocathodes with 90% polarization and QE > 1% for DOE NP

Nuclear Physics Accelerator R&D

PI Exchange Meeting

December 2 2024



| Layer | Thickness | |
|---|---|---|
| GaAs | 5 nm | |
| $GaAs_{0.65}P_{0.35}$ | 2.8 nm | 14x |
| GaAs | 3.8 nm | |
| $GaAs_{0.65}P_{0.35}$ | 750 nm | |
| $GaAs_{0.65}P_{0.35}$ | 54 nm | 12x |
| $Al_{0.70}In_{0.30}P$ | 64 nm | |
| $GaAs_{0.65}P_{0.35}$ | 2500 nm | |
| $GaAs_{0.625}P_{0.375}$ | 500 nm | |
| $GaAs_{0.65}P_{0.35}$ | 500 nm | |
| ⋮ Δ 2.5% P per 500 nm step (11 steps omitted) | | |
| $GaAs_{0.975}P_{0.025}$ | 500 nm | |
| p-GaAs Substrate | | |

Sylvain Marsillac & Matt Grau, ODU
Joe Grames & Matt Poelker, Jefferson Lab
Erdong Wang, BNL

# Project Main Goal

The main goals:

- 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 composition 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 composition and Lifetime studies | | X | X | X |
| Enhanced Strained superlattice/DBR Photocathodes Evaluation | | | X | X |

# Budget

| | FY23($k) | FY24($k) | Total($k) |
|---|---|---|---|
| a) Funds allocated | $179,000 | $179,000 | $358,000 |
| b) Actual costs to date | $179,000 | $171,000 | $350,000 |

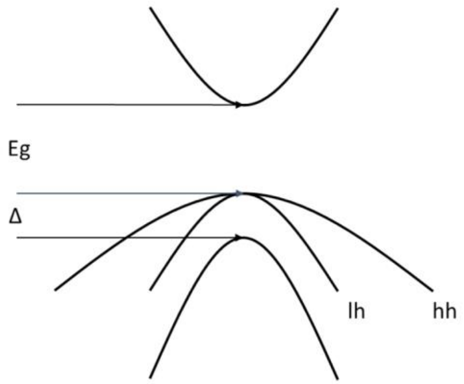
| PI | ID # | Item/Task |
|---|---|---|
| Matt Poelker | 000001.04.05.028.002 (MOCVD2) | Accel R&D - MOCVD2 Photocathode - ODU |

| | FY22 ($k) | FY23 ($k) | Totals ($k) |
|---|---|---|---|
| a) Funds allocated | $70 | $70 | $140 |
| b) Actual costs to date | $70 | $49 | $119 |

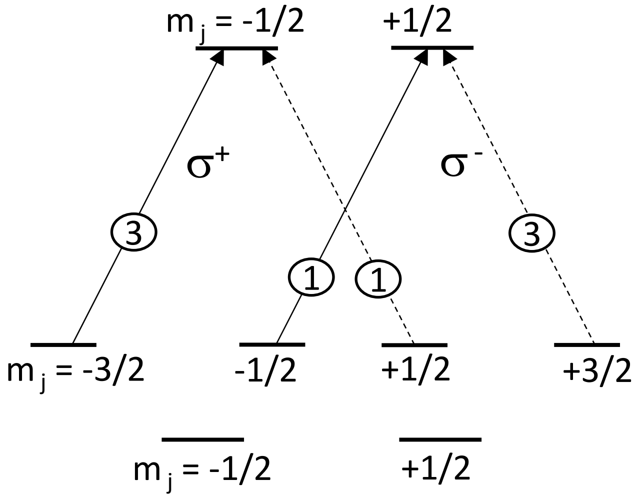
| PI | ID # | Item/Task |
|---|---|---|
| Joe Grames | 000001.04.05.037.001 (MOCVD3) | Accel R&D - MOCVD3 Photocathode - ODU |

| | FY24 ($k) | Totals ($k) |
|---|---|---|
| a) Funds allocated | $30 | $30 |
| b) Actual costs to date | $0 | $0 |

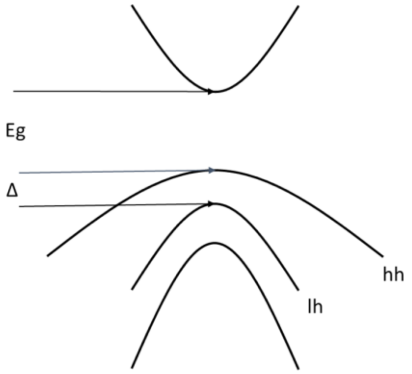
# Overview: Making polarized electron beams with GaAs



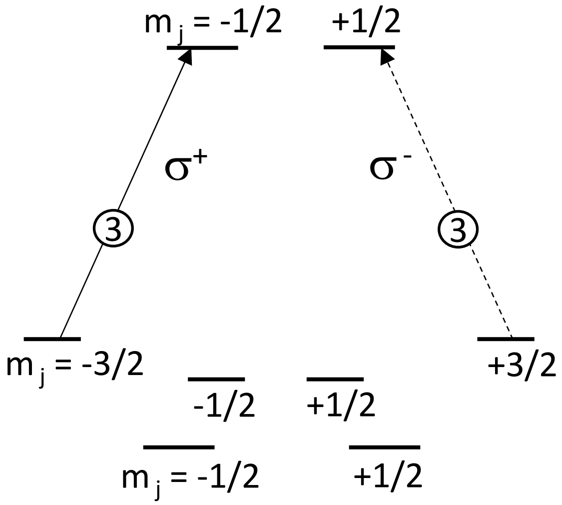
Bulk GaAs – no strain



Maximum Polarization 50%

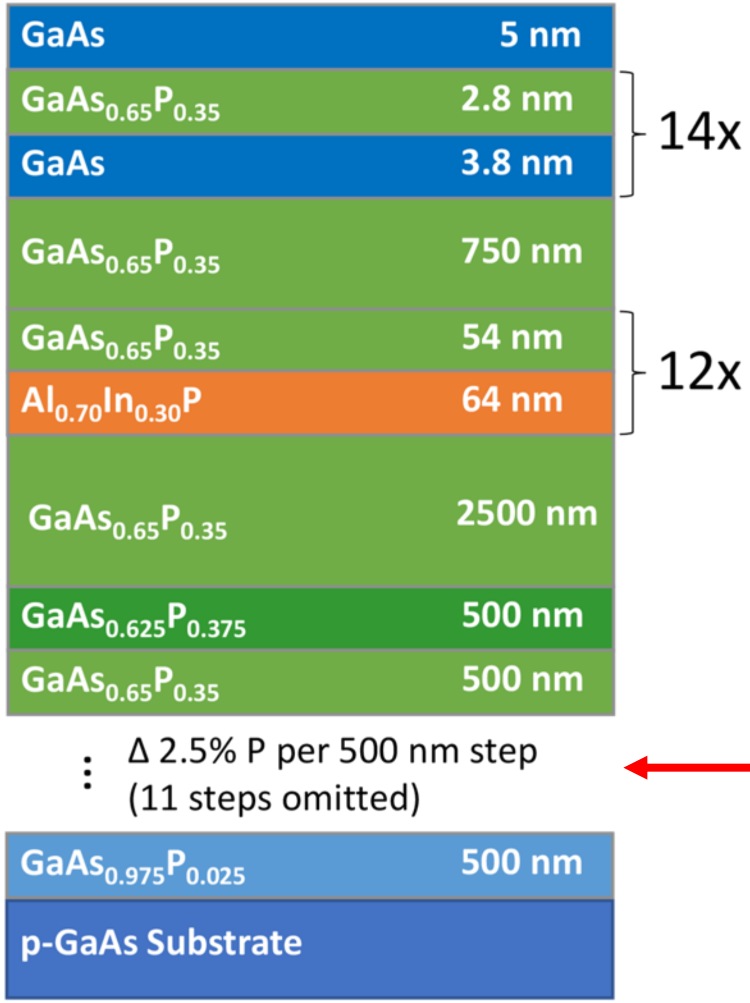


Strained GaAs



Maximum Polarization 100%

# Overview: Device Structure SSL with DBR



GaAs 5 nm

$GaAs_{0.65}P_{0.35}$ 2.8 nm

GaAs 3.8 nm

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$GaAs_{0.65}P_{0.35}$ 750 nm

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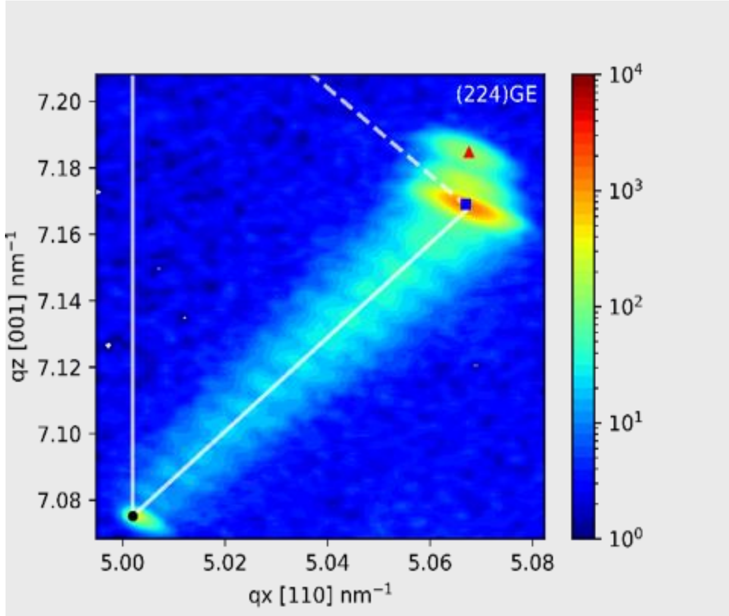
$GaAs_{0.65}P_{0.35}$ 500 nm

⋮ Δ 2.5% P per 500 nm step (11 steps omitted)

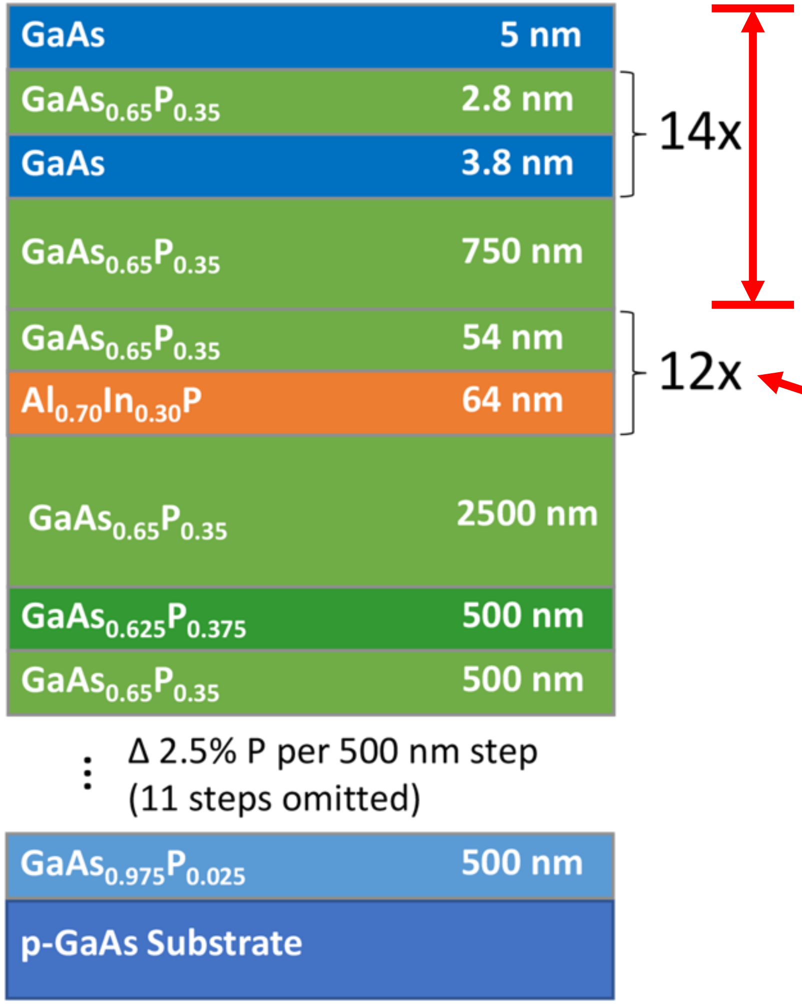
$GaAs_{0.975}P_{0.025}$ 500 nm

p-GaAs Substrate



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

# Overview: Device Structure SSL with DBR



| | |
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| $GaAs_{0.975}P_{0.025}$ | 500 nm |
| p-GaAs Substrate | |

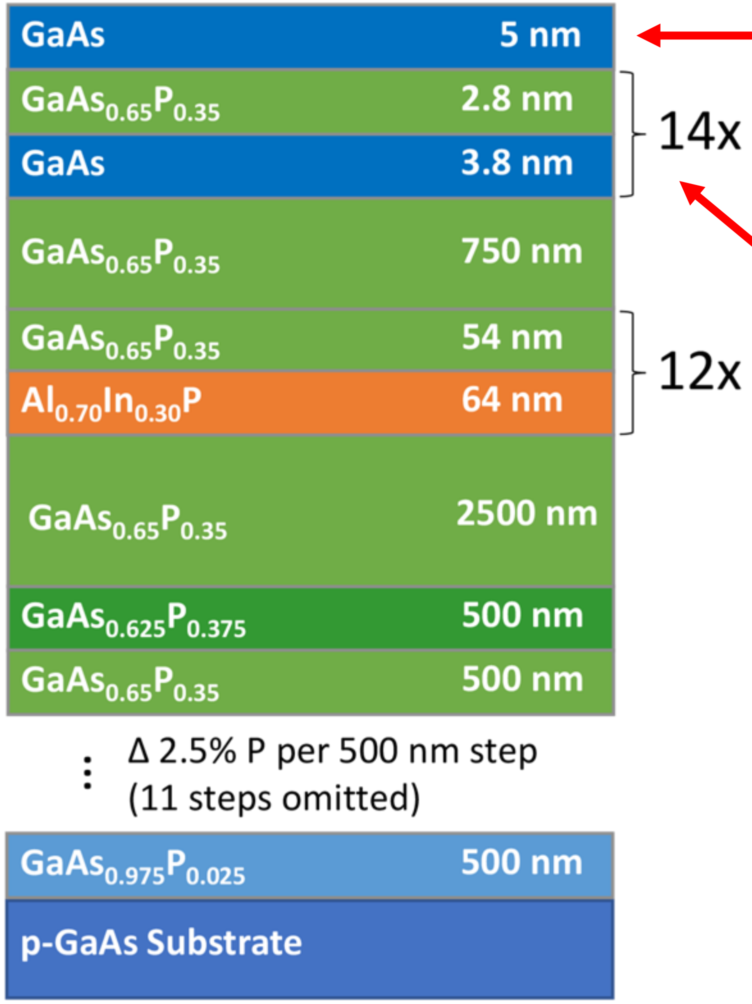
14x

12x

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

Superlattice which forms the Distributed Bragg Reflector (DBR)

# Overview: Device Structure SSL with DBR



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$GaAs_{0.65}P_{0.35}$ 500 nm

⋮ Δ 2.5% P per 500 nm step
(11 steps omitted)

$GaAs_{0.975}P_{0.025}$ 500 nm

p-GaAs Substrate

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

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

# Main Layers & Tools

***Two main Layers***:

1. Superlattice
2. DBR

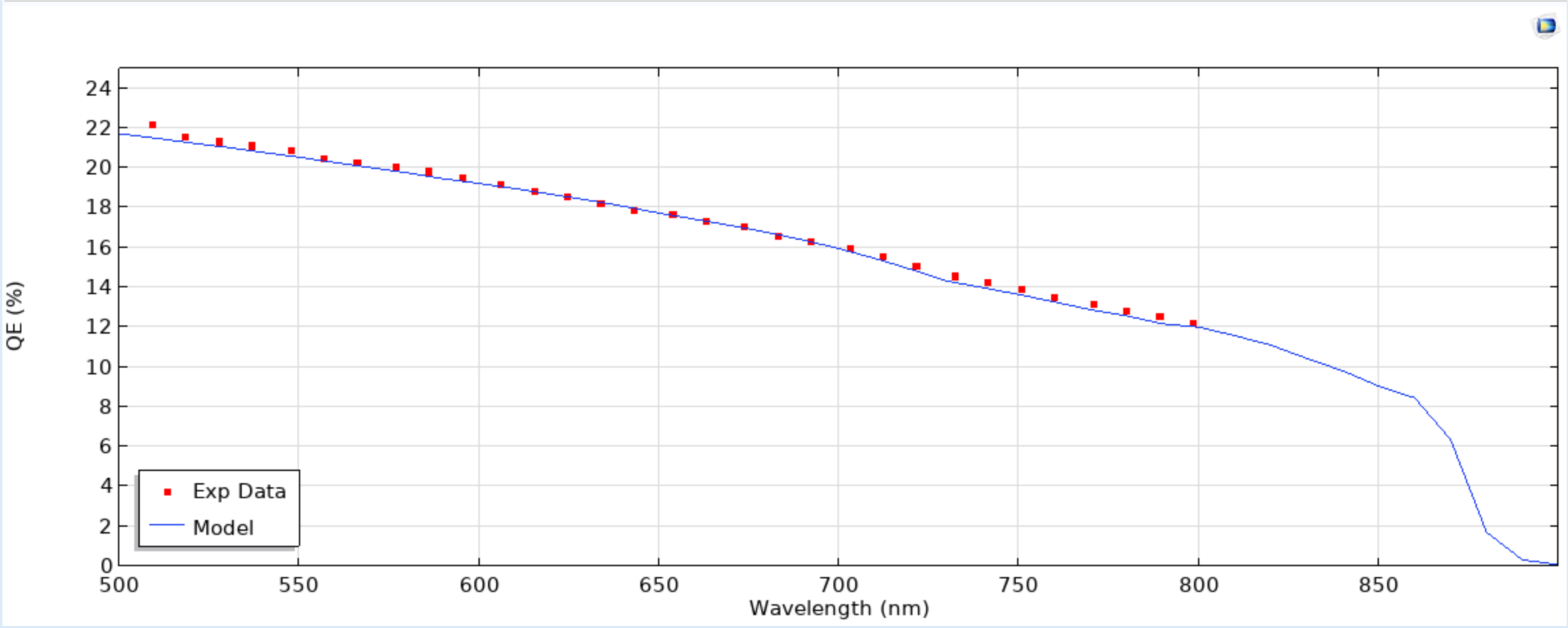
***Three main Tools***:

1. Modeling
2. Fabrication Process and Materials characterizations
3. Device Characterization: Polarization and QE

***Major Issue in Year 2:*** Lack of GaAs wafers availability due to supply chain interruption from China

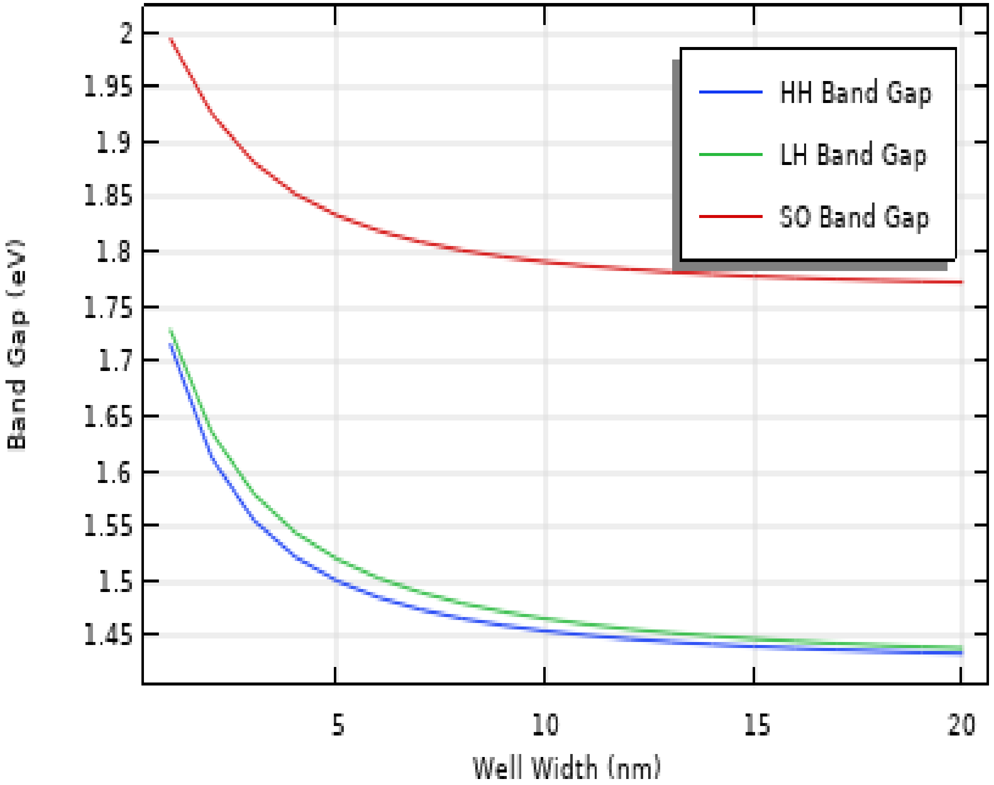
# Modeling: Benchmarking bulk GaAs

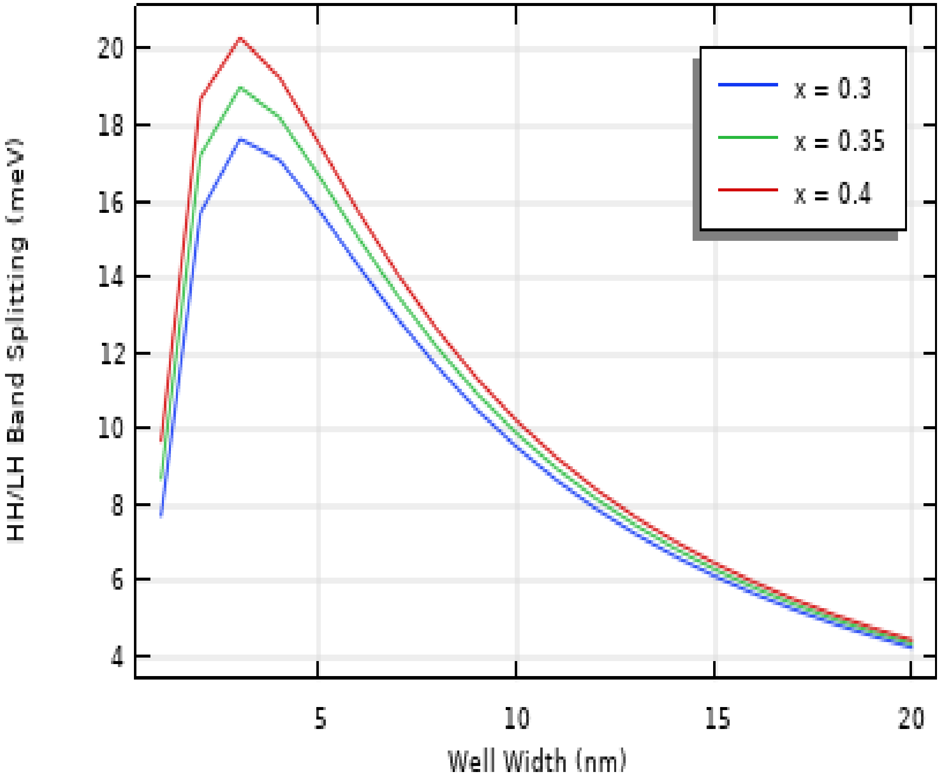
- Bulk GaAs model benchmarked and understood



Data from - W. Liu, S. Zhang, M. Stutzman, and M. Poelker, Effects of ion bombardment on bulk GaAs photocathodes with different surface-cleavage planes, Phys. Rev. Accel. Beam **19**, 103402 (2016)

# Task 1: Superlattice (Modeling)

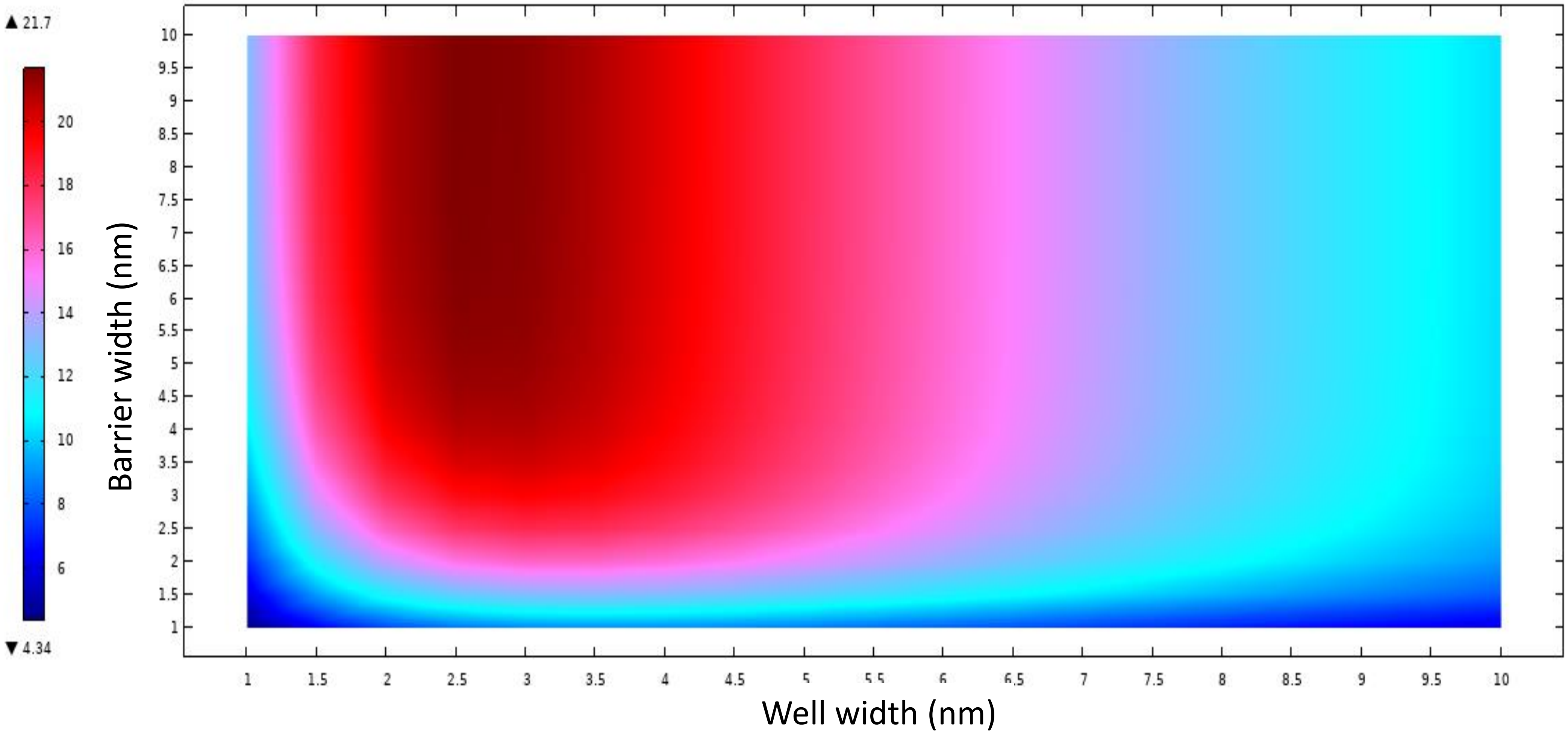




*Energy levels for x=0.35 as a function of well width for* $GaAs_{1-x}P_x$ *with x = 0.35*

*HH/LH Band splitting for* $GaAs_{1-x}P_x$ *for different x as a function of well width (0.3 to 0.4)*

# Task 1: Superlattice (Modeling)

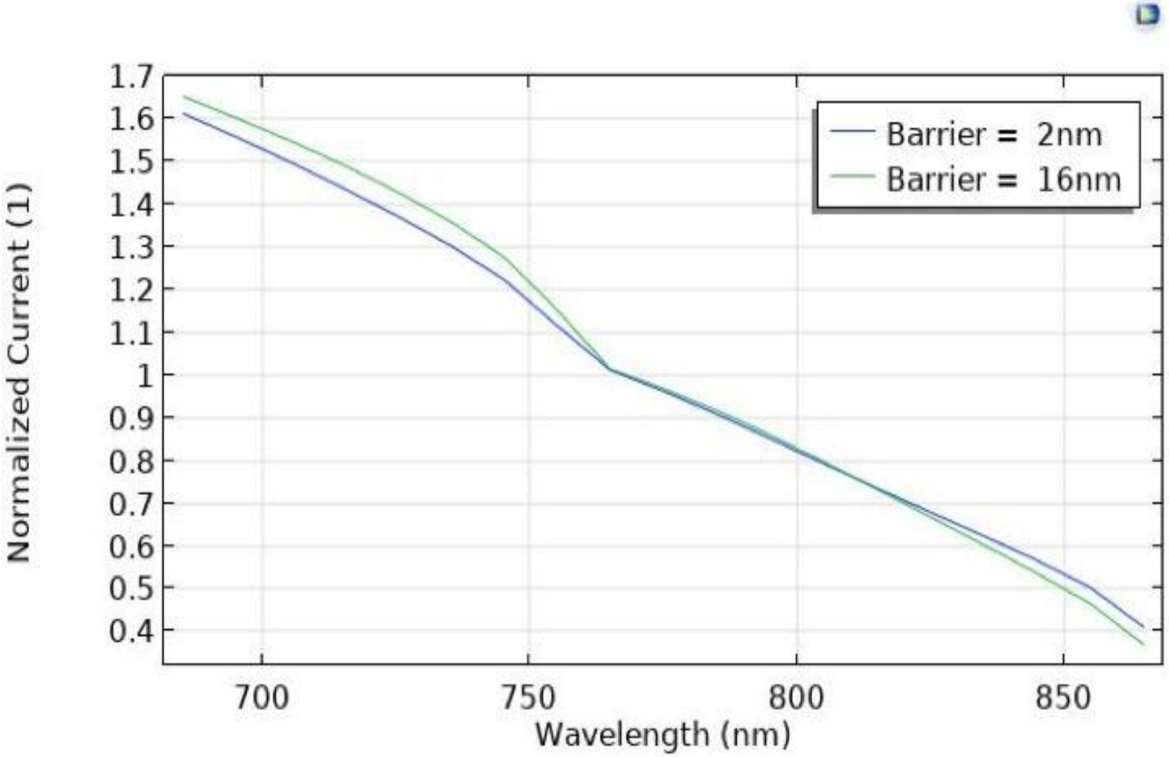


*HH/LH Band splitting as a function of Well and Barrier widths for* $GaAs_{1-x}P_x$ *with* $x=0.35$

# Task 1: Superlattice (Modeling)

Transport Model takes into account (when necessary)

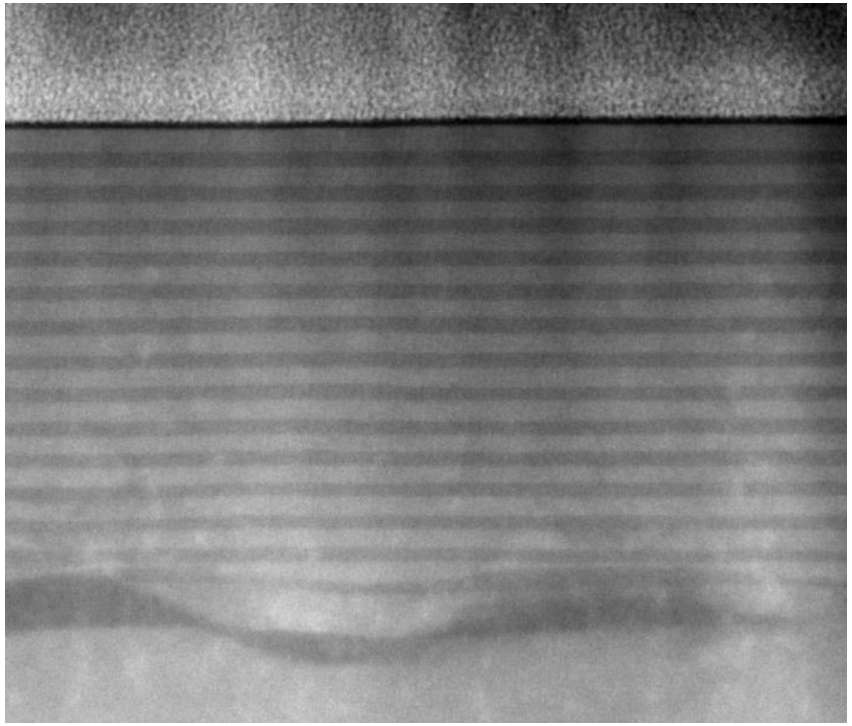
- Diffusion
- Drift
- Generation/Recombination
- Tunneling
- Emission



*Results for normalized current as a function of wavelength for various barrier height*

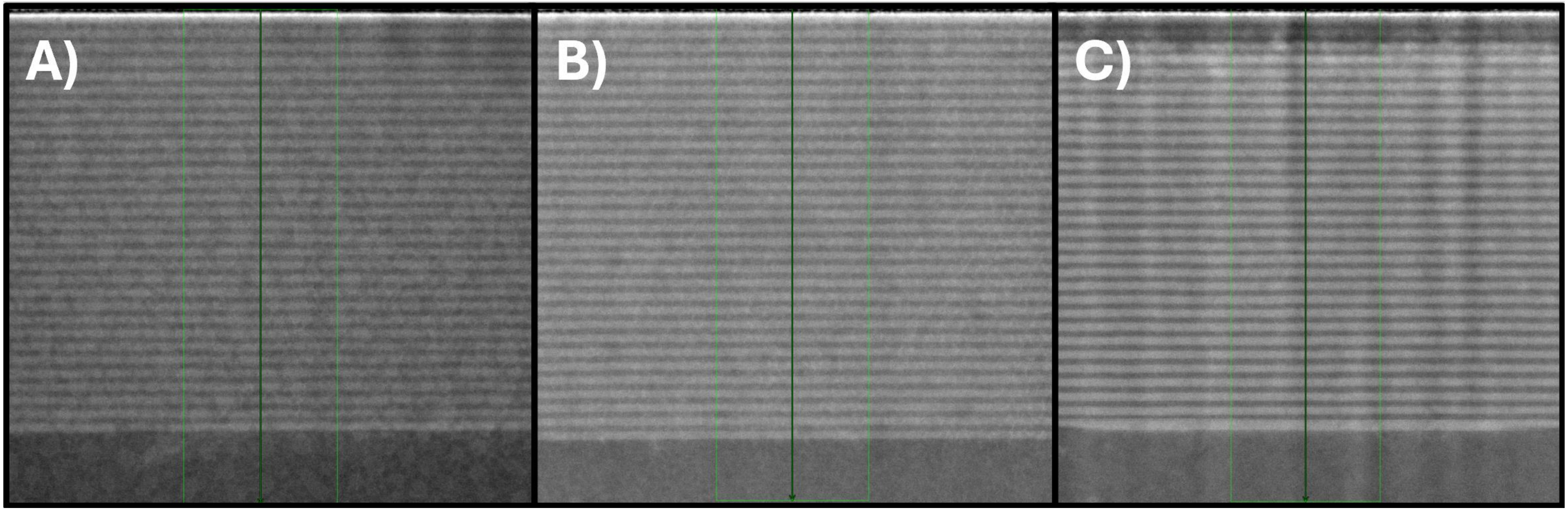
# Task 2: Superlattice (Growth Temperature)

- Observation of poor interface under superlattice
- During growth, the interface is where we drop the growth temperature from 720°C to 600°C.
- Grow test structures of $GaAs_{(1-x)}P_x$ with varying values of x to establish our Langmuir curves at growth temperatures of 600°C, 650°C, and 720°C
- Growth of MMG at 600°C and 650°C failed: need to keep 720°C.
- Growth of DBR at 600°C failed: Grew at 650°C then superlattice at 580°C, 600°C or 650°C.



TEM image of our superlattice. A poor growth layer is formed at the bottom of the superlattice where a high transition in growth temperatures occurs.

# Task 2: Superlattice (Growth Temperature)

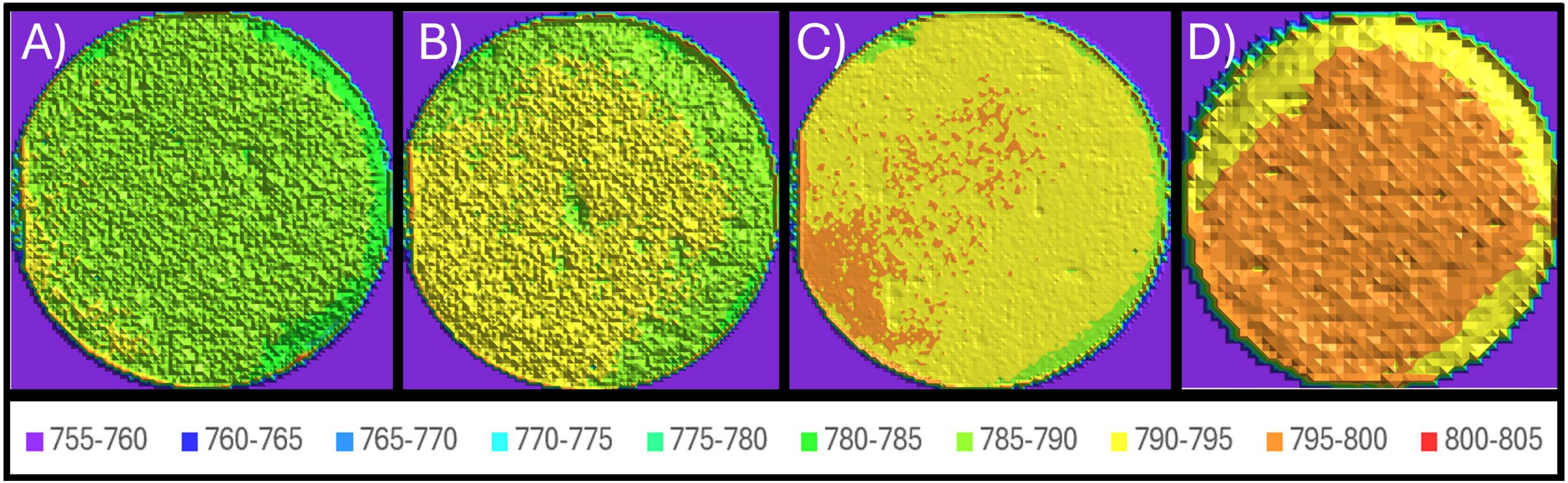


*30 pair superlattice grown at A) 580°C, B) 600°C, and C) 650°C.*

- No issues observed at DBR/SSL interface
- Growth at 650°C shows layer deformation in the top couple pairs.

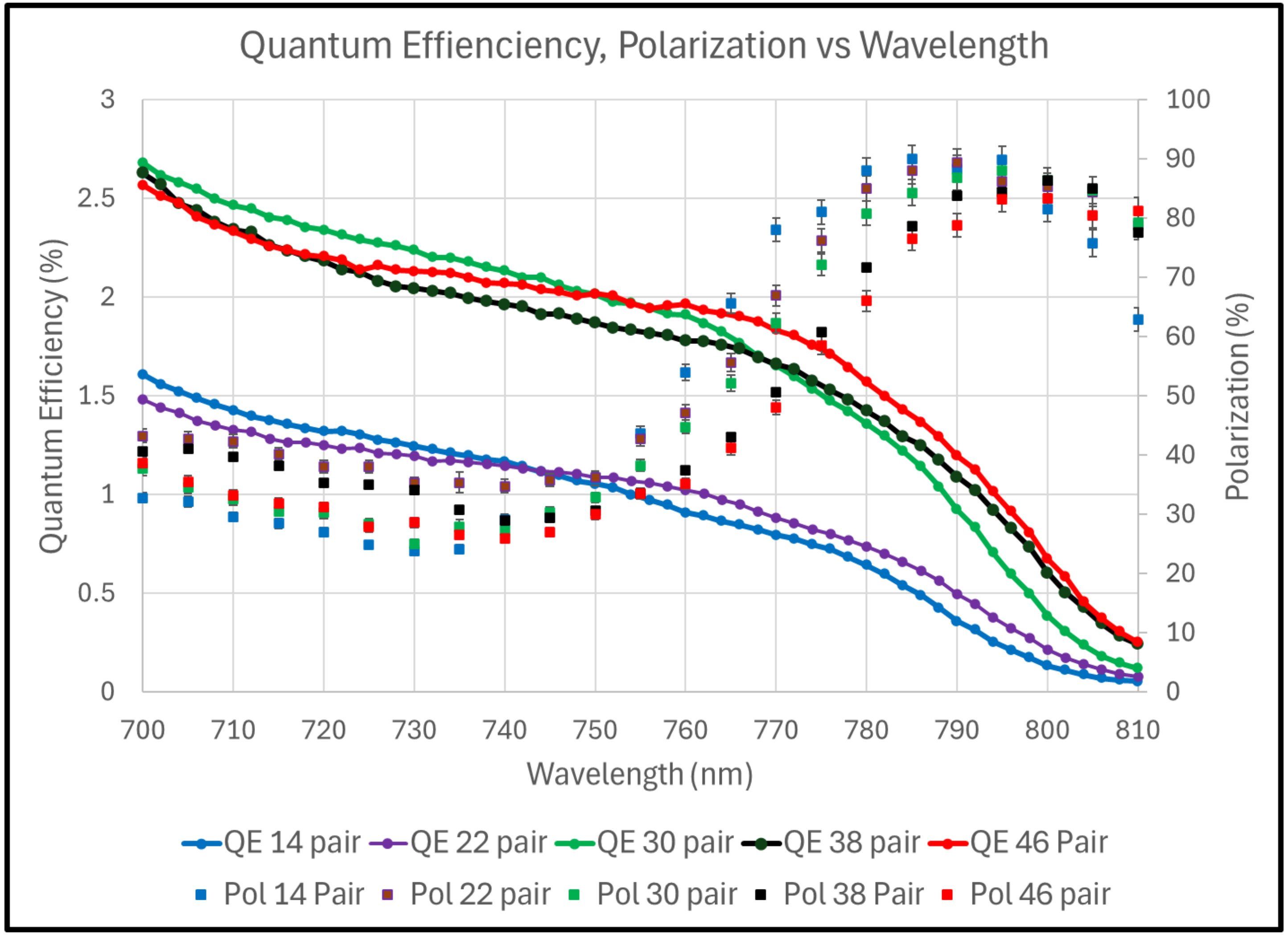
# Task 3: Superlattice (Number of pairs)

- Strain on the device: affect phosphorous incorporation
- Photocathodes without DBR: polarization peak at 785 nm, with DBR at 775 nm
- As the superlattice grows: possible strain reduction which could reduce phosphorus content and lead to peak shifting



*PL maps of superlattices grown at 600°C with A) 14 pairs, B) 22 pairs, C) 38 pairs, D) 46 pairs (the 30 pairs is currently under test).*

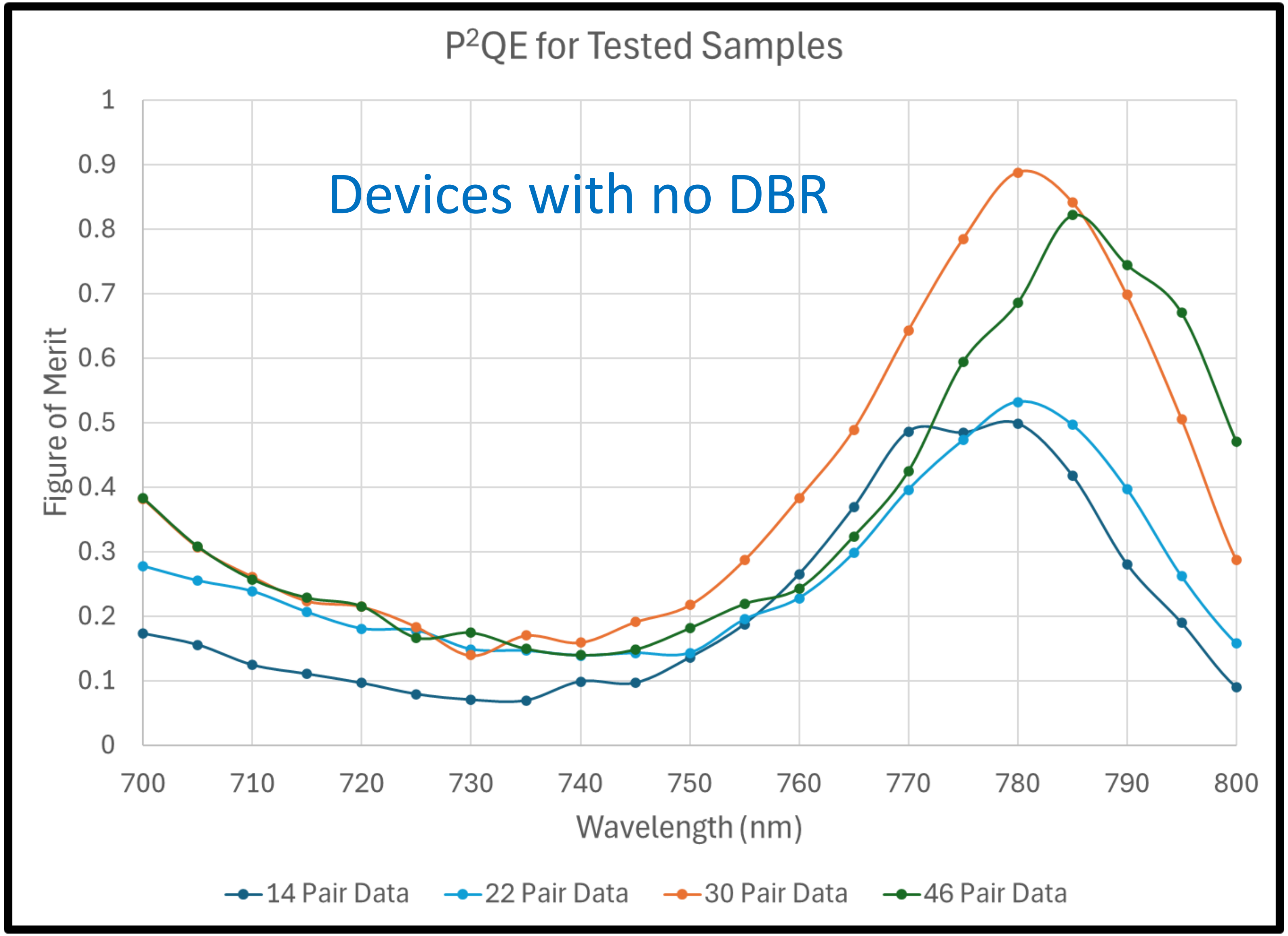
# Task 3: Superlattice (Number of pairs)



## Devices with no DBR

| Number of Pairs | Peak Polarization | QE at Peak Polarization |
|---|---|---|
| 14 | 90.0% @ 785nm | 0.51% |
| 22 | 89.5% @ 790nm | 0.50% |
| 30 | 88.1% @ 795nm | 0.65% |
| 38 | 86.4% @ 800nm | 0.60% |
| 46 | 83.4% @ 800nm | 0.68% |

# Task 3: Superlattice (Number of pairs)

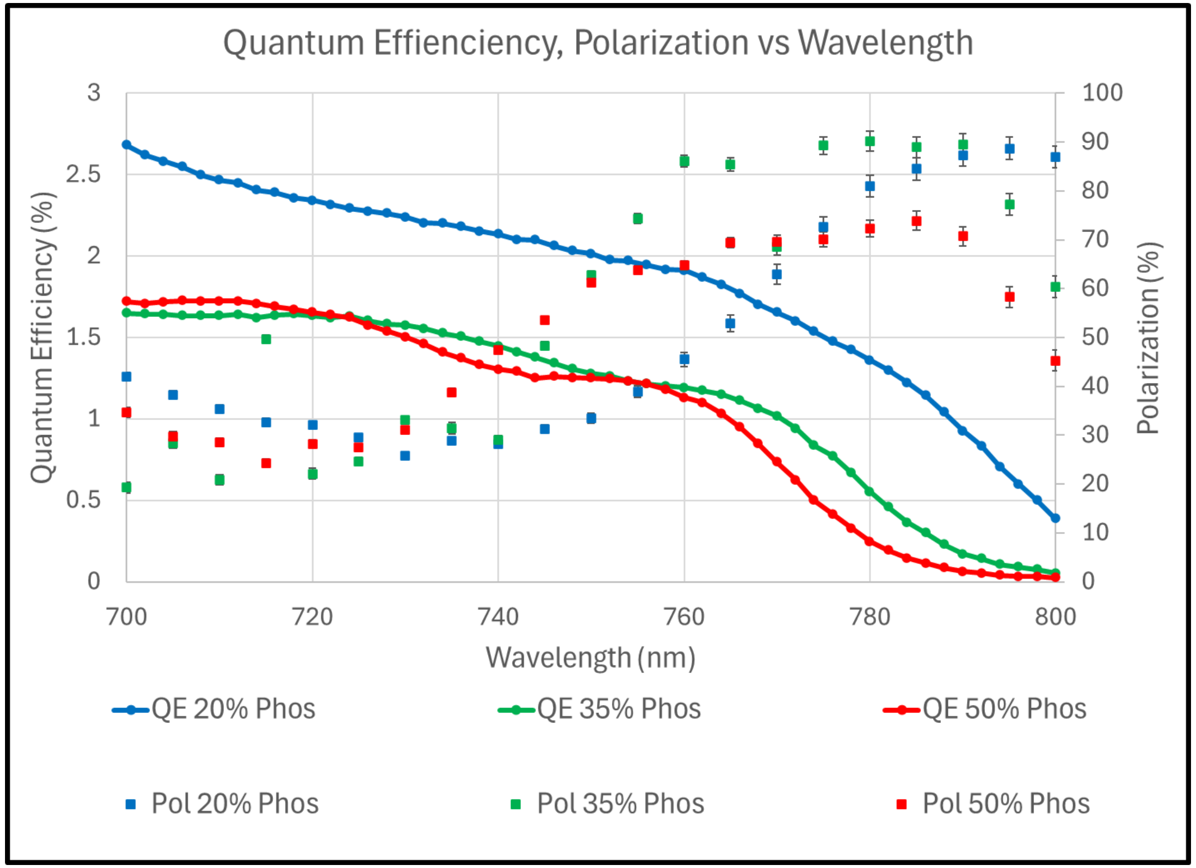


# Task 4: Superlattice (Layer Composition)

- Experimental Setup
  - All devices were grown on a 35% phosphorus virtual substrate
- Results
  - Devices with lower phosphorus composition had their polarization peak at higher wavelengths.

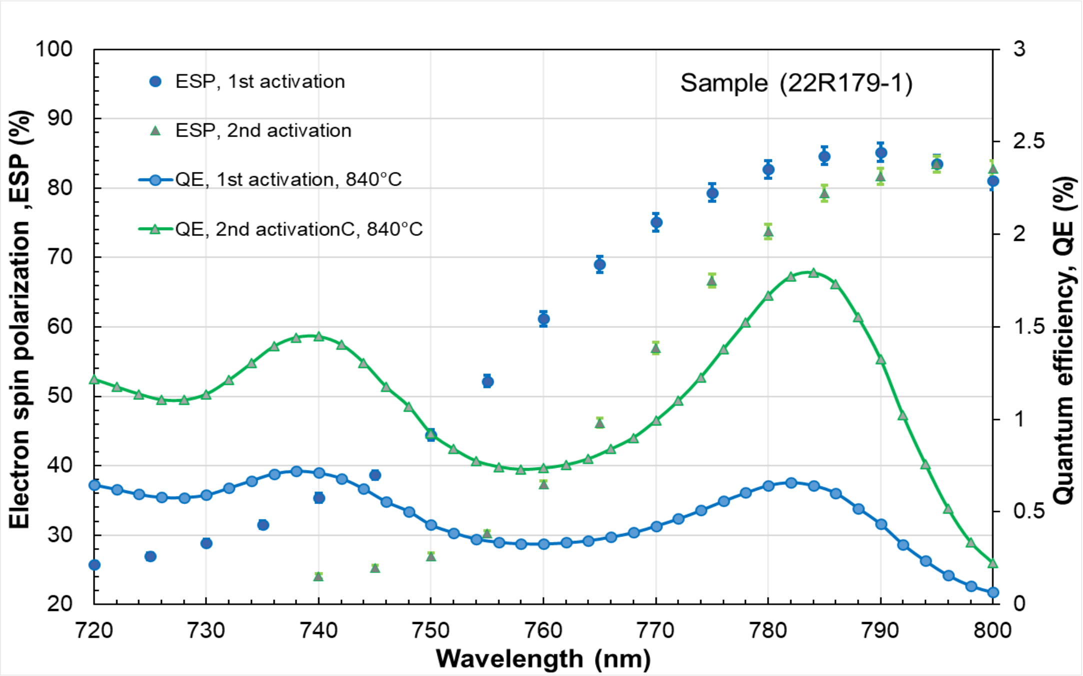
| Pho( %) | QE( %) | Pol(%) |
|---|---|---|
| 20 | 1.4 | 81 |
| 35 | 0.6 | 90 |
| 50 | 0.3 | 72 |

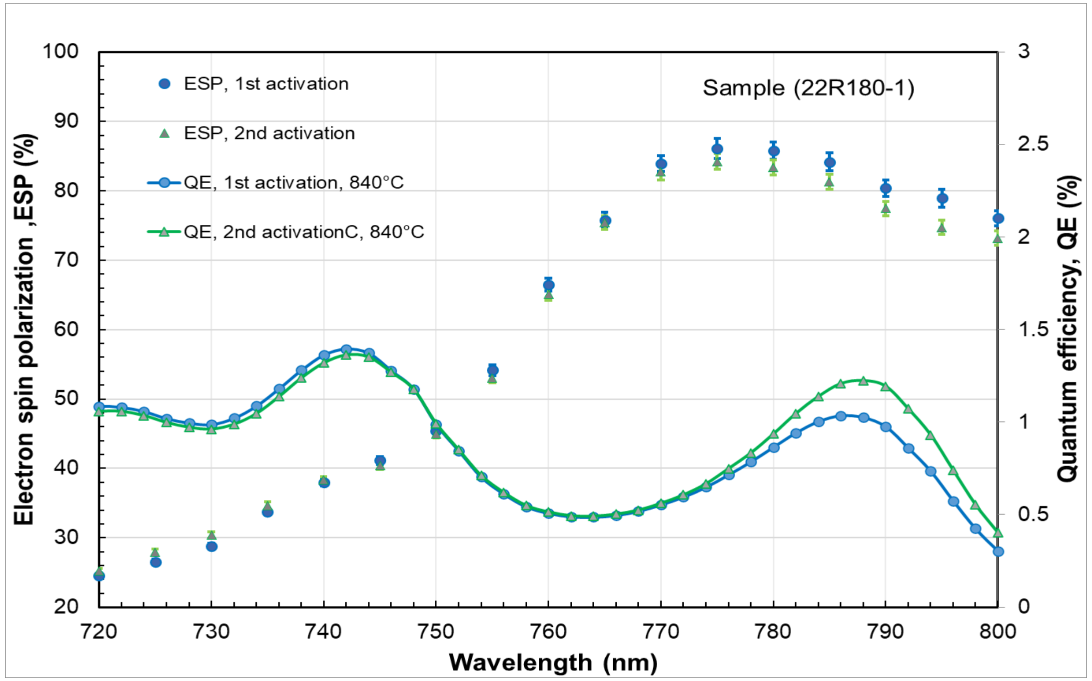
## Devices with no DBR



# Task 5: DBR (Thickness and Composition)

- Year 1: Implementation of a new material for DBR: $In_{0.30}Al_{0.70}P$ instead of $AlAs_{0.61}P_{0.39}$
- Issues with DBR: Thickness and Composition non uniform
- Modification of deposition process

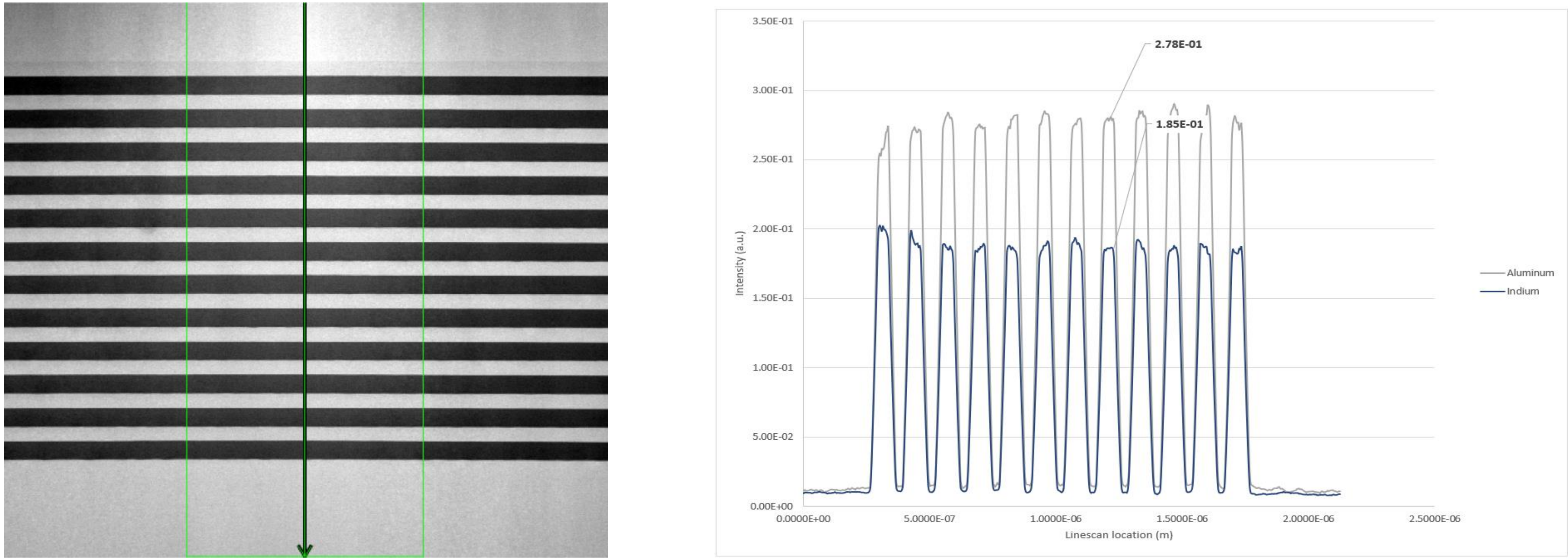




Measurements on two different wafers from two different runs with the same process: lead to different polarization and QE (position and intensity)

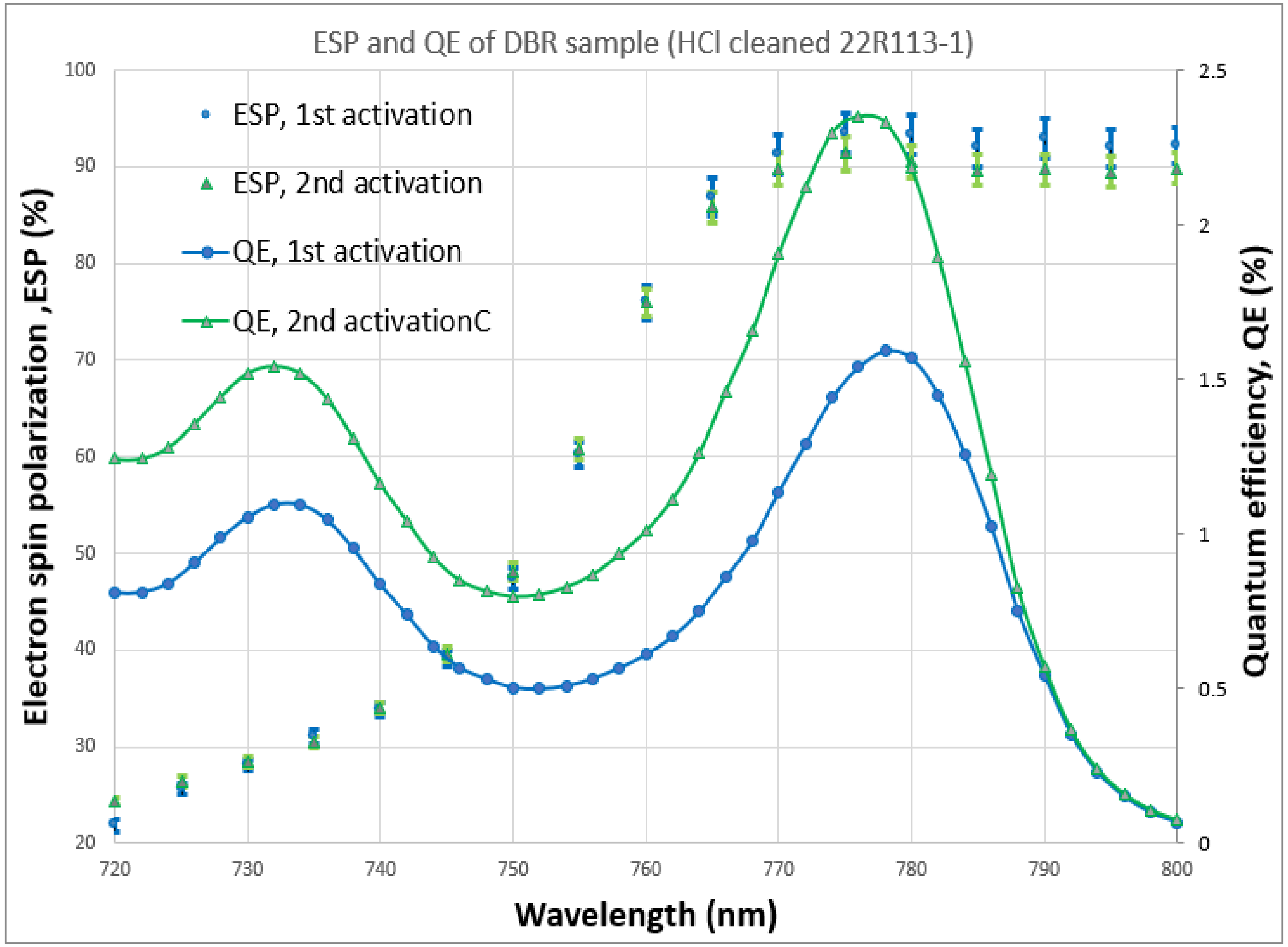
# Task 5: DBR (Thickness and Composition)

- Process modification allows for proper control of both thickness and composition



(Left) TEM image of the DBR used in our devices. (Right) Data collected from EDS analyzed used to determine the composition and thicknesses of the individual layers in the DBR

# Best Device with DBR



BNL microMott

Pol ~ 92%

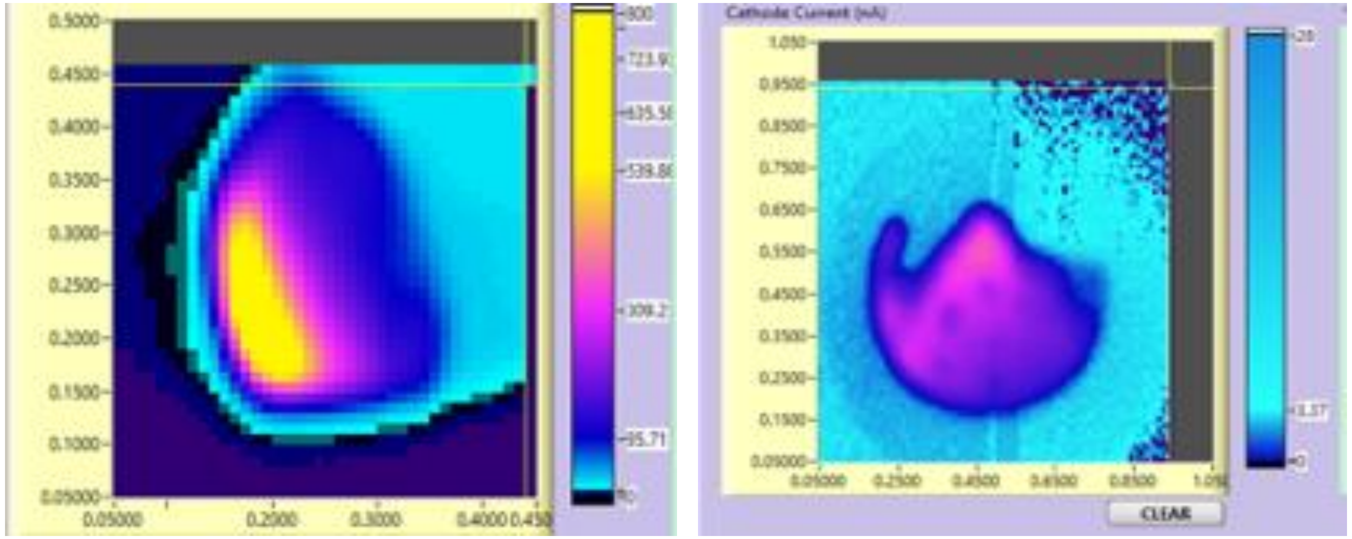
QE ~ 2.3%

$\lambda_{peak}$ ~ 785 nm

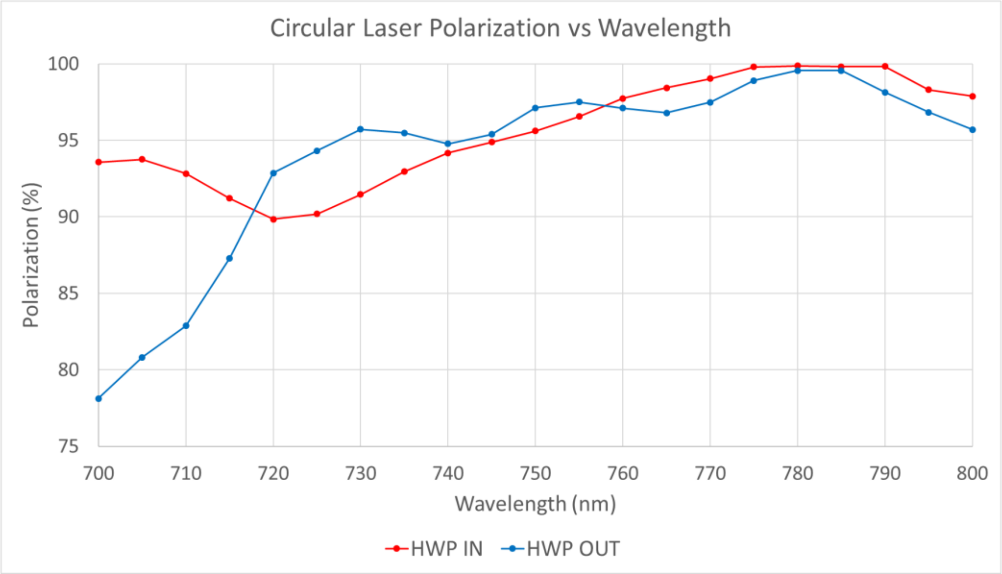
# JLab MicroMott Polarimeter

A series of upgrades were added to the microMott in 2024

- Increased surface uniformity from adjustable Cesium position
- Lower base pressure during runs from new bellows pump
- Laser calibration places circular polarization greater the 99.5 % at 780 nm

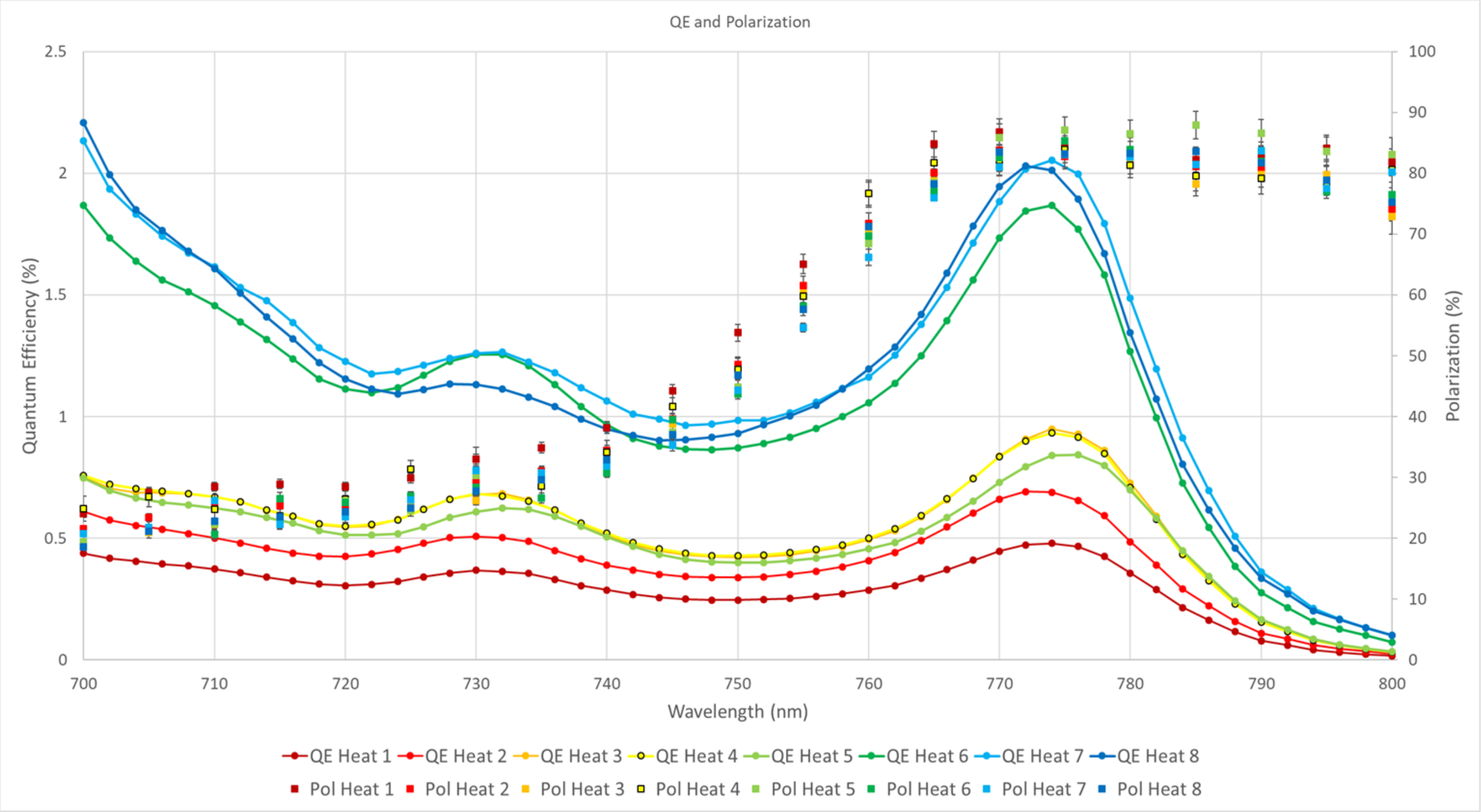


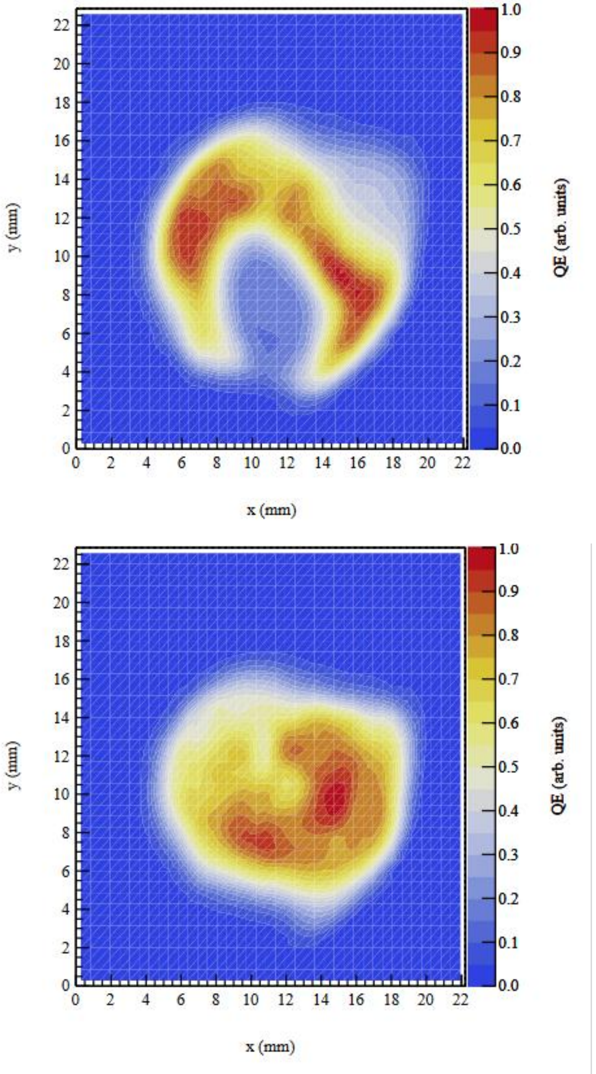
Enhanced activation uniformity



# Heat treat and activation study

- Surface contamination present due to lack of capping layer
- An optimized heat cleaning recipe was developed
- Heating at 550 C increase QE by 200 % with negligible polarization loss

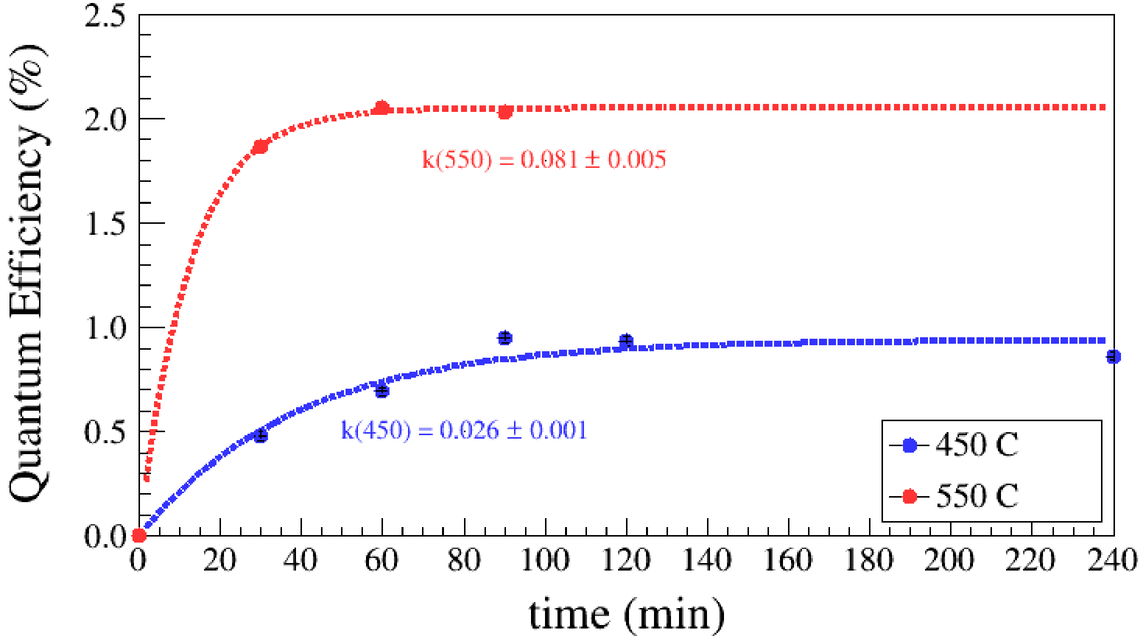


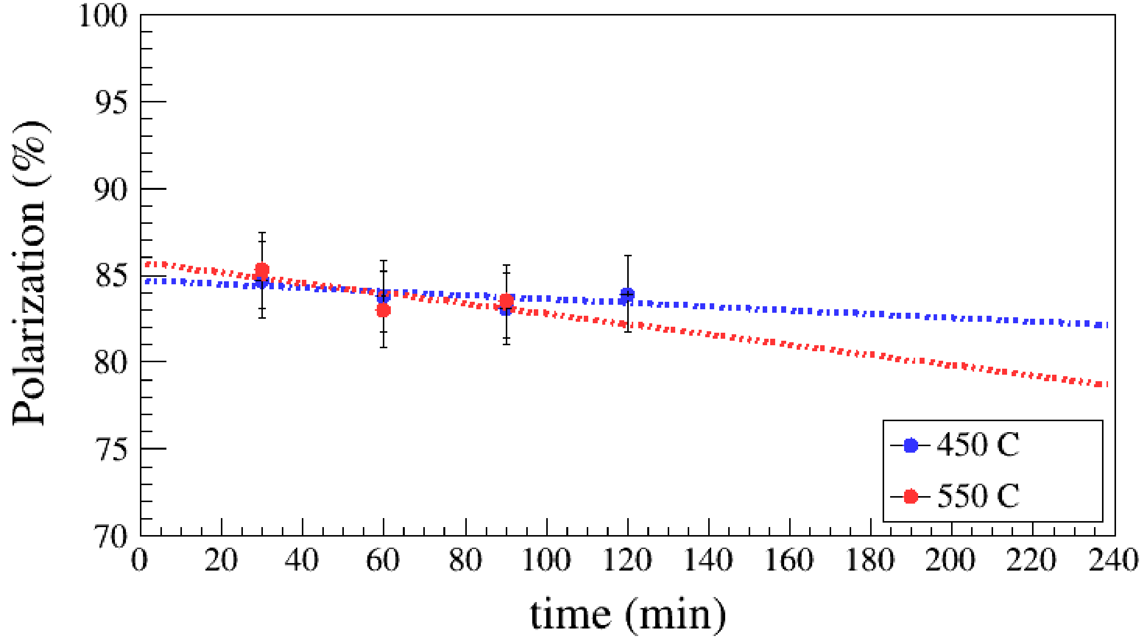


Increased uniformity at 550 C

# Heat treat and activation study (continued)

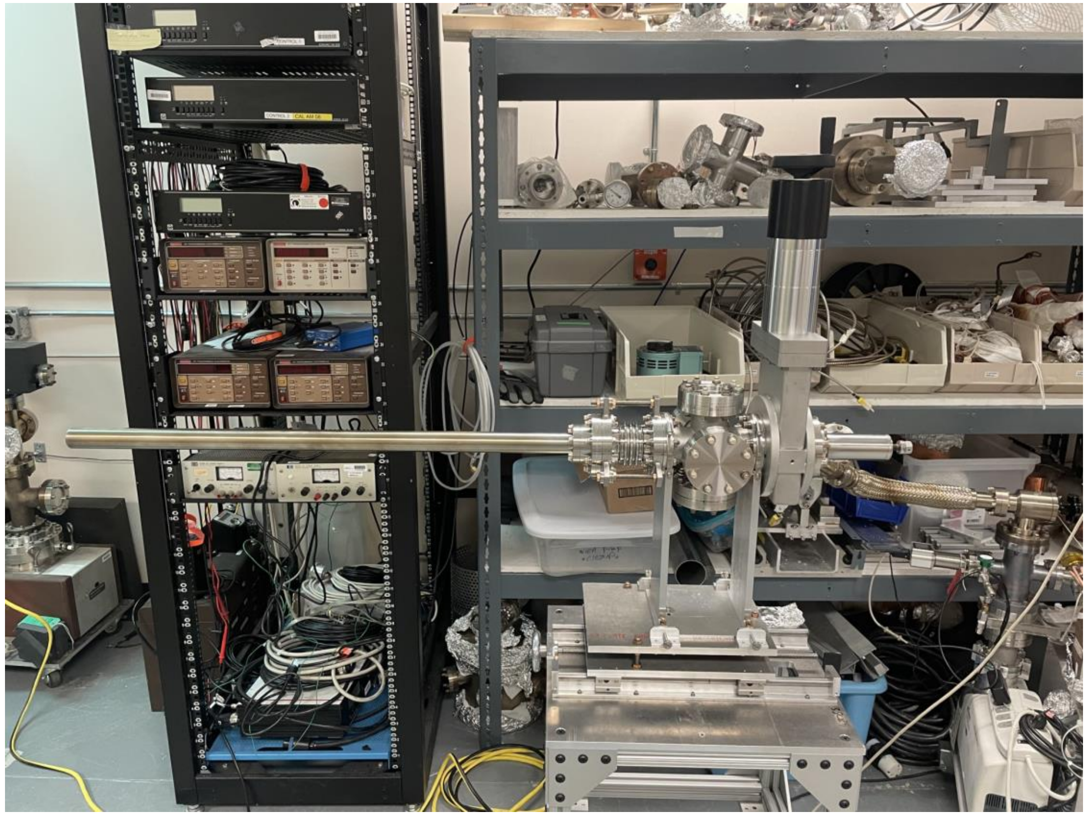
- Prolonged heat provide diminishing returns (can only get surface so clean)
- On short scales polarization is unchanged
- QE results are fit to an asymptotic functional form using rate constant and peak QE
- Resulting optimization includes an initial 1.5 hr heat at 450 C followed by a 1 hr heat a 550 C for best results





# UITF progress

- New pucks for mounting ODU 350 um samples
- New suitcase for easy insertion into UITF deposition chamber
- Ongoing laser work to bring variable wavelength light to UITF



# 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 Superlattice
    - Best Growth Temperature: 600C
    - Number of pairs: best at 30 pairs, then saturates
    - Composition: matching between MMG and SSL yields best results
- Enhanced testing facilities:
    - Higher uniformity and heat treatment enhanced
- Best Device
    - with DBR: Polarization: 92%; QE: 2.3%
    - Without DBR: Polarization: 90%; QE: 0.6%