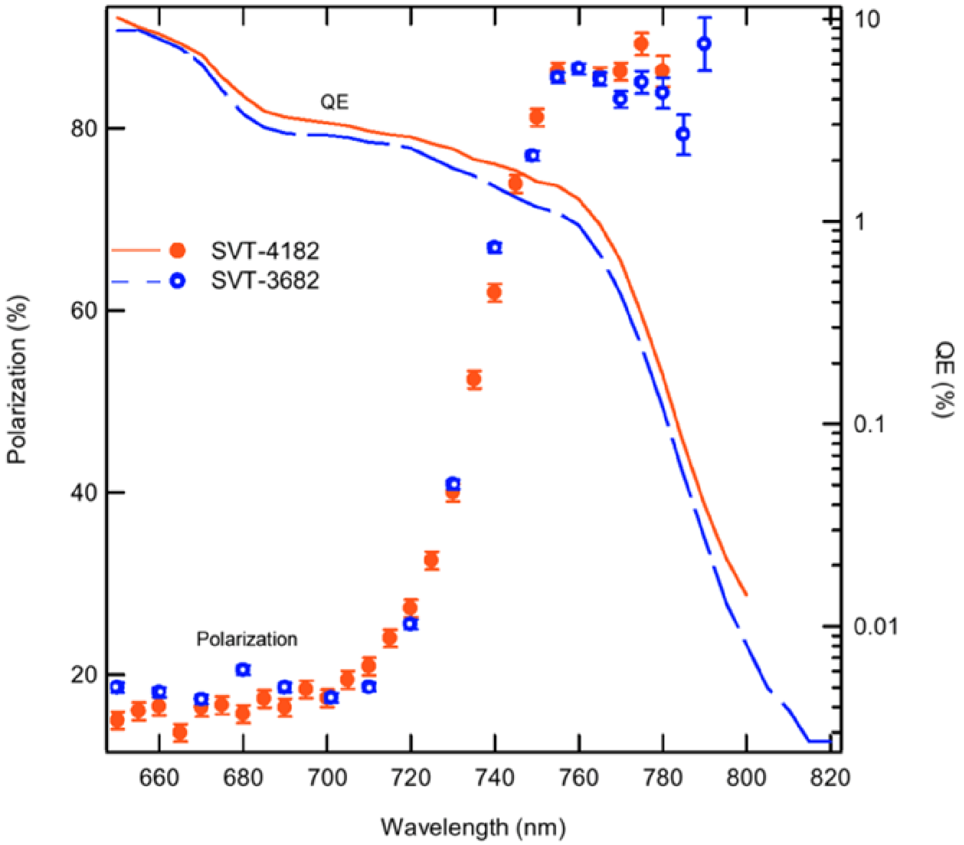
Photocathodes with 90% polarization and QE greater than 1% for DOE NP

Annual NP Accelerator R&D + Data Science AI/ML virtual PI Exchange meeting - November 30, 2021



Matt Poelker and M. Stutzman, Jefferson Lab
Sylvain Marsillac, ODU
Erdong Wang, BNL

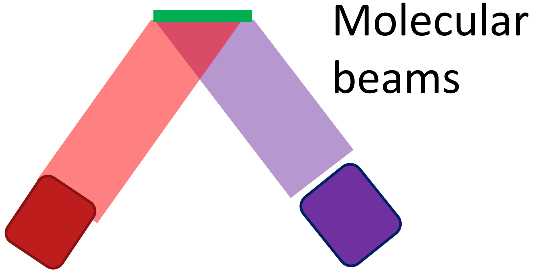
MBE, GSMBE, CBE and MOCVD

MBE

Gas Source Molecular Beam Epitaxy

elemental As, P, Ga

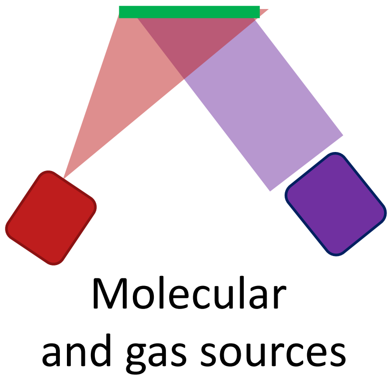
- Pressure ~10^{-8} mbar
- Growth rates ~ 1 µm/hr
- Very precise control



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

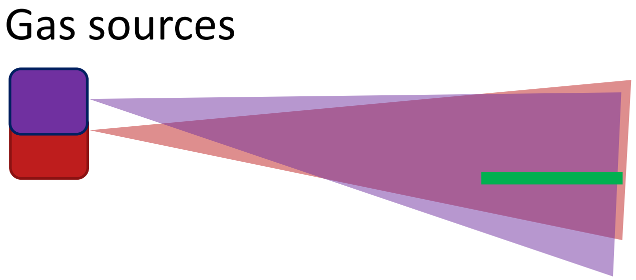
- Pressure <10^{-4} mbar
- Growth rates 0.5-1 µm/hr

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



Objective

- SPIRE/Bandwidth Semiconductor used MOCVD to grow single-strained-layer GaAs/GaAsP photocathodes (good)
- SVT used MBE to grow strained-superlattice GaAs/GaAsP photocathodes (better)
  - MBE, for purity and precision
    - Beryllium doping
    - Slow growth rate
- In this work JLab, ODU and BNL: focus on MOCVD
  - Strained Superlattice photocathodes
  - Strained Superlattice photocathodes with DBR
- We are about 3 months behind schedule

Project Goals

Tasks Year 1	**Q1**	**Q2**	**Q3**	**Q4**
Calibration of p-$GaAs_{0.65}P_{0.35}$ (ODU)	■			
Calibration of metamorphic grade from GaAs to $GaAs_{0.65}P_{0.35}$ (ODU)	■			
Calibration of GaAs/$GaAs_{0.65}P_{0.35}$ strained superlattice (ODU)		■		
Mott system: assemble and pump down (BNL)	■	■	■	
System commissioning and calibration (BNL & JLab)	■	■	■	
Fabrication runs strained-superlattice (ODU & JLab & BNL)			■	
Strained-superlattice Photocathodes **Evaluation (JLab)**				■

Tasks Year 2	**Q1**	**Q2**	**Q3**	**Q4**
Calibration of p-$AlAs_{0.6}P_{0.4}$ (ODU)	■			
Calibration of $GaAs_{0.65}P_{0.35}$ /$AlAs_{0.6}P_{0.4}$ DBR (ODU)		■		
Strained-superlattice Photocathodes Evaluation (BNL)	■	■	■	
Fabrication runs strained superlattice with DBR (ODU & JLab & BNL)			■	
Measure CsTe/CsI coated SL-GaAs (BNL)		■	■	■
Strained superlattice/DBR Photocathodes Evaluation (JLab & BNL)				■

Budget

FY20 loaded budget = 180k$

- Support for ODU
- Graduate student, summer term
- Procurements: sample evaluation, Mott apparatus upkeep
- 1.7 weeks for Matt, 2.5 weeks for Marcy

	FY20 ($k)	FY21 ($k)	Totals ($k)
a) Funds allocated	180,000	180,000	360,000
b) Actual costs to date	100,703	0	100,703

Device Structure

a. Metamorphic grading from GaAs to $GaAsP_{0.35}$ to create relaxed layer
b. Superlattice has strain to increase polarization
c. Highly p-doped surface to inhibit surface charge limit

GaAs	5 nm	p=5 × 10^{19} cm^{-3}	(c)
GaAs/GaAsP SL	(3.8/2.8 nm) ×14	p=5 × 10^{17} cm^{-3}	(b)
$GaAsP_{0.35}$	2750 nm	p=5 × 10^{18} cm^{-3}	
Graded $GaAsP_x$ (x = 0~0.35)	5000 nm	p=5 × 10^{18} cm^{-3}	(a)
GaAs buffer	200 nm	p=2 × 10^{18} cm^{-3}	
p-GaAs substrate (p>10^{18} cm^{-3})			

MOCVD growth parameters

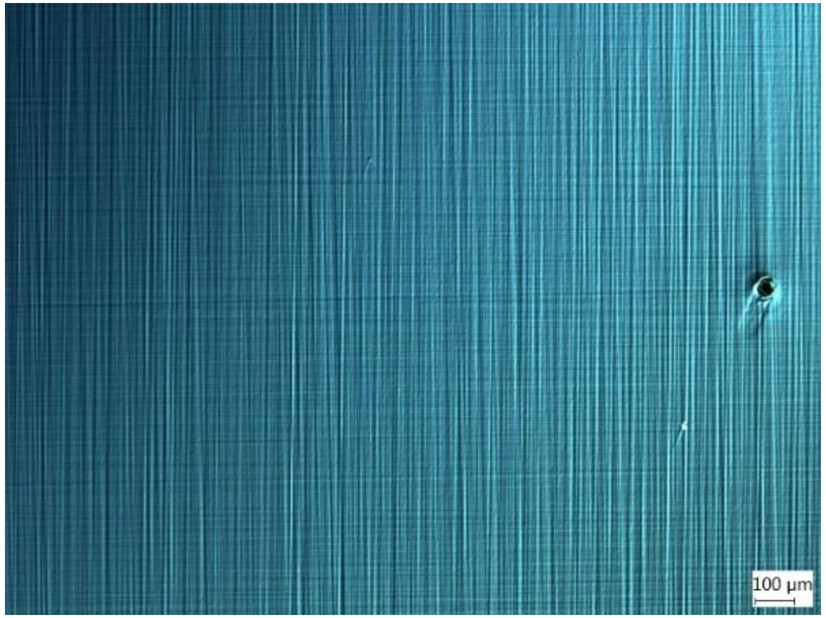
- Key Precursors
  - Trimethyl Gallium ($Ga(CH_3)_3$)
  - Arsine (AsH_3) and Phosphine (PH_3)
  - Diethyl Zinc ($Zn(CH_3CH_3)_2$)
  - Carbon Tetrachloride (CCl_4)
  - Lower diffusivity of carbon in GaAsP should improve lifetime of device surface
- Substrate: 2” GaAs wafers with either 0 or 2^o offcut in the 110 direction. Offcut improves growth quality
- Growth rate range: 3-8 μm/hr
- Temperature: 650-750^{o}C

MOCVD system at Rochester Institute of Technology

Characterization: Nomarski Microscopy

- Microscopic technique with very high resolution in highly contrasting samples
- Shows surface quality indicated by faceting, pitting, and other irregularities

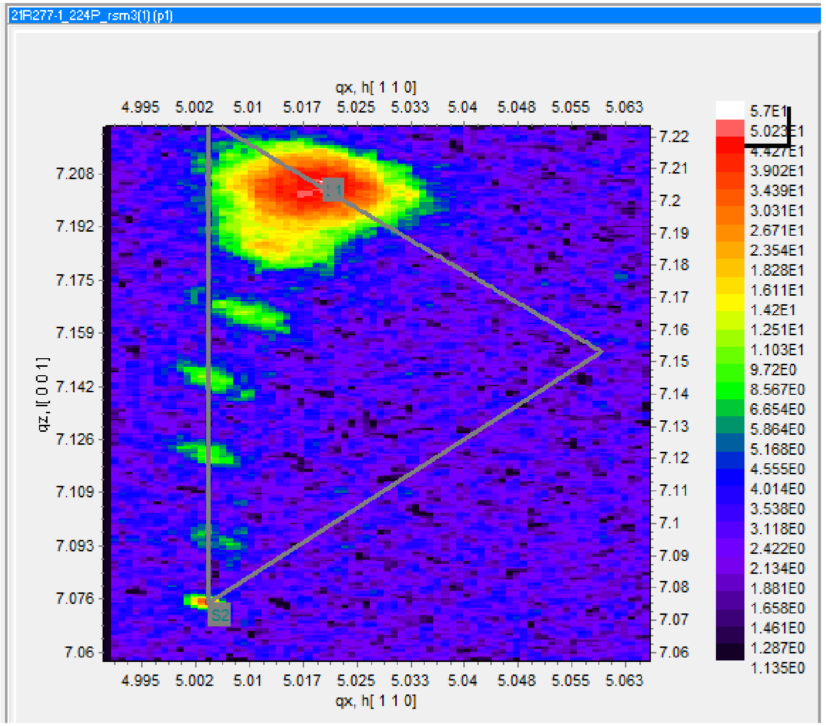
10 µm/hr 650^{o}C Growth Temp with no Superlattice
With a 2^{o} (110) offcut on GaAs



10 µm/hr 650^{o}C Growth Temp with no Superlattice
With no offcut

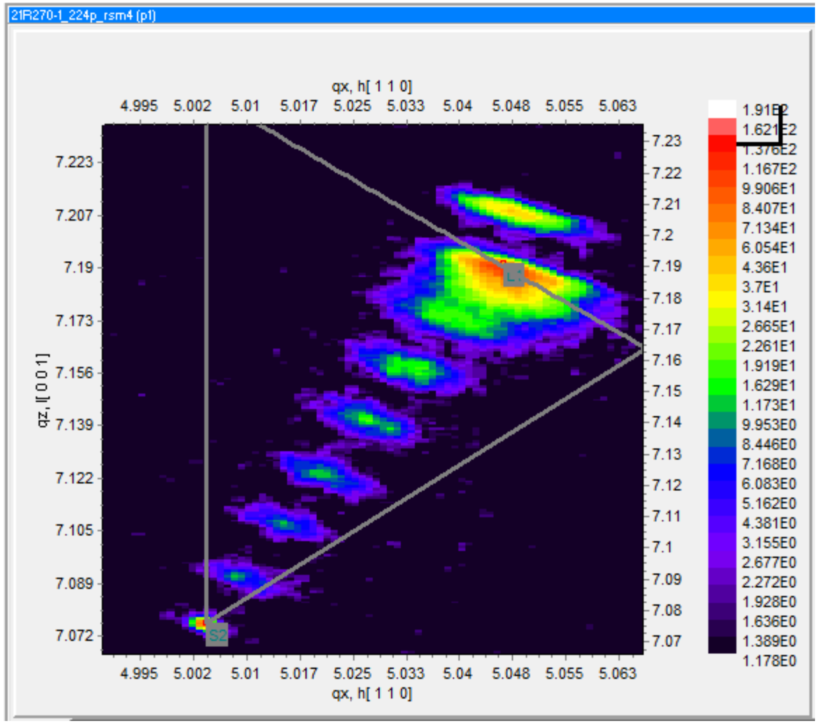
Characterization: Reciprocal Space Mapping (RSM)

- Specialized high resolution XRD technique to show relaxation of deposited films
- Key to determining quality of the deposited metamorphic grading



3µm/hr 730°C Growth Temp

Close to vertical line: more strain



10µm/hr 730°C Growth Temp

Close to diagonal line: less strain

Results

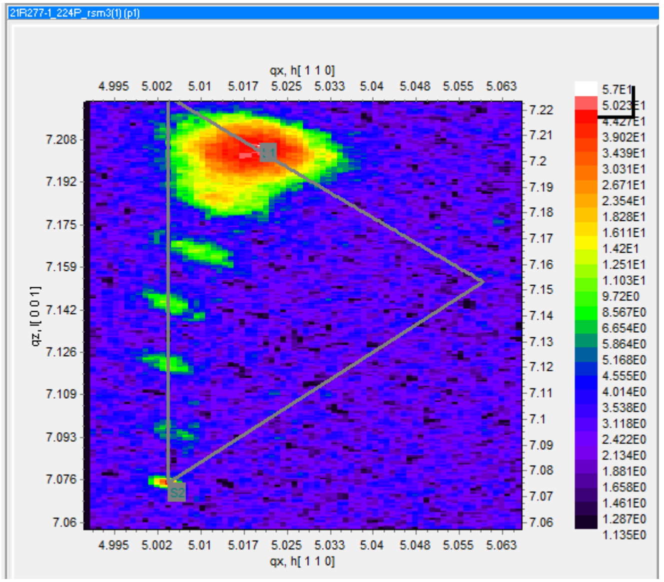
- Numerous sample growth studies performed at Rochester Institute of Technology, with different temperatures and growth rates
- Three types of growth studies
  - Metamorphic Grading
  - Superlattice
  - Full Devices

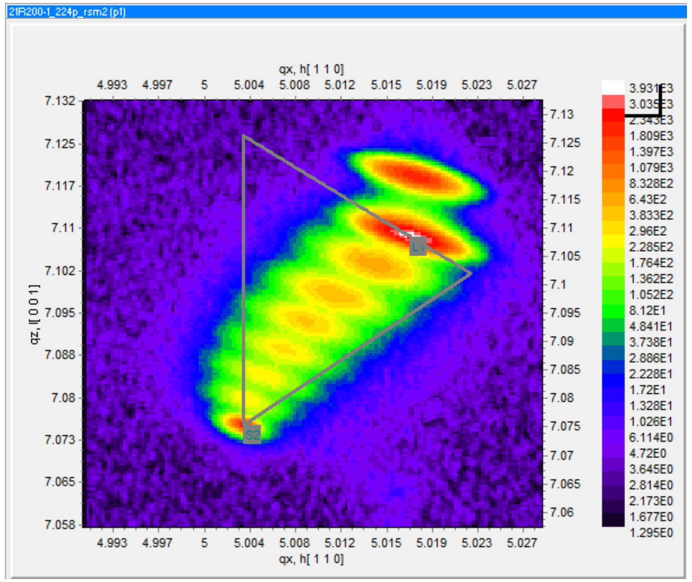
Results: Metamorphic Grading

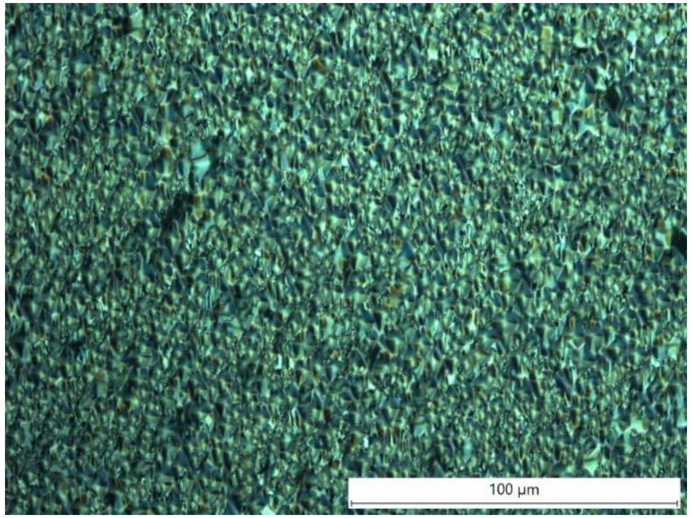
- High-quality strain relaxation of underlying layers is key to getting intended GaAs strain in the emitting region
- Necessary because of growing on lattice mismatched substrate.
- RSM used to characterize extent of relaxation in metamorphic layers
- Key parameters changed:
  - Growth Rate
  - Growth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

Results: Metamorphic Grading

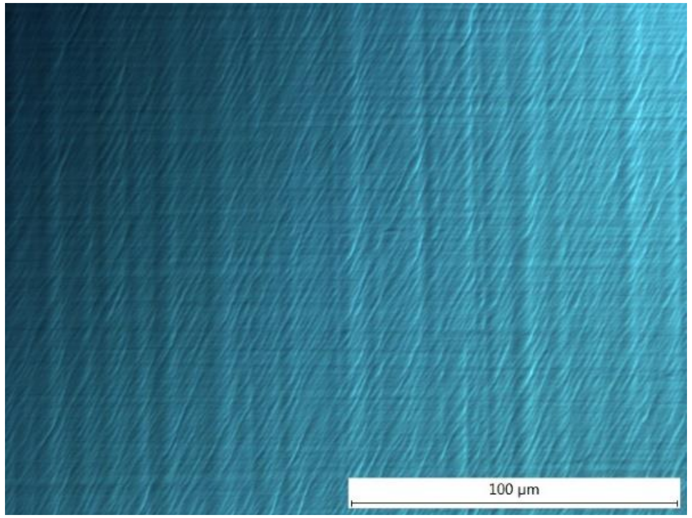
- Slower Growth Rate resulted in highest strained films (left)
- High Temperature with smaller composition change between steps is more promising (right)







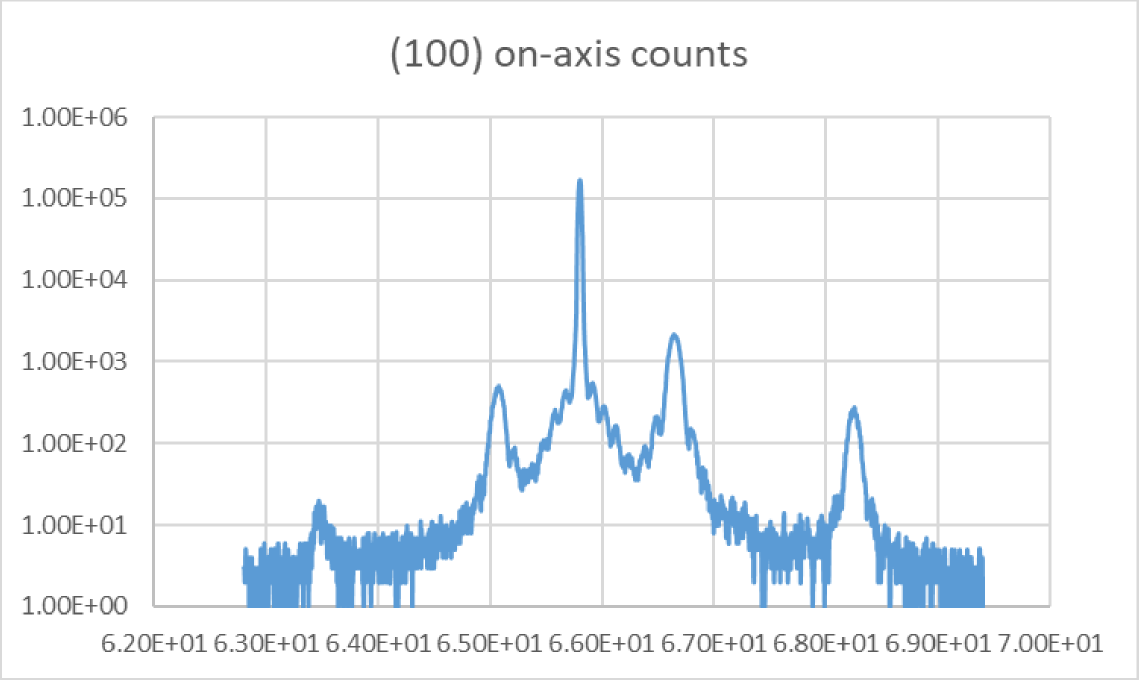
3µm/hr 730°C Growth Temp



10µm/hr 650°C lower phosphorous grade

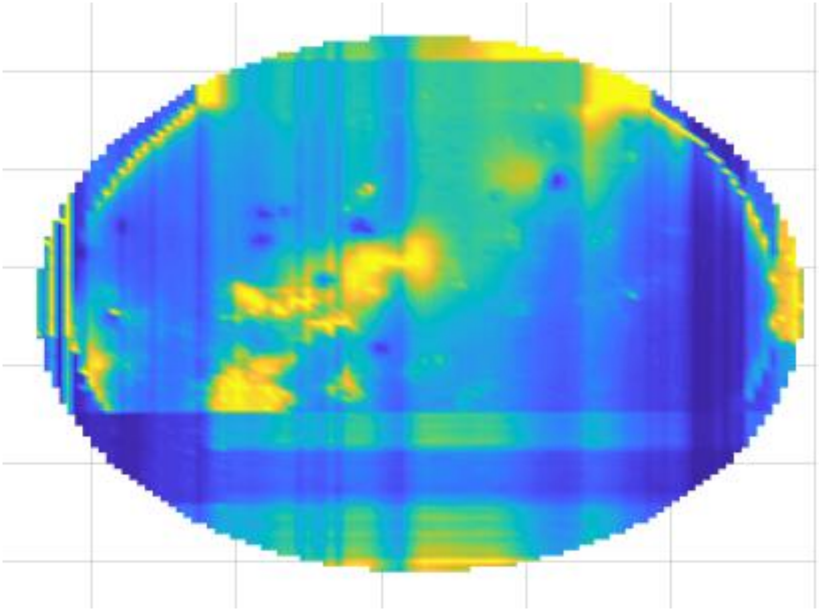
Results: Superlattice

- Alternating GaAs/GaAsP maintains the strain in the GaAs regions
- Initially grown on GaAs wafers to ensure sufficient doping and layer thicknesses
- Later grown on metamorphic grading so the GaAs is the strained layer
- Interference fringes in XRD show high quality superlattice structure



Results: Device

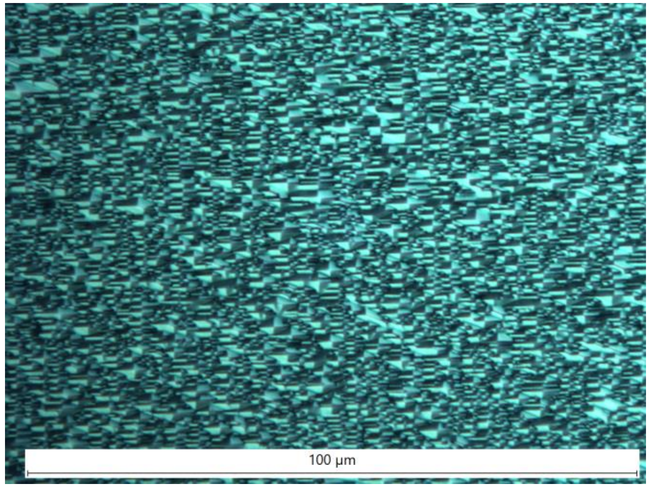
- Superlattice grown on metamorphic layer
- Not fully relaxed metamorphic layer causes uniformity issues as seen in photoluminescence (PL) mapping



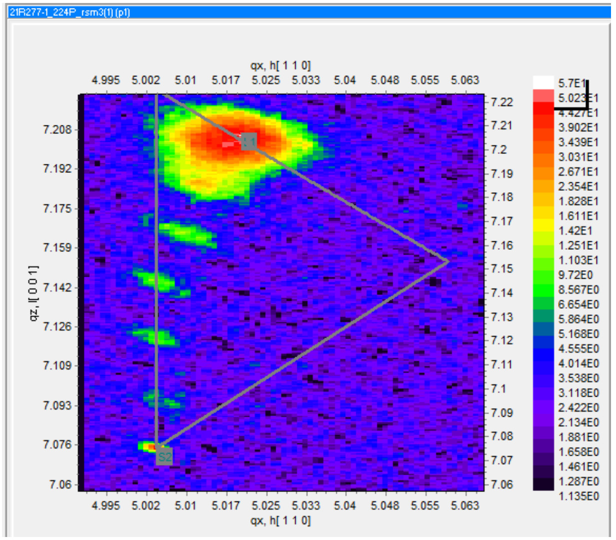
Results: Device Continued

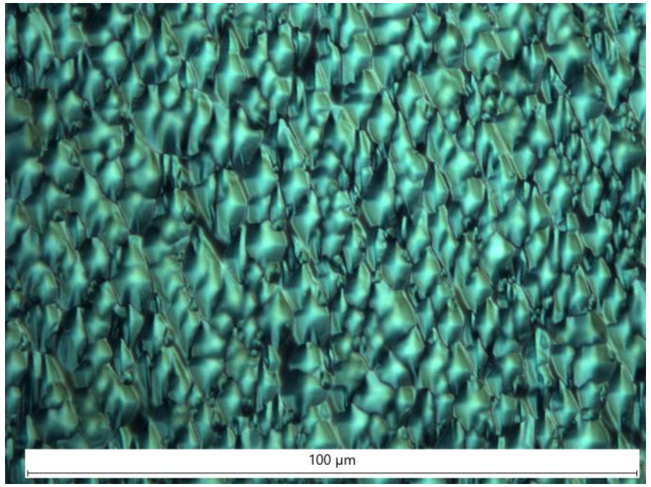
- Surface quality initially poor but subsequent runs improved surface quality
- Refining runs to improve relaxation

Surface completely matted,
RSM not performed

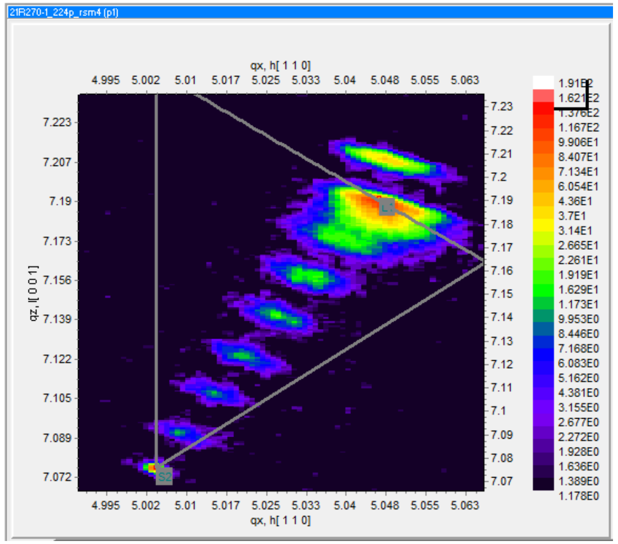


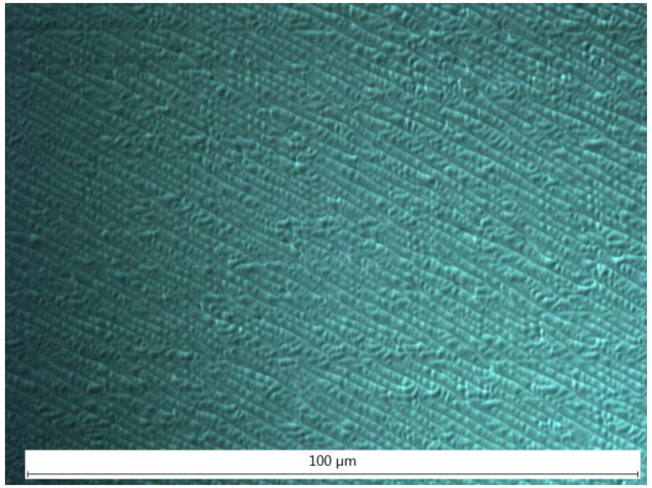
10µm/hr 650°C Growth Temp





3µm/hr 730°C Growth Temp





10µm/hr 730°C Growth Temp
PL Map taken on this sample

Conclusion

- Multiple devices and superlattice structures have been grown
- Successful doping and compositional calibration of all layers
- Key Remaining Challenge: Relaxation of the metamorphic layer
- Solution: Change offcut of the wafer to facilitate more relaxation, modify substrate temperature and growth rate
- Characterization
  - Surface analysis (SIMS, TEM) planned, working with JLab Procurement Department and NCSU to make this happen
- Ready for first polarization measurements
  - Marcy verifying microMott functionality
  - Student Ben Belfore to work at JLab, using the microMott polarimeter, some training required

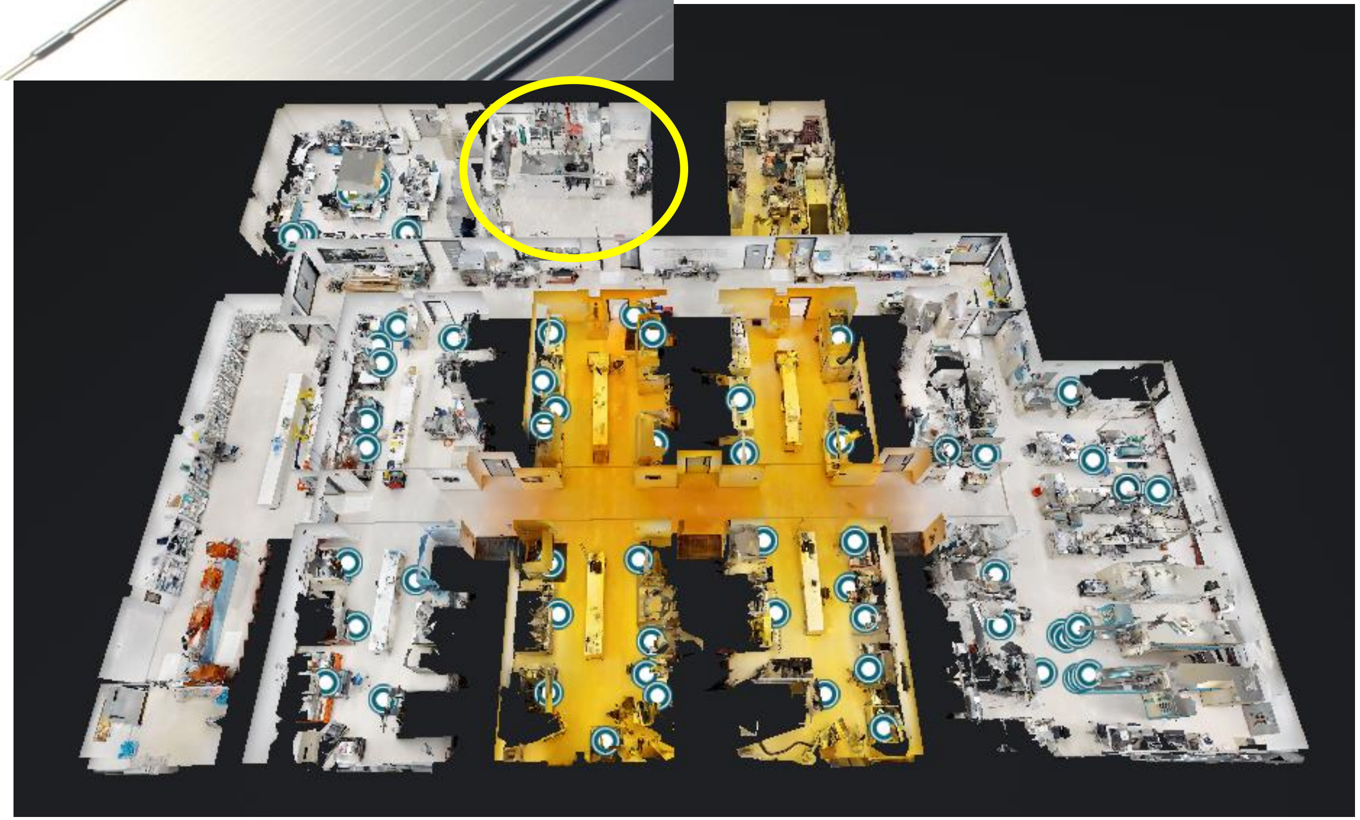
backup

MOCVD: Photocathode progress

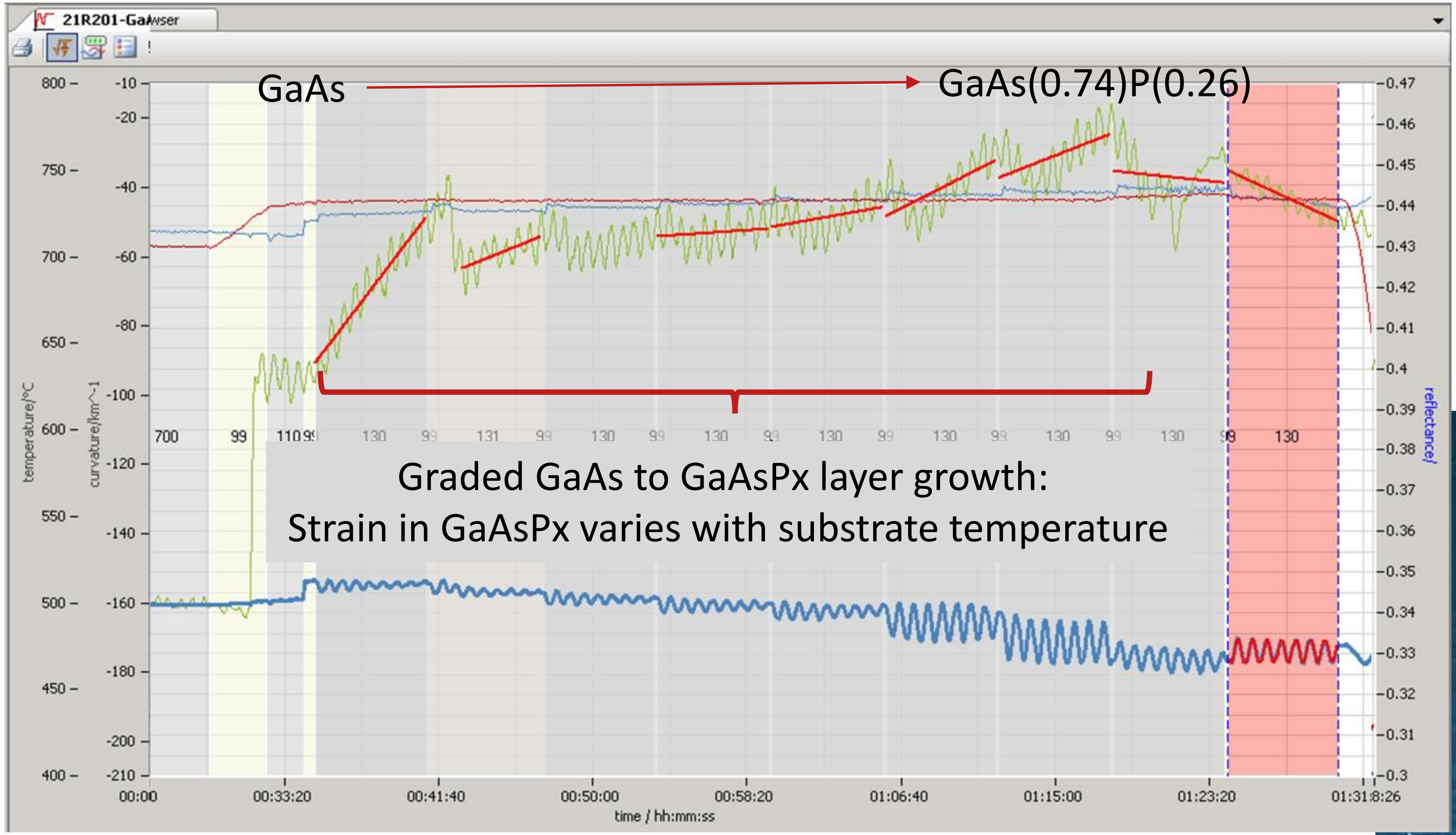
The Rochester Institute
of Technology
III-V EPICenter

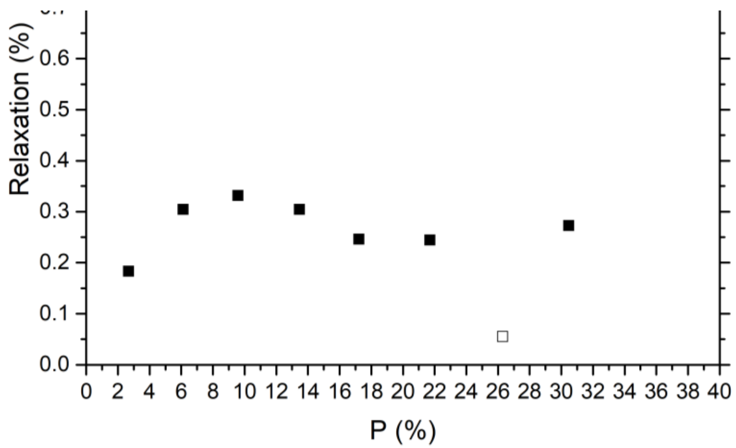
Dr. Sylvain Marsillac,
Old Dominion University

Ben Belfore
ODU Graduate
Student



Results: MOCVD

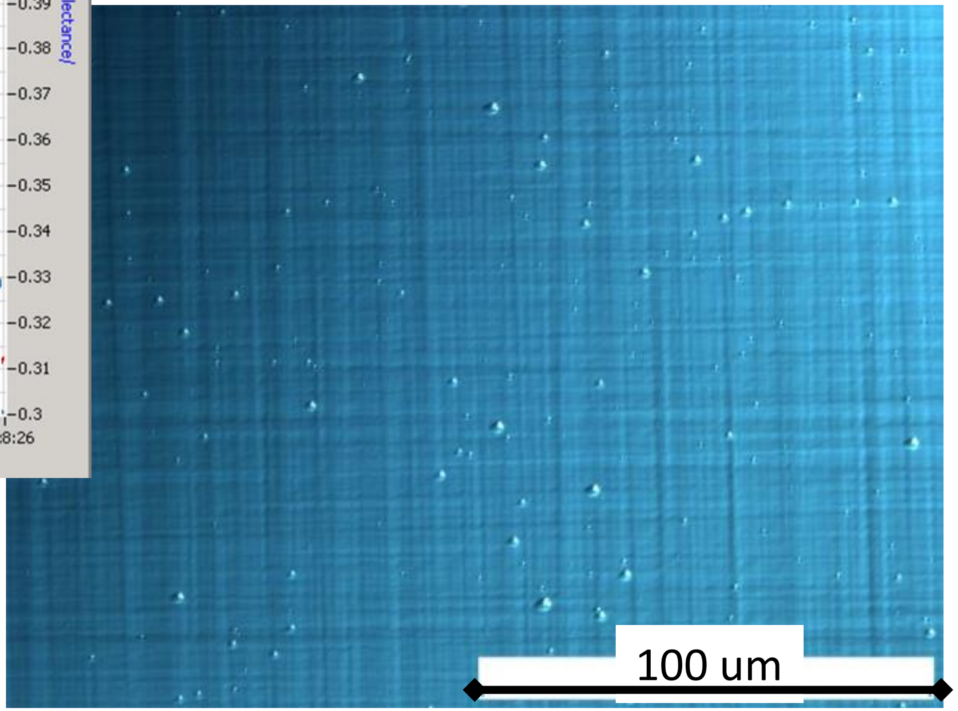




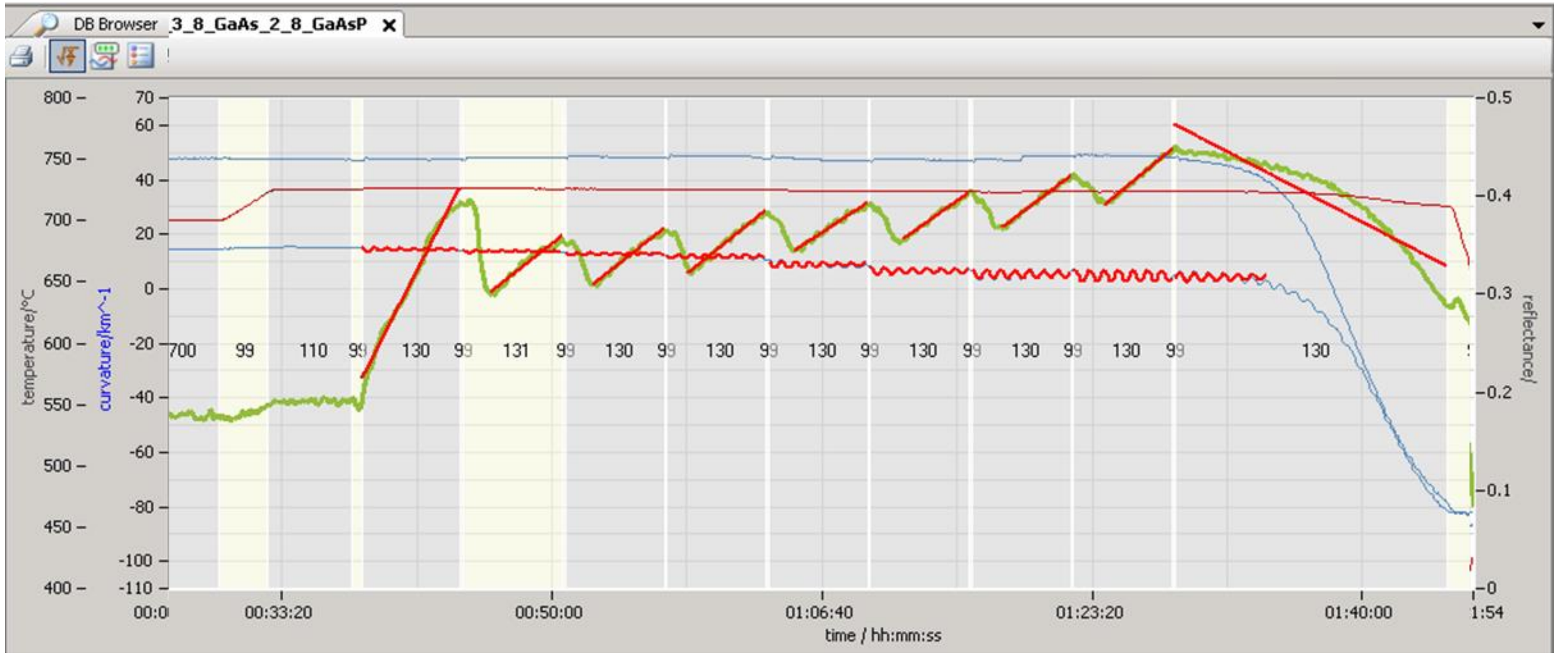
Higher temperatures yielded improved surface with moderate relaxation throughout

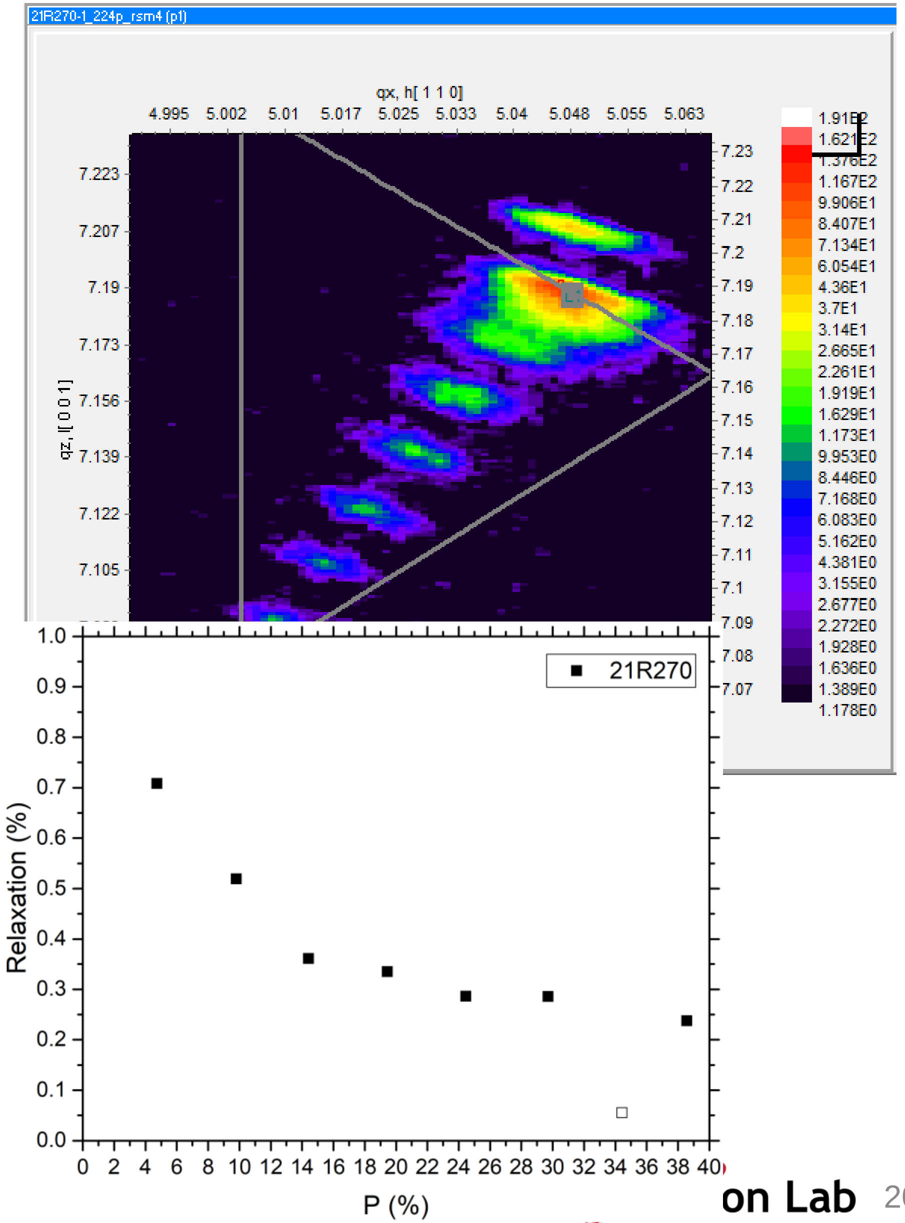
730°C growth temperature

Optimizing temperatures, graded layer profile



MOCVD monitoring: graded layer optimization





(100) 2° <110>

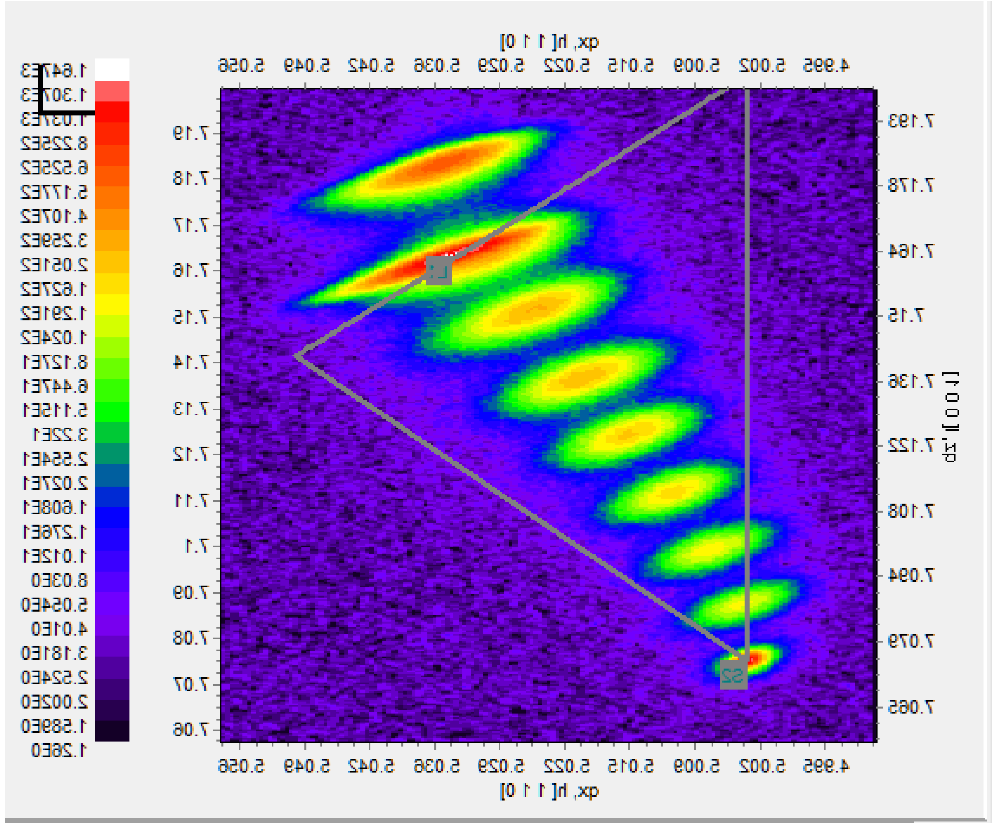
Average ΔP = 4.95%

Higher temperature and higher ΔP steps begins well, levels out to 30% relaxation, and surface degrades during thick 35% buffer

~10 µm/hr graded layer growth rate
V/III: 20-25
730°C growth temperature

Results: MOCVD photocathode progress

- Graded layer “metamorphic” test runs
  - Optimizing parameters for highest relaxation
  - Hall effect measurements for dopant characterization
- Superlattice runs
  - Growing superlattice on each metamorphic run
  - Optimizing parameters with zinc dopant
- Characterization
  - Surface analysis (SIMS, TEM) planned
  - **Ready for first polarization measurements**
  - JLab: MicroMott Polarimeter
  - BNL: Specs Mott Polarimeter
    - Operational, testing various samples



X-ray reciprocal space mapping

Crystal growth by Ben Belfore under the supervision of Sylvian Marsillac, Old Dominion University
MOCVD system at Rochester Institute of Technology

Photocathodes with 90% polarization and QE > 1% for DOE NP

Matt Poelker , JLab

Erdong Wang and Wei Liu, BNL

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

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Project description and tasks (BNL part)

- Commission a new low voltage Mott polarimeter.
- Evaluate samples provided by Prof. Marsillac, comparing results with those obtained by TJNAF

- Tasks year 1: (All completed)
  - Mott system: assemble and pump down
  - System commissioning and calibration
  - Strained-superlattice photocathode evaluation

BNL Budget summary

Item/Task	Baseline Total Cost	Costed & Committed	Estimate To Complete	Estimated Total Cost
	(AY$)	(AY$)	(AY$)	(AY$)
Photocathodes with 90% polarization and QE > 1% for DOE NP	100,000	50,975	49,025	100,000
Total	100,000	50,975	49,025	100,000

	FY2021
a) Funds allocated	100,000
b) Actual costs to date	40,464
c) Uncosted commitments	10,511
d) Uncommitted funds (d=a-b-c)	49,025

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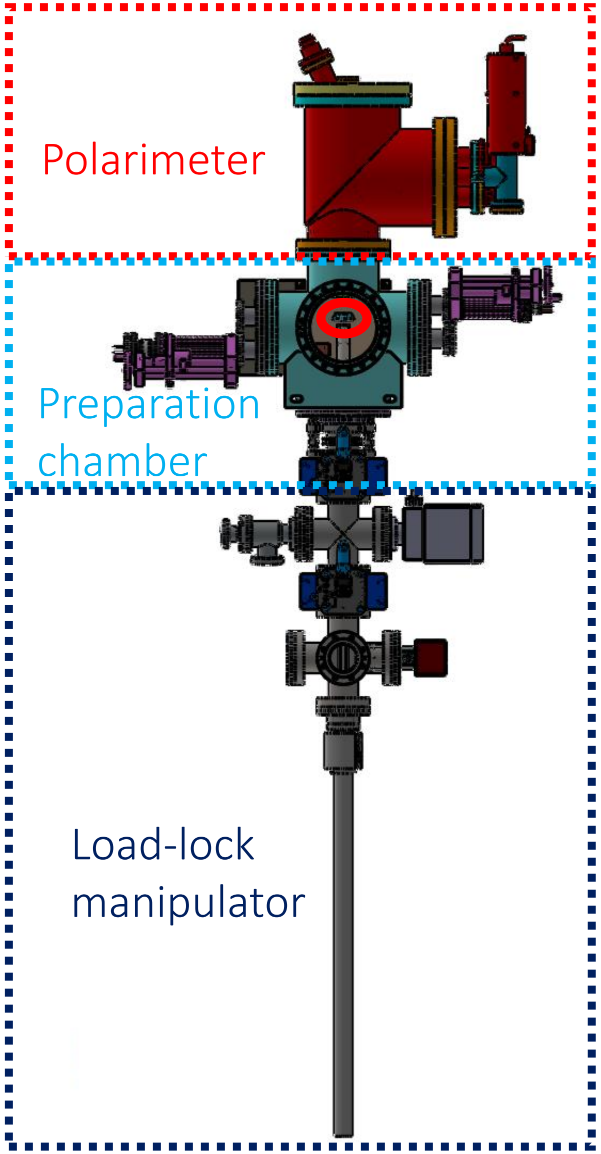
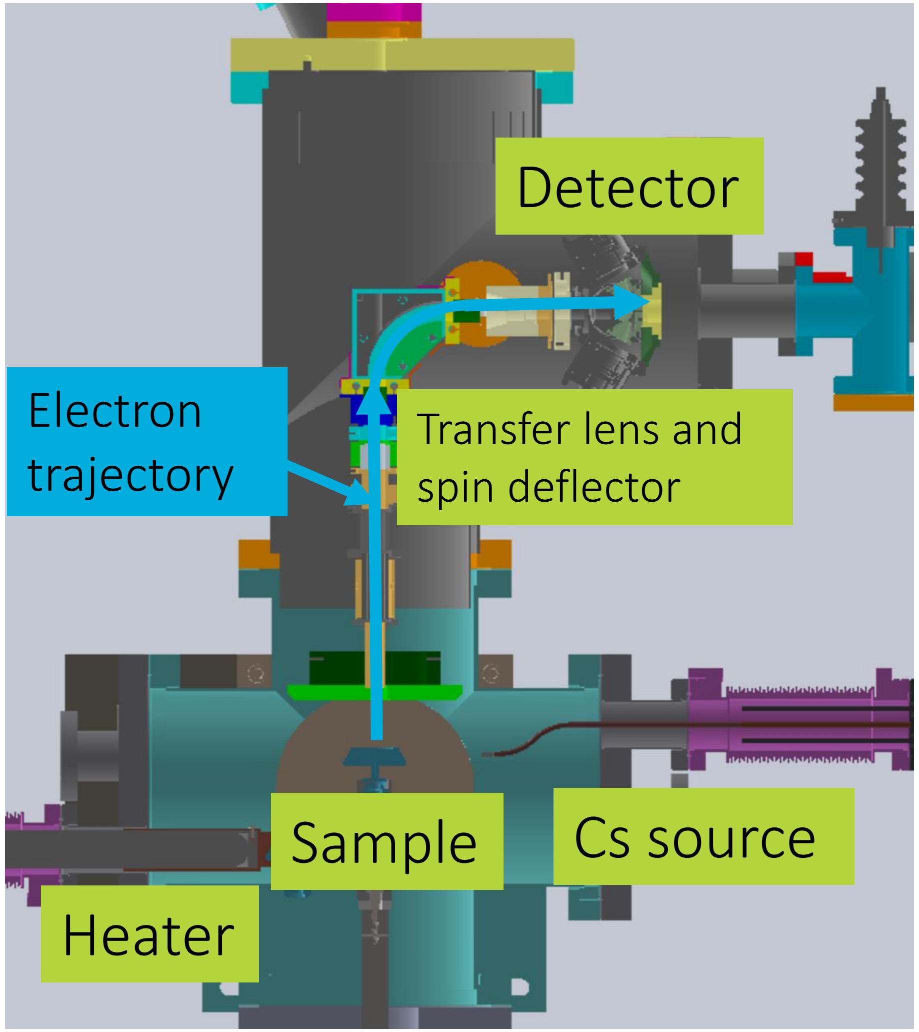
Drawing of Mott polarimeter system





The system has 3 parts:

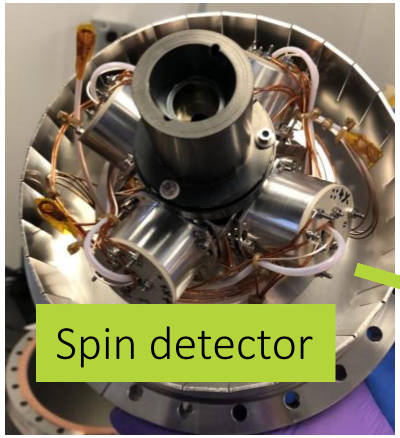
- Load-lock manipulator (BNL)
- Preparation chamber (BNL)
- Polarimeter (*Specs*)

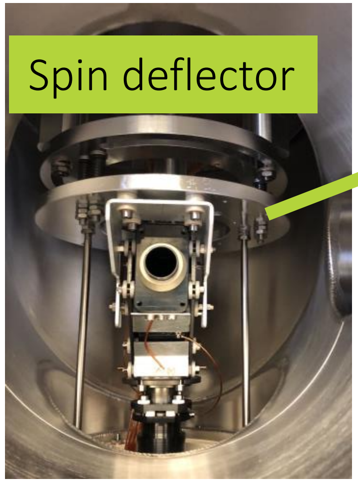
Feature of the system:

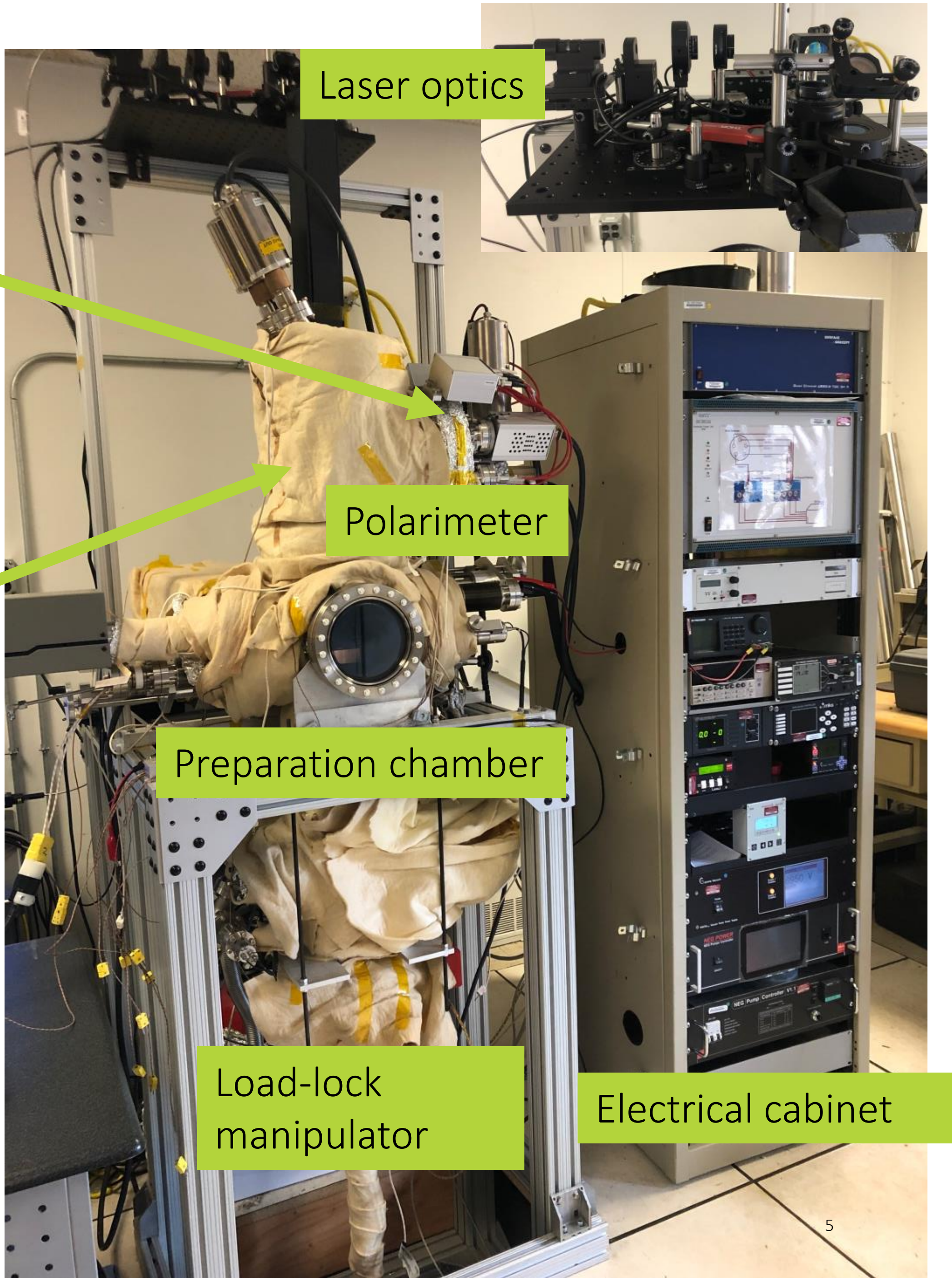
- The load-lock system is matched to the polarized gun load-lock.
- Use the same cathode puck as the gun puck.
- The Mott system is light source II beamline compatible.

Specs Mott polarimeter system Overview

- Laser: 450 -850 nm, 1-5 mW/nm
- Voltage: up to 25 kV
- Vacuum: low 10^{-11} torr
- Photocurrent: <1 mA







Operating of the system

- Load a fresh photocathode sample into the system. Then, bake the system up to 200 ℃ to obtain vacuum pressure of low 10^{-11} torr
- Heat clean the photocathode sample at 550 ℃
- Activate the photocathode with Cs,(Te) and O_2
- Measure QE and ESP

Process	Laser power	Laser wavelength	Voltage on cathode	Voltage on detector	Voltage on lens	Vacuum pressure
Activation	20-40 uW	532 nm	-200 V	0 V	0	<1e-9 torr
Measure QE	10-100 uW	500 -800 nm	-200 V	0 V	0	~1e-11 torr
Measure ESP	0.1-10 uW	700-800 nm	-200 V	25 kV	0-2000 V	~1e-11 torr

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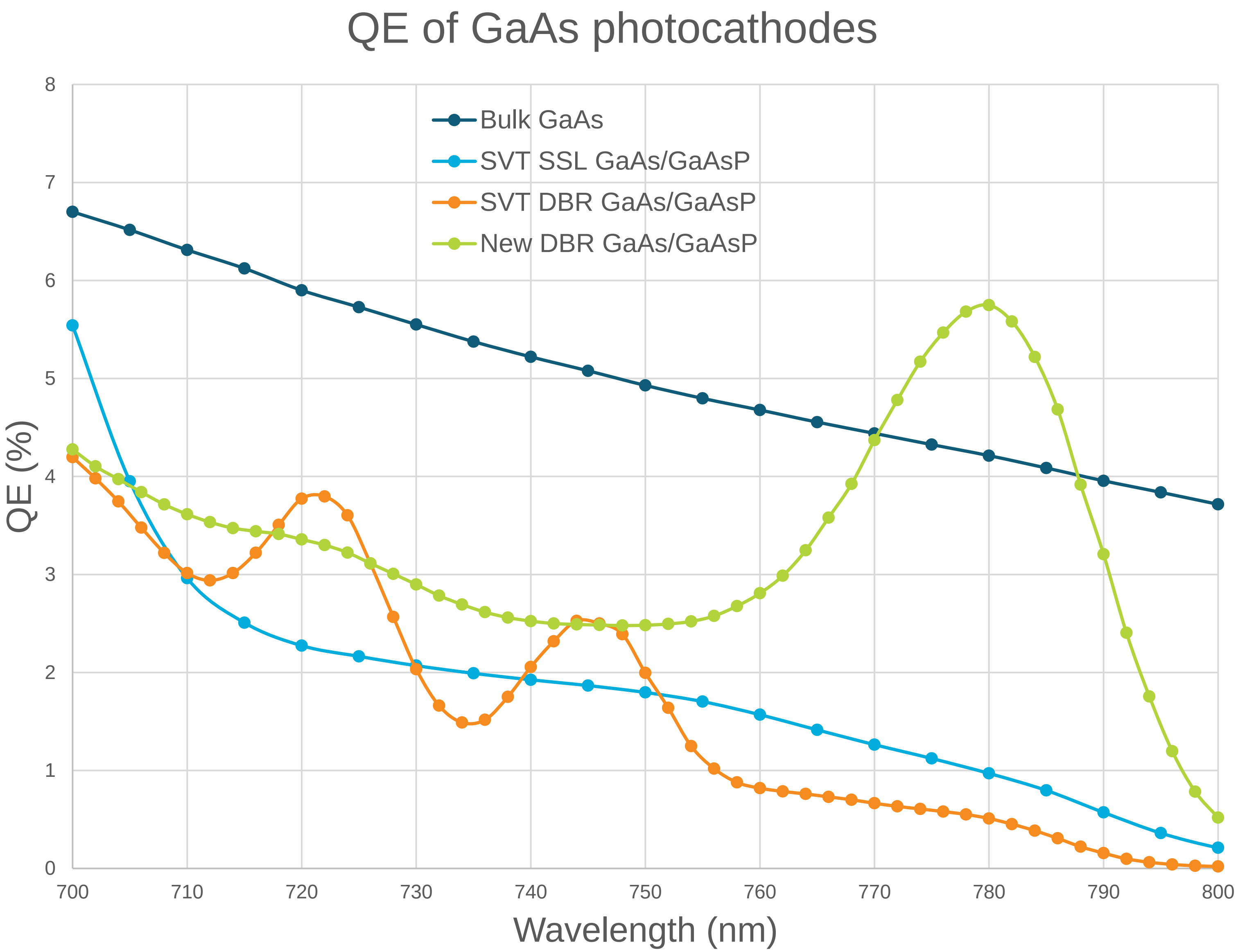
Measured QE

- All photocathode samples are heated clean and activated at same condition.
- The bulk GaAs was firstly tested to confirm the system can get reasonable QE compared with our other activation chamber.
- Tested samples:
  - ➢ Bulk GaAs(AXT)
  - ➢ SVT SL (SVT)
  - ➢ SVT DBR (SVT)
  - ➢ Luca's DBR (Sadia)



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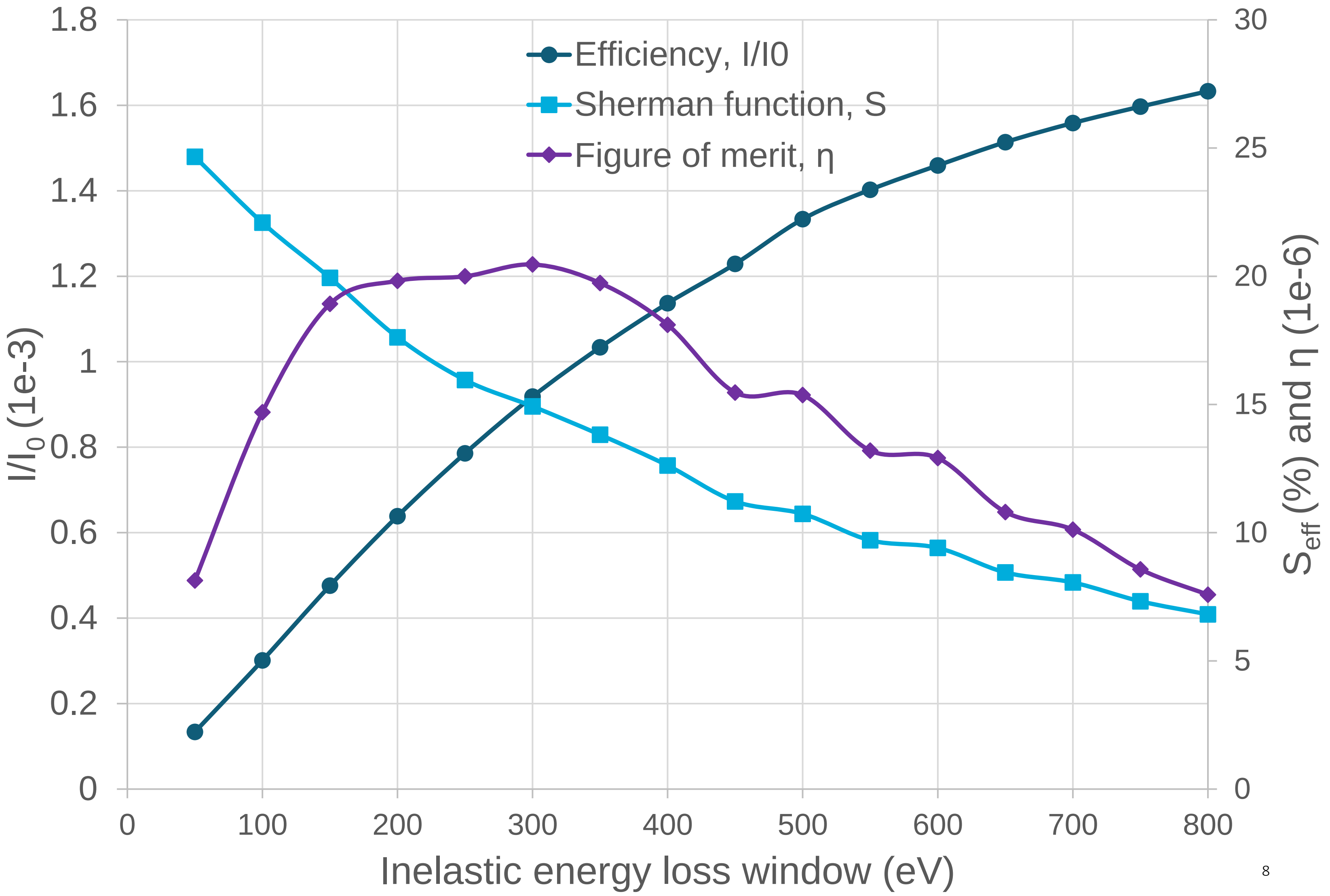
Polarimeter performance

- The initial energy of electron from photocathode is 200 eV
- The Sherman function is almost linear for ΔE<200 eV
- The theoretical effective Sherman function is 0.27



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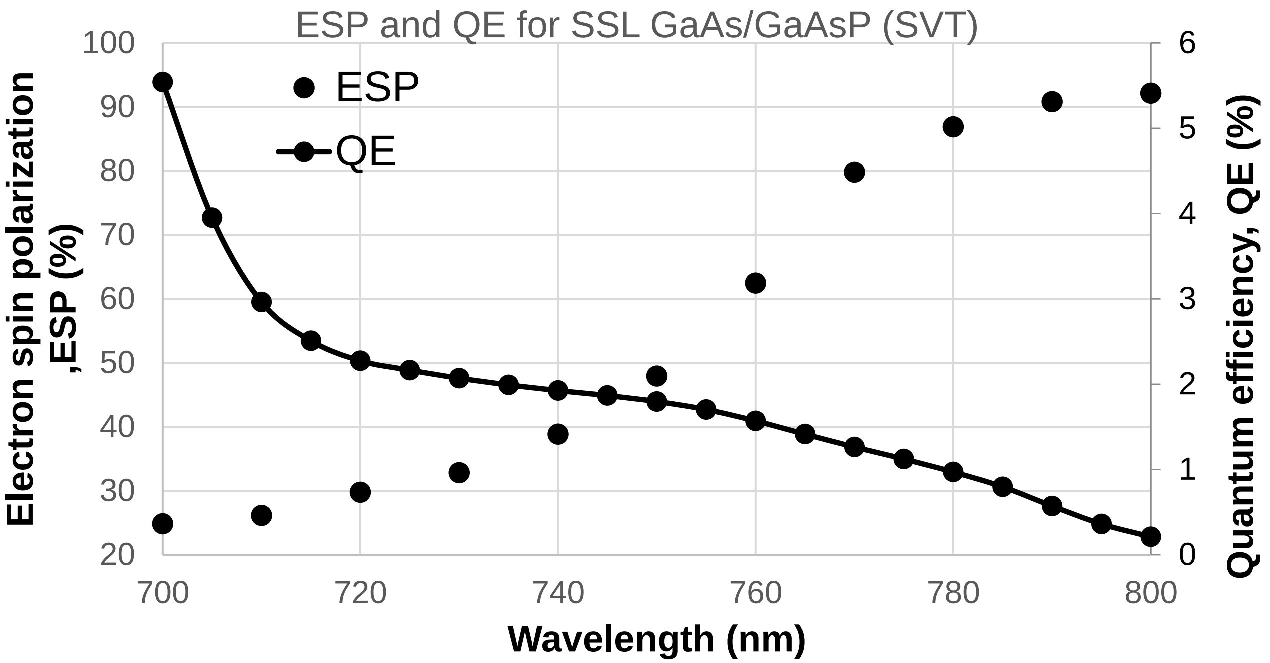
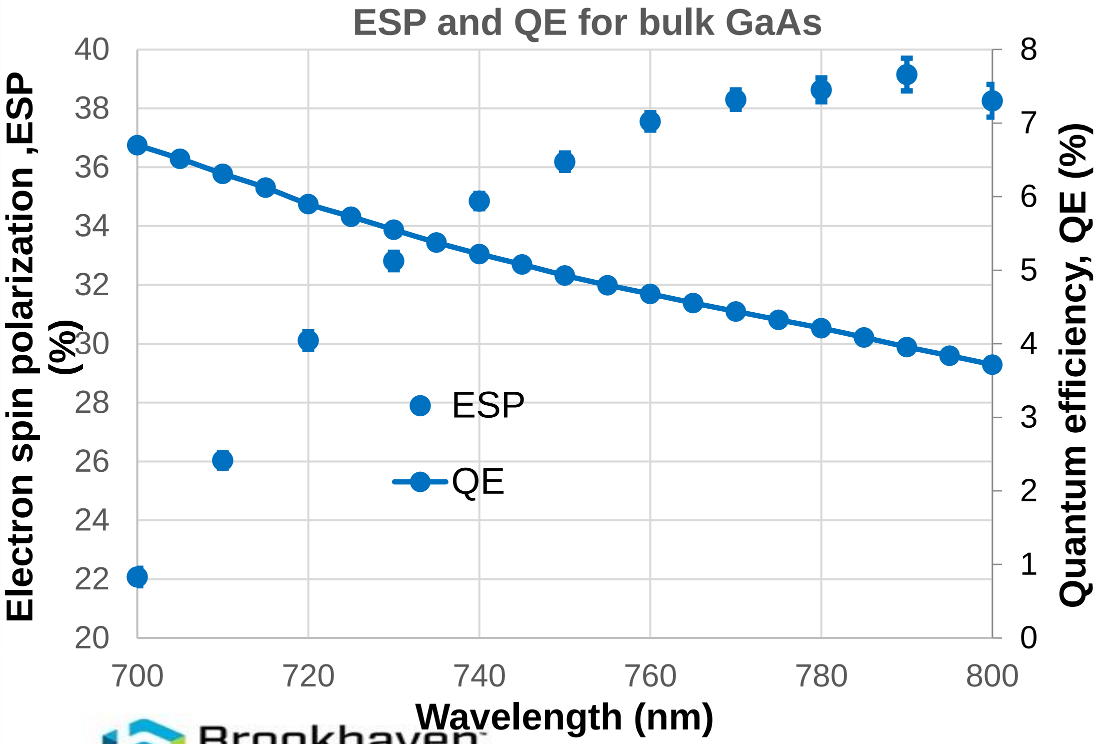
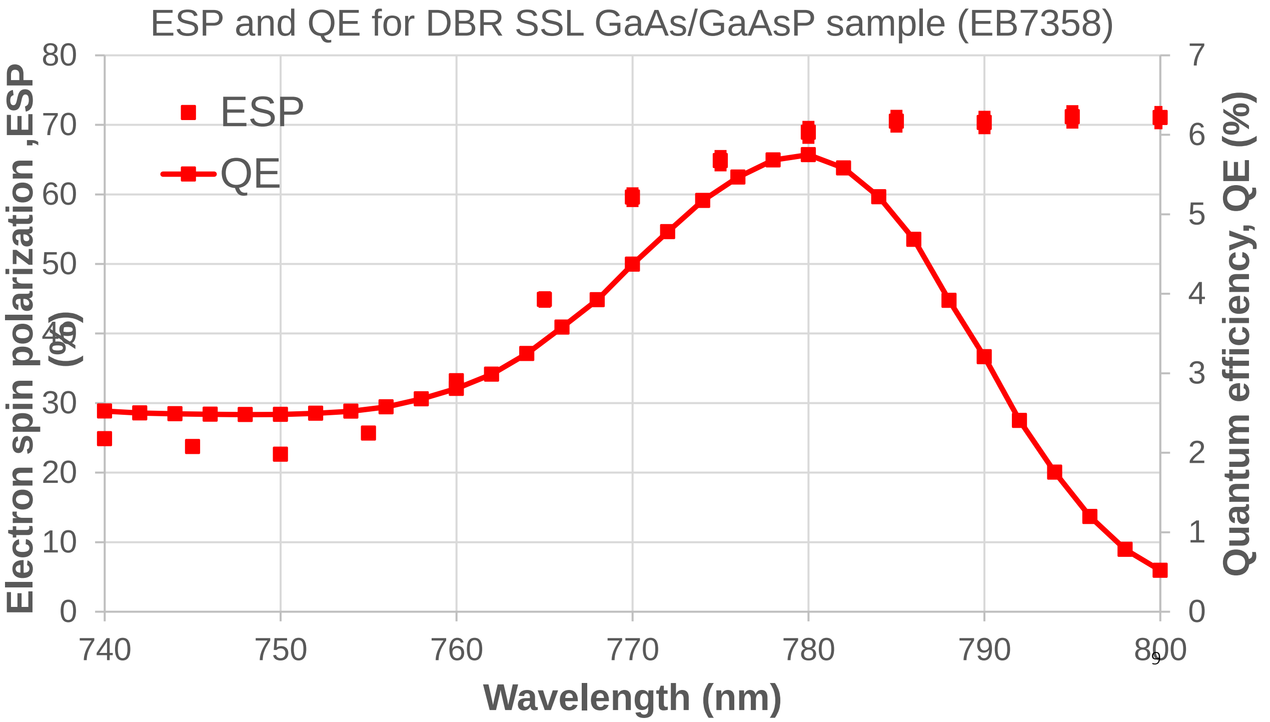
Measured ESP

- Several GaAs samples have been measured.
- Reasonable ESP for bulk GaAs and SSL GaAs/GaAsP photocathodes are obtained with error < 2% of the value







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Conclusion

- We purchased *Specs* Mott polarimeter system.
- Cathode activation system and Mott system have been integrated and commissioned.
- Reasonable QE and ESP of GaAs photocathodes have been measured.
- The polarimeter has a good performance, ESP error is smaller than 2% of the ESP value.
- We achieved all the 1st year goals.

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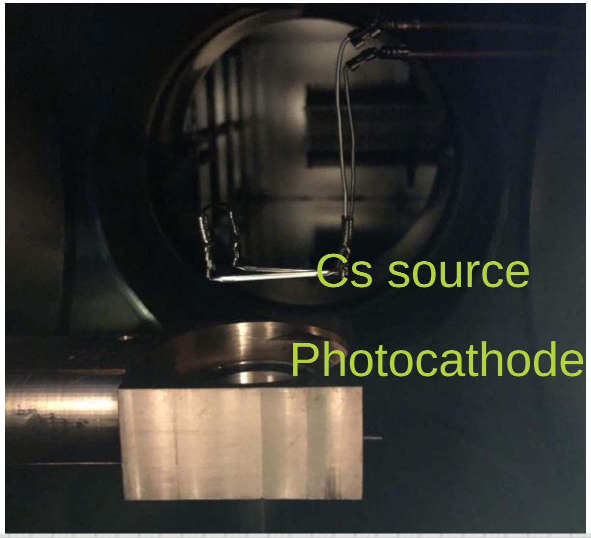
Back up

Activation of GaAs photocathode



- Starts activation when the temperature goes down below 40 ℃.
- Activation is performed by yo-yo technique with Cs and O_2.
- Photocurrent usually reach peak value after 8-12 yo-yo cycles.
- Photocurrent has a slightly decrease after stopping activation.