Enhanced Quantum Efficiency of Photocathodes with Polarized Emission

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in collaboration with
Matt Poelker, Jefferson Lab (JLab):

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US Dept. of Energy SBIR
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Outline

- Company introduction
- Photocathodes
- Molecular Beam Epitaxy
- GaAsP/GaAs Superlattice Photocathode
- Our approach: extending operational characteristics of photocathodes by adding integrated mirrors
- Conclusion

SVT Associates, Inc. Company Overview

- **Located in Eden Prairie, MN (Minneapolis Metro Area)**
- **Founded in 1993 as MBE equipment provider**
- **35 employees**
- **Currently supplies vacuum processing modules for MBE and other thin films deposition (e.g. CIGS)**
- **SVTA's applications laboratory conducts R&D into materials, supplies epi-wafers and devices, test and develops hardware**
- **One of today's leading suppliers with > 120 systems in the field**

SVTA Product Line

(www.svta.com)

Process Knowledge

MBE Systems and Components

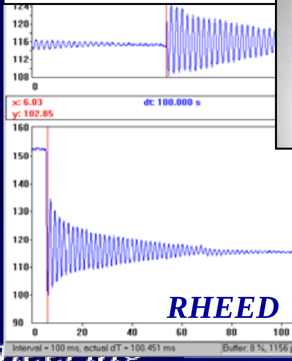
ALD, PLD UHV Deposition

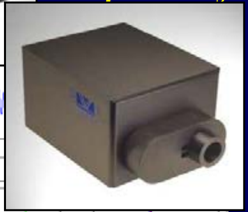
In-situ Process Monitoring & Control

Applications Lab MBE Growth & Devices Fab.

AcuFlux

Pyrometric Interferometry





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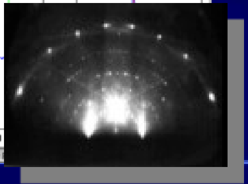
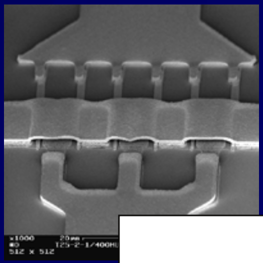




SVTA-UV-C Solar-Blind Detector

A S S O C I A T E S

Solutions through Epitaxy Engineering

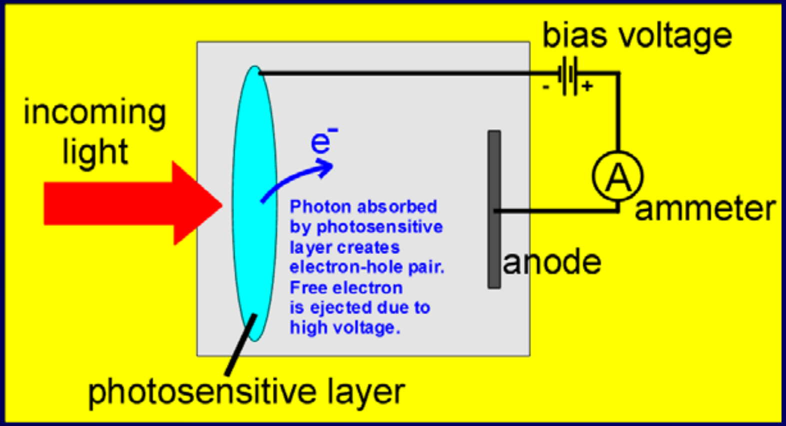
Semiconductors Research at SVT

- US Government and Industrial research grants
- Established research collaboration with many universities: Illinois, North Carolina State, Florida, Stanford ...
- Highly technically oriented, PhD scientists & engineers
- > 100 book chapters, publications and presentations
- Significant Antimonide, Nitride and ZnO accomplishments
  - High power HEMT & MOSHEMT
  - Commercialized solar blind UV detector products
  - High efficiency photocathode
  - Innovative LED utilizing Quantum Structures
  - New mid Infrared Laser and LWIR Photodiode
  - Rainbow colored MgZnCdO

Photocathodes

- *Photocathodes for conversion of light into electron current*
  - *Electrons and holes created by photon absorption*
  - *Electrons ejected due to applied high voltage*
  - *Electron current captured or reabsorbed by phosphor*

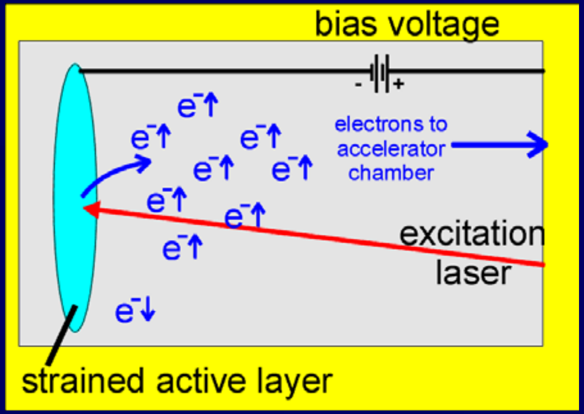
Basic Photocathode Operation (transmissive mode)



- *Application: Night vision / image intensifiers, highly sensitive photodetectors*

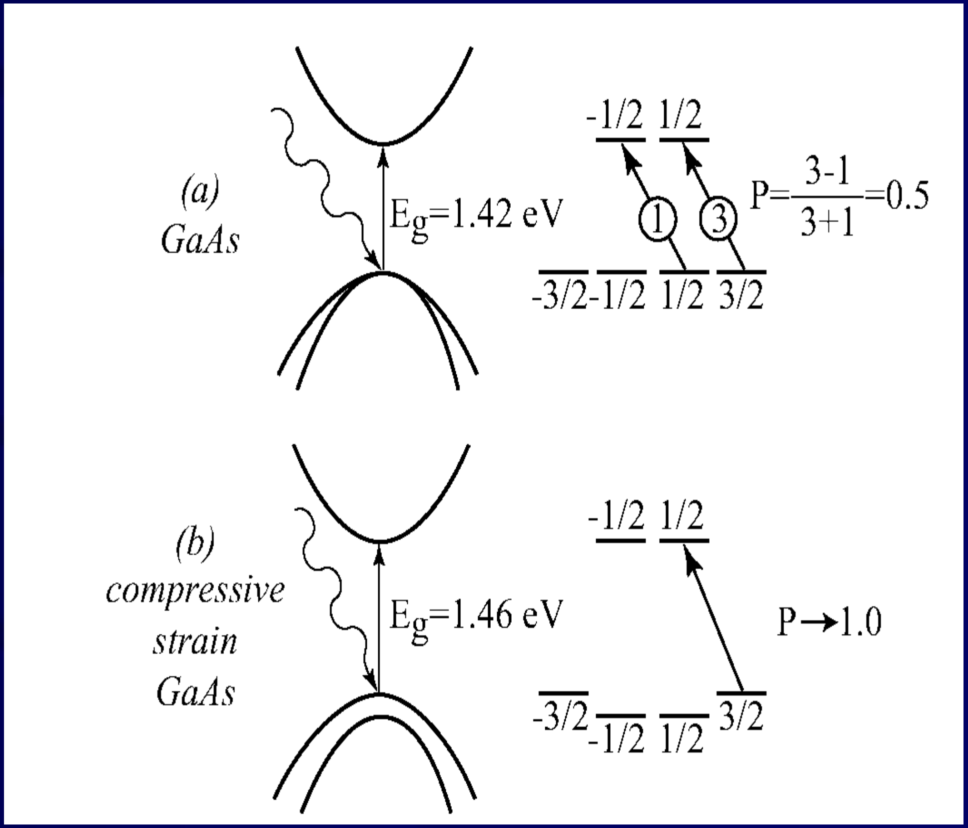
- *Application: Spin polarized emitter*
  - *Emission heavily favoring an "up" or "down" spin of electrons*
  - *Useful in some high energy physics experiments, spin polarized electron microscopy*

Spin Polarized Emission (reflective mode)



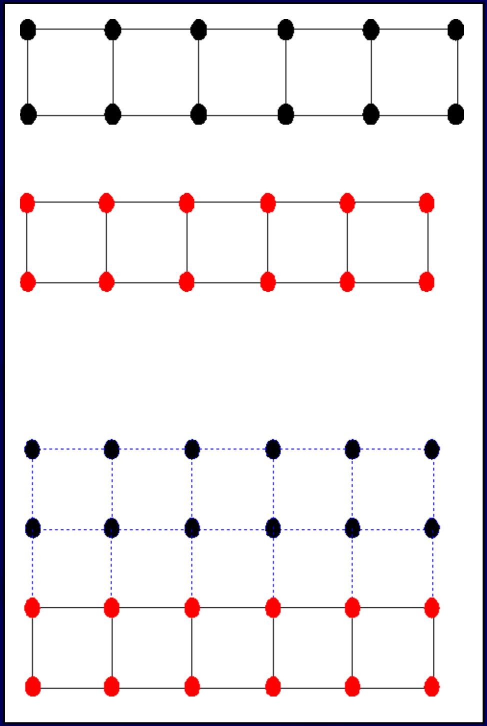
Polarized Emitters

- Photocathode emission
  - Circularly polarized light
- Unstrained GaAs
  - 50% max polarization
- Compressively strained GaAs
  - lattice constant < 5.65 Å
  - valence band splitting
  - 3/2 ⟶ 1/2 transition favored
  - 100% max polarization



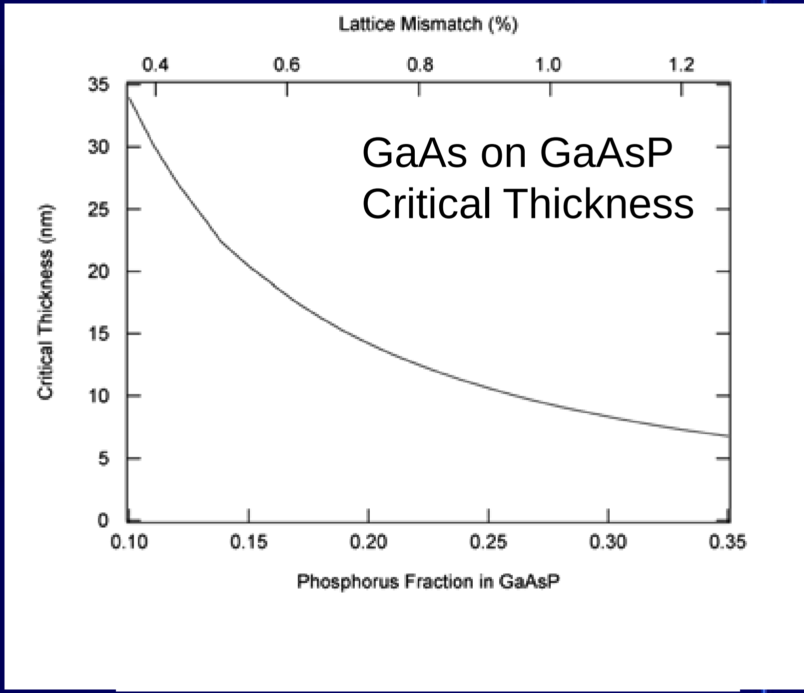
Creating Strained GaAs Layers

- Heteroepitaxy
- New layers will form based on previous lattice
- Compressive strain
  - Growth on lattice with smaller lattice constant
- Larger difference in lattice size → increased strain force



Limits to Strained Layers: Critical Thickness

- Strain forces increase with thickness
- Strain reaches threshold, lattice relaxes
- "Critical Thickness"
  - Layer thickness where relaxation occurs
  - Relaxed lattice- bulk crystal state
  - Thickness inversely proportional to strain (difference in lattice constant)
- Misfit dislocations created
  - Scattering, absorption of photons
  - Non-uniformities

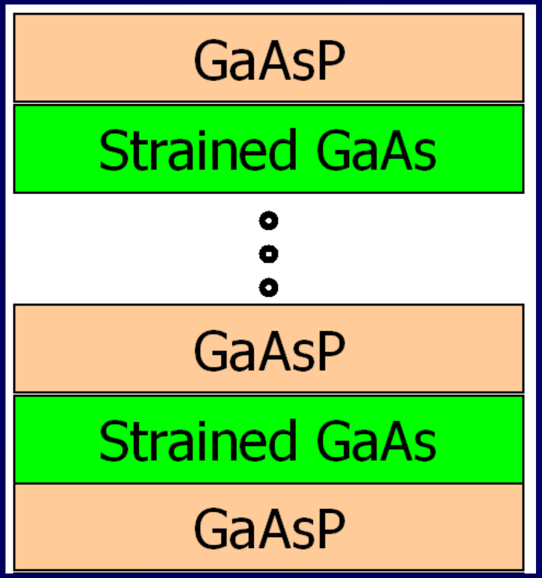


Photocathode Polarized Emitters

- Device Considerations
  - Strained GaAs layer
    - Highly p-type doped
    - Thick to provide enough emission current
  - Structure Growth
    - Uniform
    - Excellent crystallinity
  - Substrate for epitaxy
    - High quality
    - Robust

Strained Superlattice Photocathode

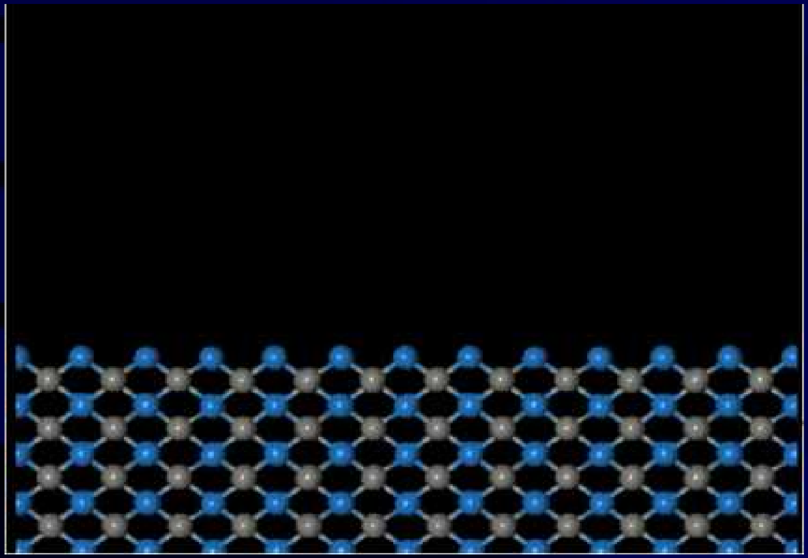
- Strained GaAs on $GaAs_xP_{1-x}$
- Multiple GaAs layers sandwiched by $GaAs_xP_{1-x}$
  - Each GaAs layer below critical thickness
  - Multiple GaAs layers to provide thick overall active volume for electron emission
  - Superlattice- repetition of thin layers
- MBE for epitaxy
  - Thin layers (< 50 Å)
  - Utilizes phosphorus
  - Abrupt, uniform interfaces



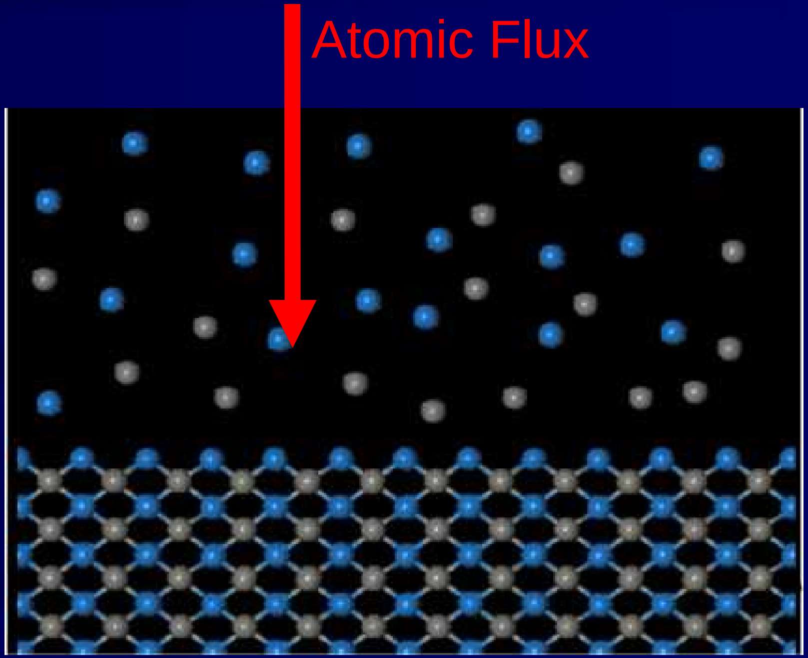
SVT ASSOCIATES *Solutions through Epitaxy Engineering*

Epitaxy

Growth of thin film crystalline material where crystallinity is preserved, “single crystal”

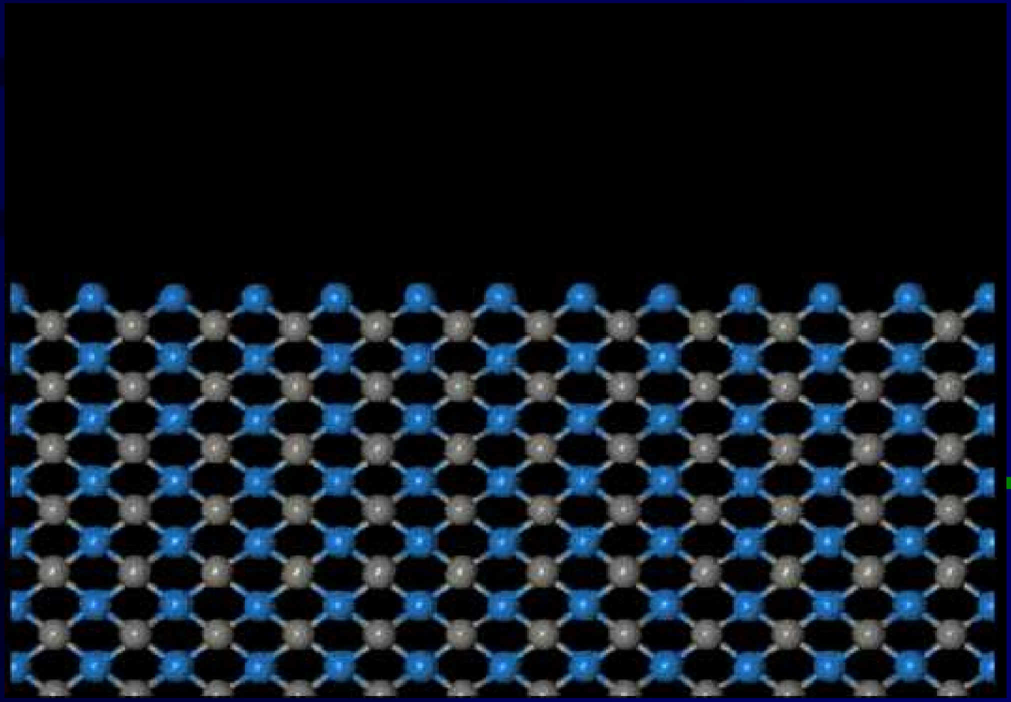


Bare (100) III-V surface, such as GaAs



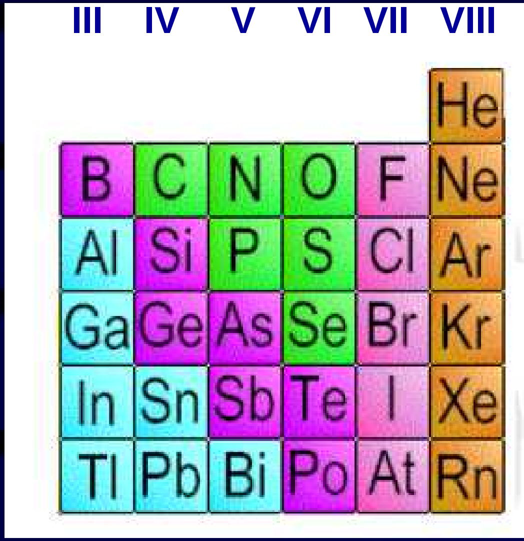
Deposition of crystal source material (e.g. Ga, As atoms)

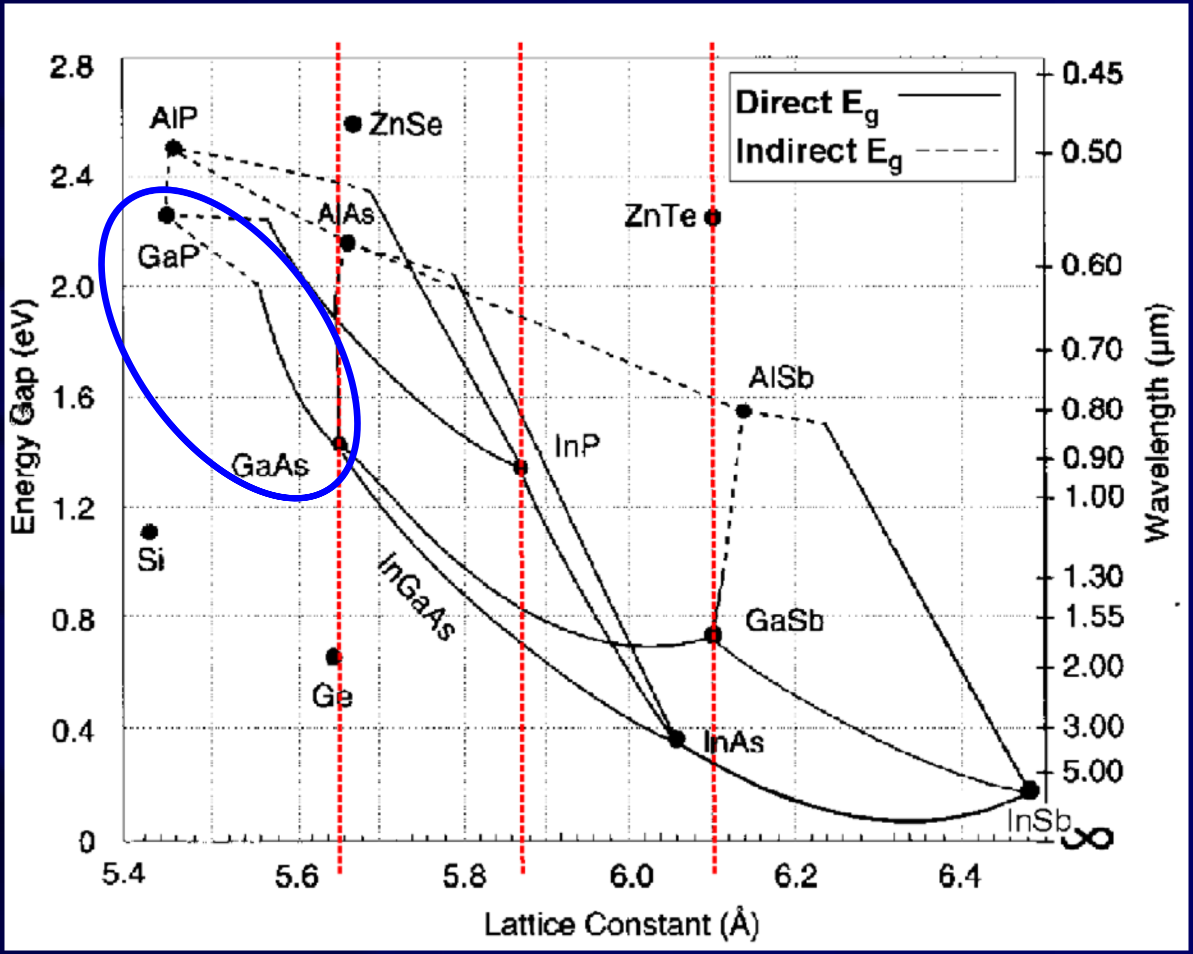
Result: Newly grown thin film, lattice structure maintained



Starting surface

III-V Compound Semiconductors





Solutions through Epitaxy Engineering

Molecular Beam Epitaxy (MBE)

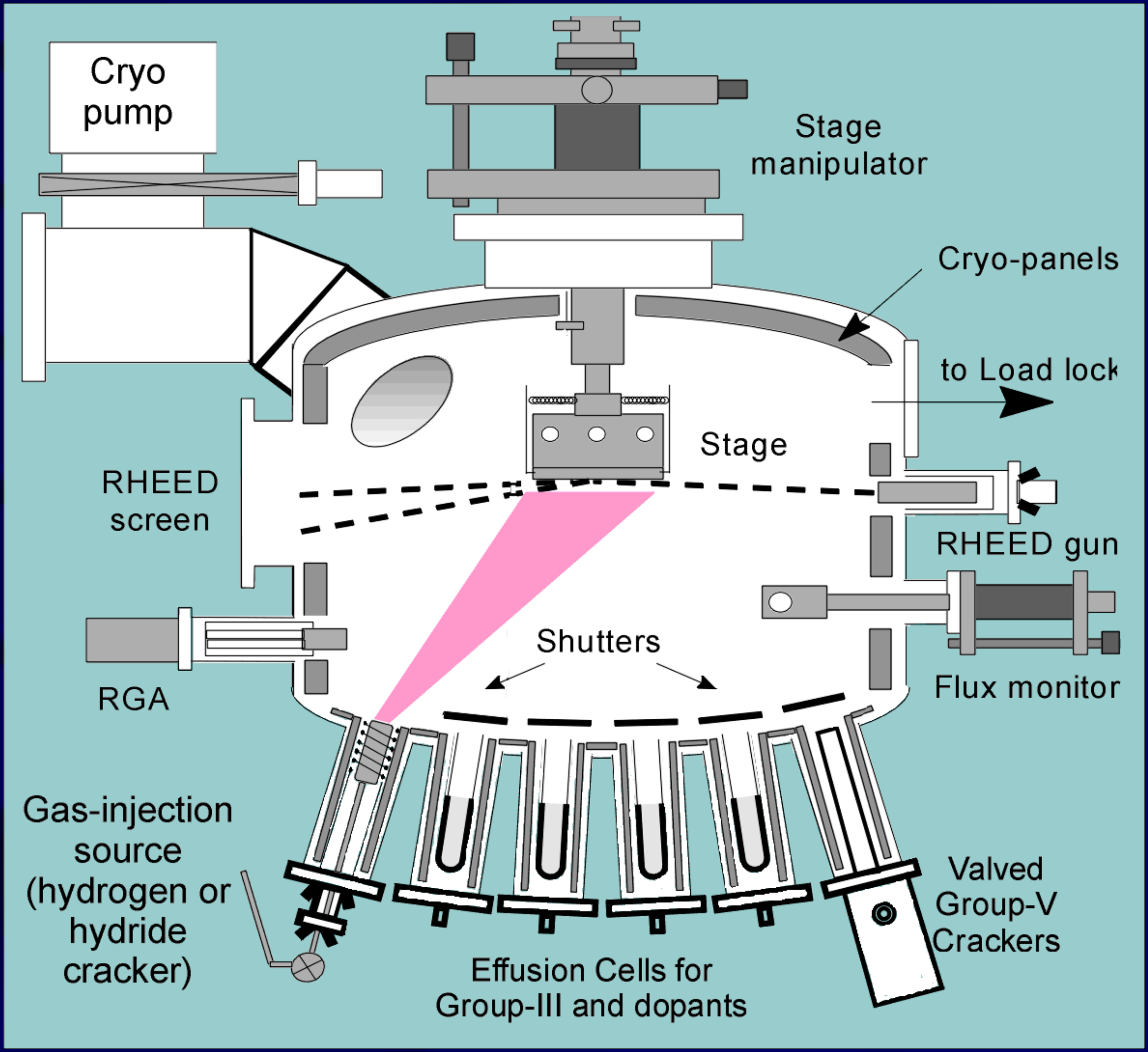
- Growth in high vacuum chamber
    - Ultimate vacuum < 10^{-10} torr
    - Pressure during growth < 10^{-6} torr

- Elemental source material
    - High purity Ga, In, Al, As, P, Sb (99.9999%)
    - Sources individually evaporated in high temperature cells

- In situ monitoring, calibration
    - Probing of surface structure during growth
    - Real time feedback of growth rate

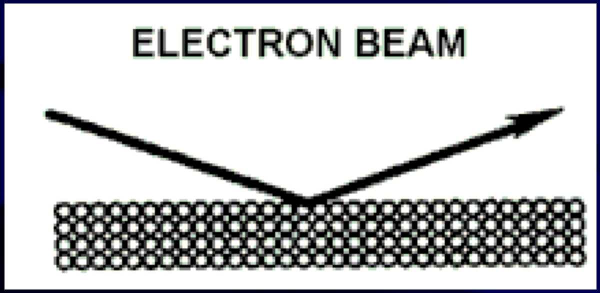
Molecular Beam Epitaxy

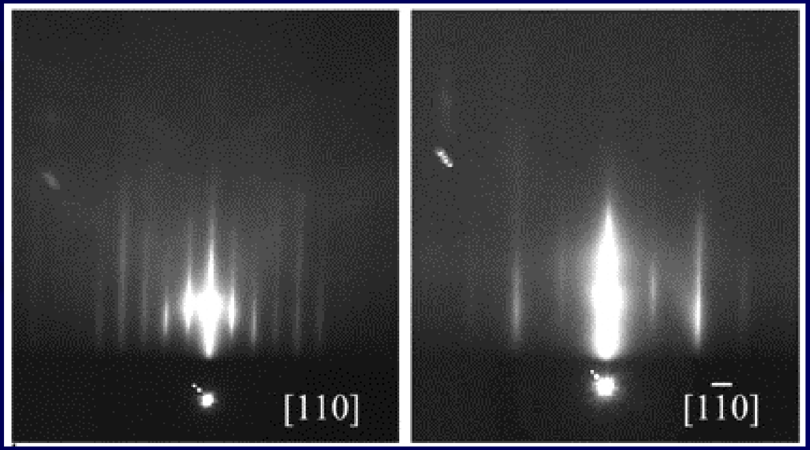
Growth Apparatus:



MBE- In Situ Surface Analysis

- Reflection High Energy Electron Diffraction (RHEED)
- High energy (5-10 keV) electron beam
- Shallow angle of incidence
- Beam reconstruction on phosphor screen





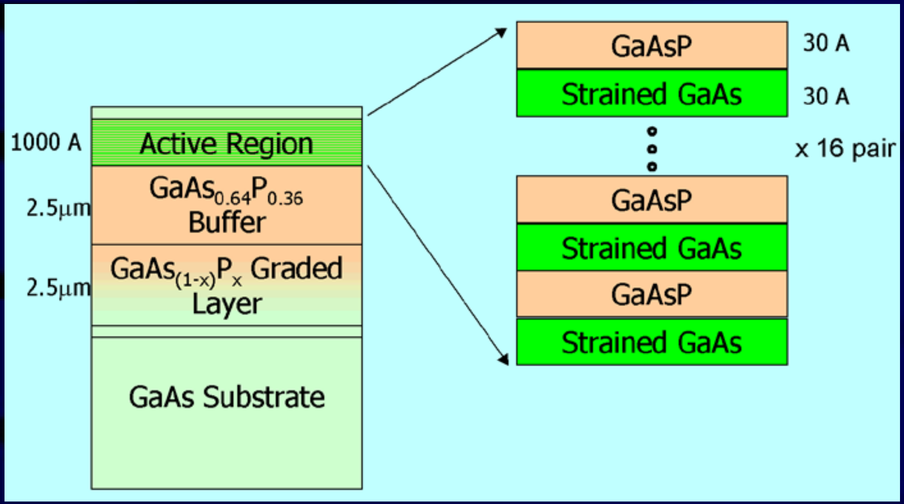
RHEED image of GaAs (100) surface

MBE System Photo

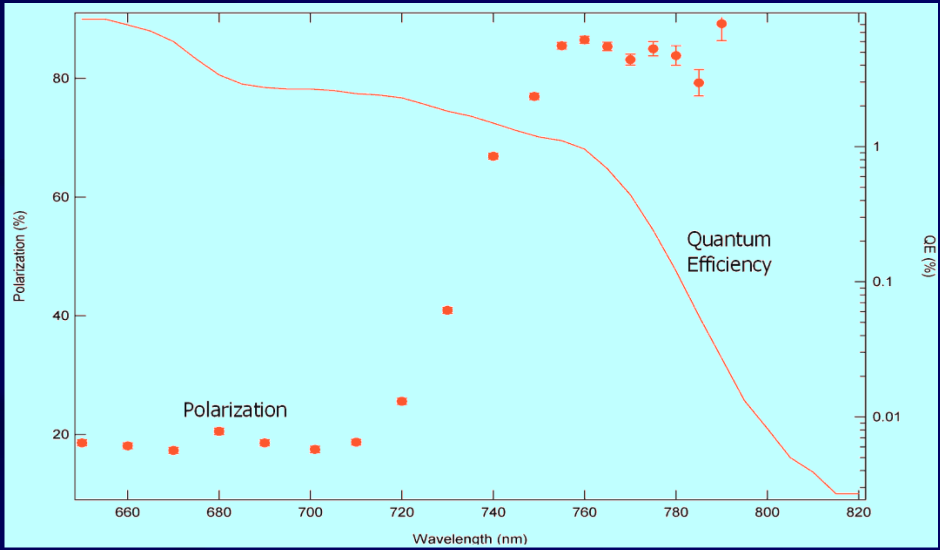
MBE- Summary

- Ultra high vacuum, high purity layers
- No chemical byproducts created at growth surface
- High lateral uniformity (< 1% deviation)
- Growth rates 0.1-10 micron/hr
- High control of composition and thickness
- Lower growth temperatures than MOCVD
- In situ monitoring and feedback
- Mature production technology

MBE Grown GaAsP SL



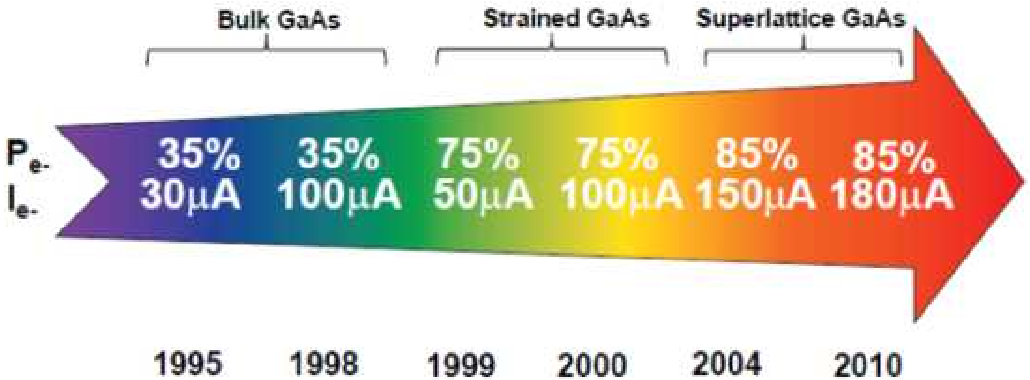
- greater than 1% QE
- achieved 86% polarization
  - material specific spin depolarization mechanism

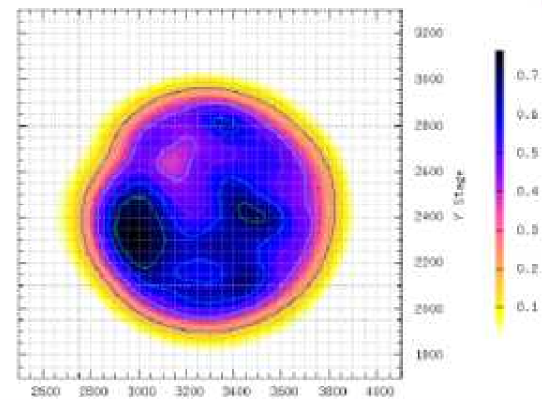


US Dept. of Energy SBIR Phase I and II contract #DE-FG02-01ER83332, collaboration with SLAC

Solutions through Epitaxy Engineering

Jlab - ILC High Current Polarized Electron Source





R. Suleiman et al., PAC'11, New York (NJ, USA), March 28 - April 1, 2011

Parameter	Value
Laser Rep Rate	1500 MHz
Laser Pulselength	50 ps
Laser Wavelength	780 nm
Laser Spot Size	350 µm FWHM
High-Pol Photocathode	SSL GaAs/GaAsP
Gun Voltage	200 kV DC
CW Beam Current	**4 mA**
Run Duration	**1.4 hr**
Extracted Charge	20 C
1/e Charge Lifetime	85 C
Bunch charge	2.7 pC
Peak current	53 mA
Current density	55 A/cm^2

MBE Grown GaAsP SL for Polarized Photocathode Emitters

- SVT supplied photocathodes with > 80% polarization
  - CEBAF/JLab, SLAC, Mainz Microtron and Bonn/ELSA

- SVT first company to supply Arsenic capped devices
  - As-capping protects surface from atmospheric contamination
  - Arsenic removed in vacuum before activation
  - Improved success rate of installed photocathodes

Improving Polarized Photocathode Emitters

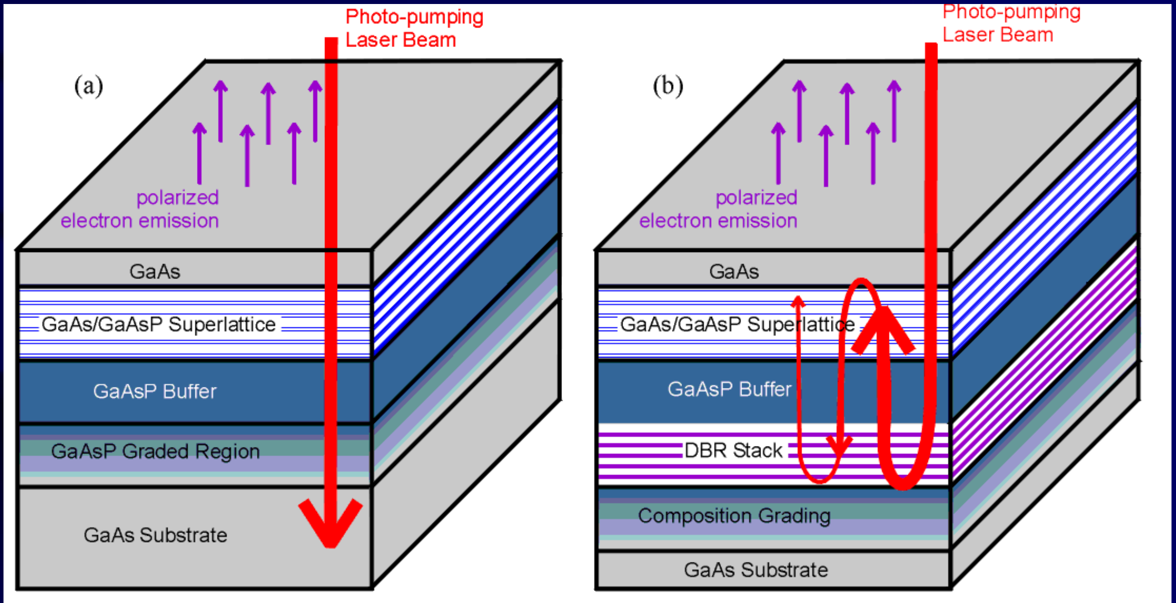
- Increased polarization?
  - Material quality
  - Alternative material systems

- Increased quantum efficiency (output current)?
  - QE ratio of incident photons to extracted polarized electrons
  - Reduce depolarizing mechanisms (material quality)
  - Only a small percentage of laser light is absorbed by superlattice active layer
  - Increase laser power -> more waste heat
  - Increase QE by maximizing pertinent photon absorption

Improving Polarized Photocathode Emitters

- "One-pass" status quo design (left), less than 10% photon absorption in active area

- Add mirror to structure to create multiple reflections of excitation beam



In a standard single-pass photocathode structure over 90% of laser energy is wasted and converts to unwanted heat.

In a photocathode with integrated reflector laser energy is redirected to make multiple passes through the superlattice active layer, increasing quantum efficiency and/or reducing parasitic heat.

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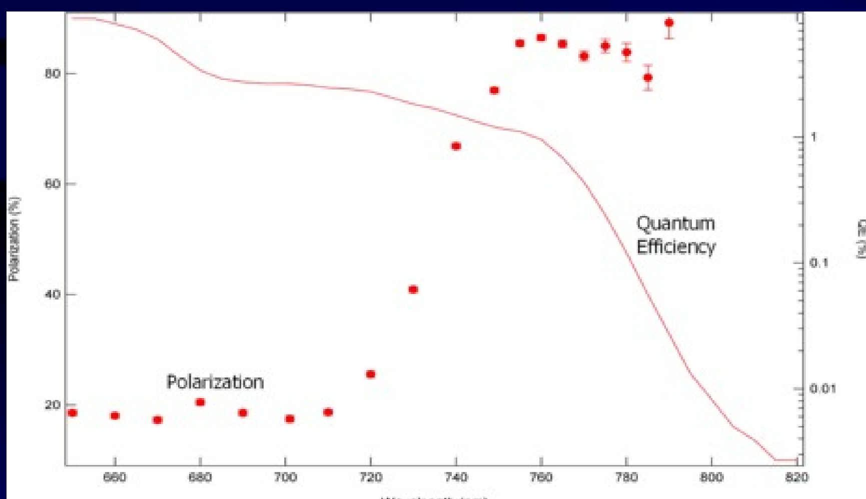
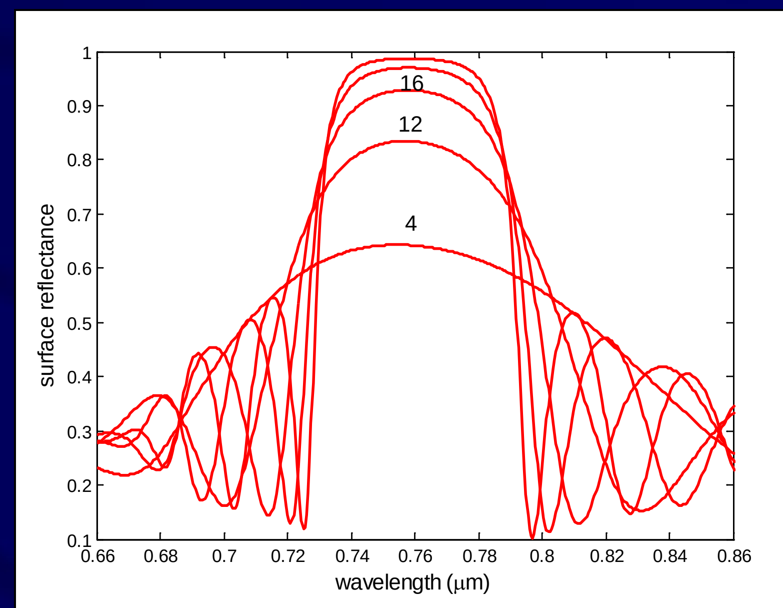
Solutions through Epitaxy Engineering

Combining DBR Mirror with Photocathode

- Distributed Bragg Reflector (DBR)
  - Pairs of layers with differing optical indexes of refraction
  - Layer thickness dependent on desired wavelength for reflection
  - Layer material must be compatible with substrate and active layer
  - Layer material must be transparent to target wavelength



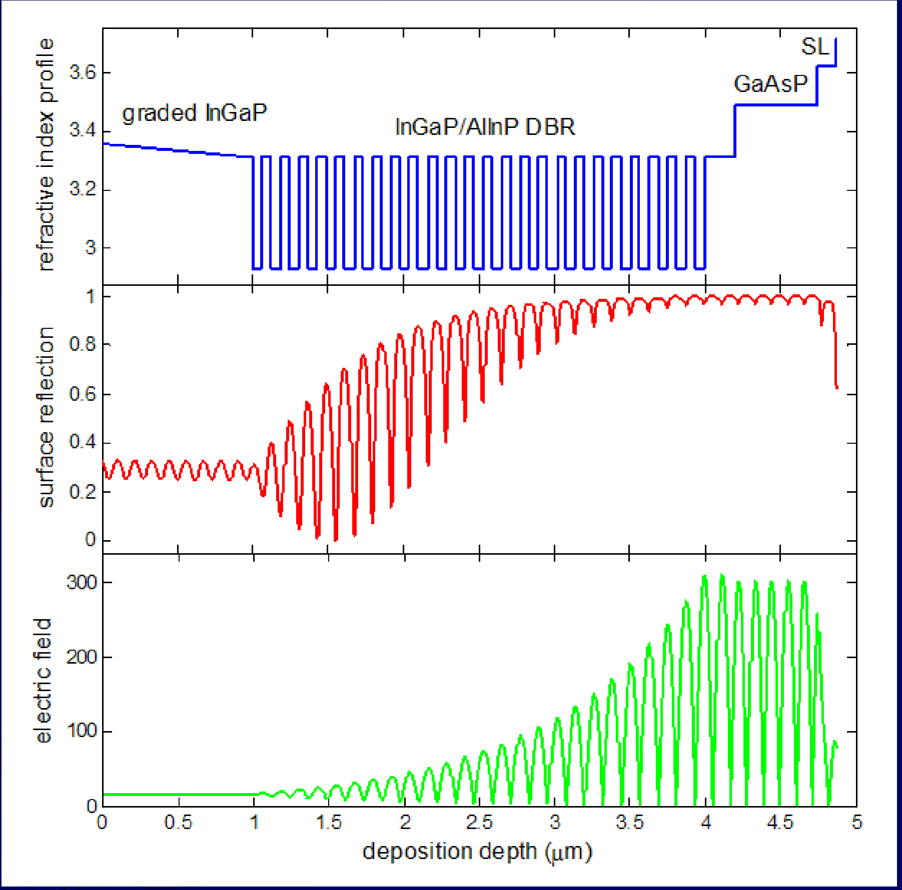


Modeling of DBR Mirror with Photocathode

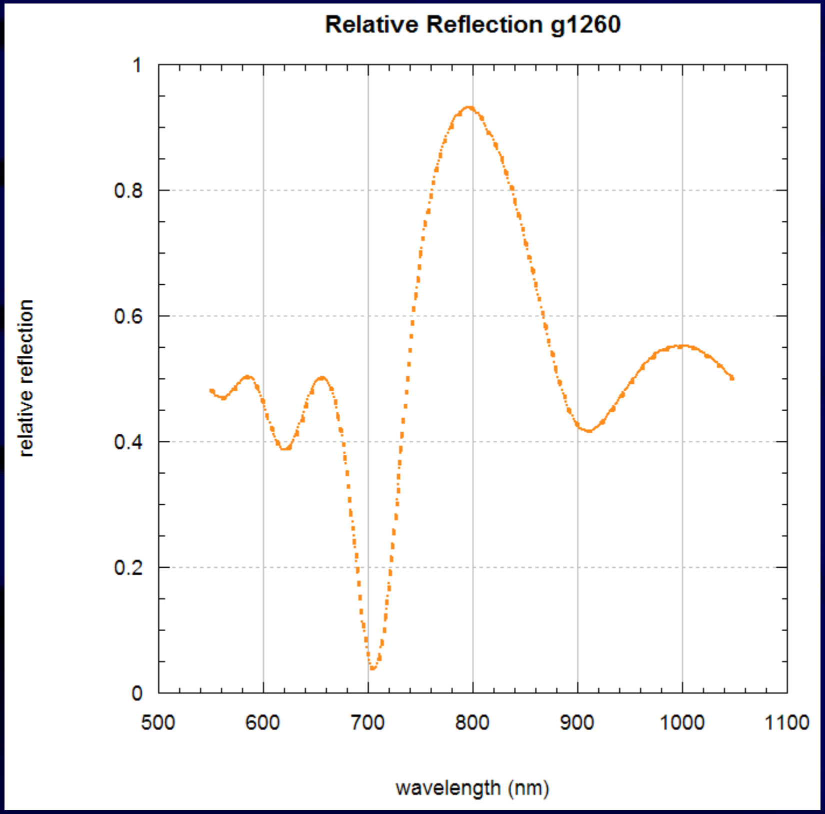
Refractive index and thickness of materials in another DBR with Fabry-Perot cavity at 760 nm.

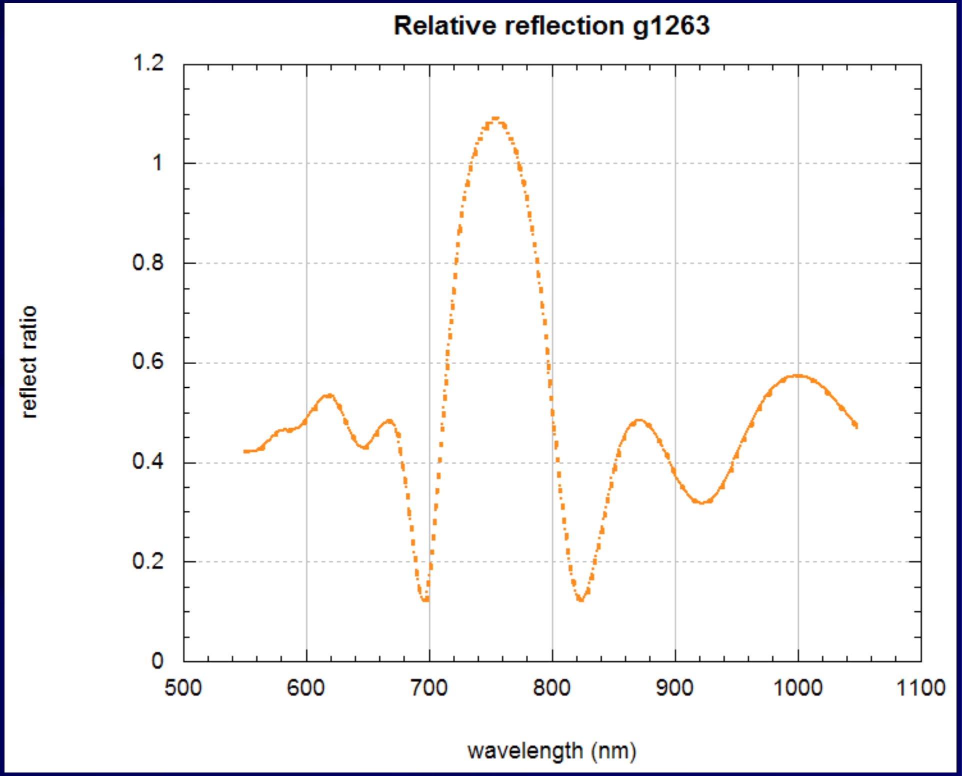
	AlInP	InGaP	InGaP buffer	GaAsP	GaAs/GaAsP SL	GaAs
n	2.9356	3.3102	3.3102	3.4888	3.6192+0.0226i	3.712+0.095i
d (nm)	64.72	57.40	145	550	120	5

- DBR and surface reflection create optical Fabry-Perot cavity
- Photons repeatedly bounce between DBR and surface
- E-field of incident light strongest in active area near ejection surface

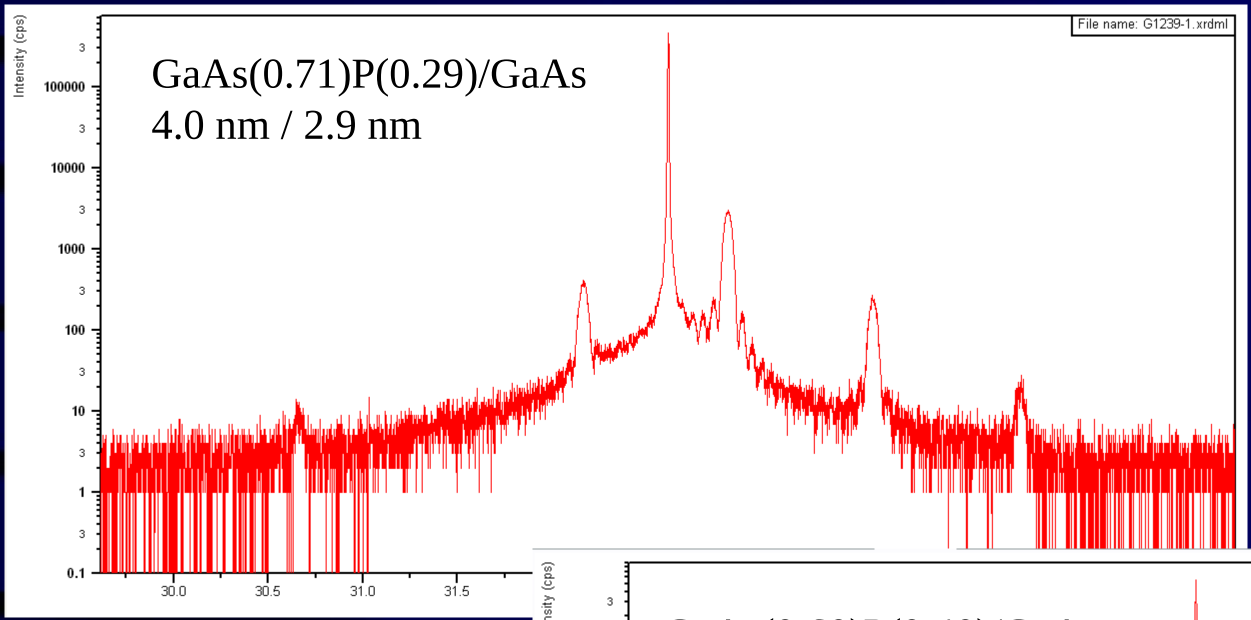


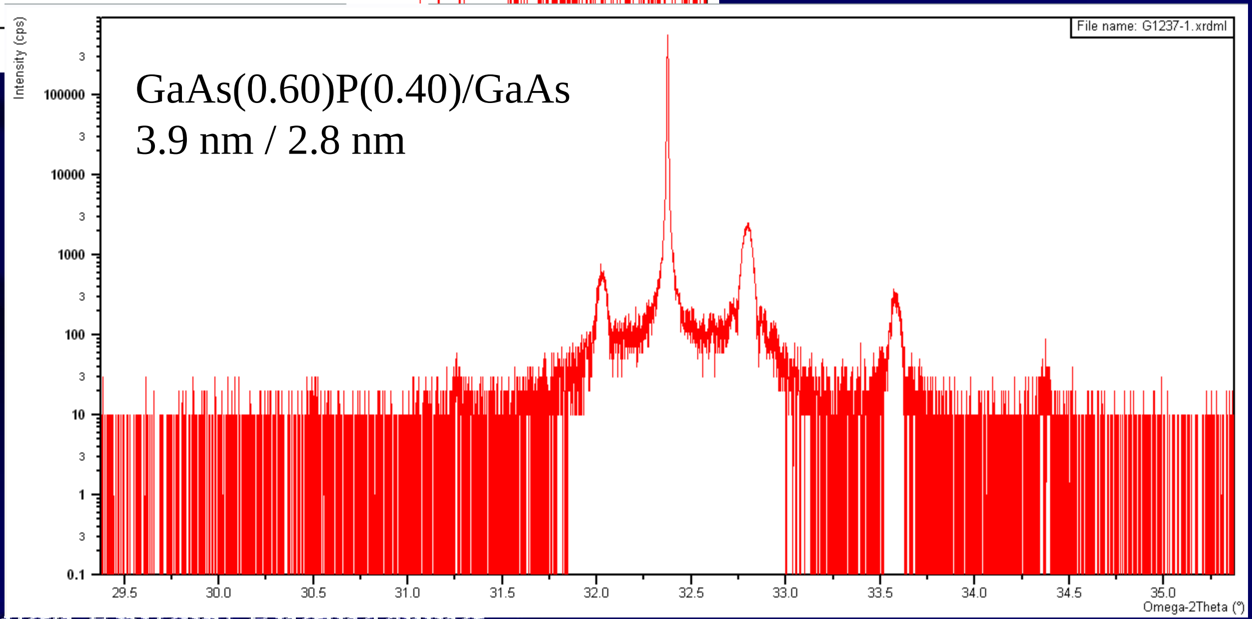
Growth and Measurement of DBR Mirror





Calibration of GaAs(x)P(1-x)/GaAs Superlattice





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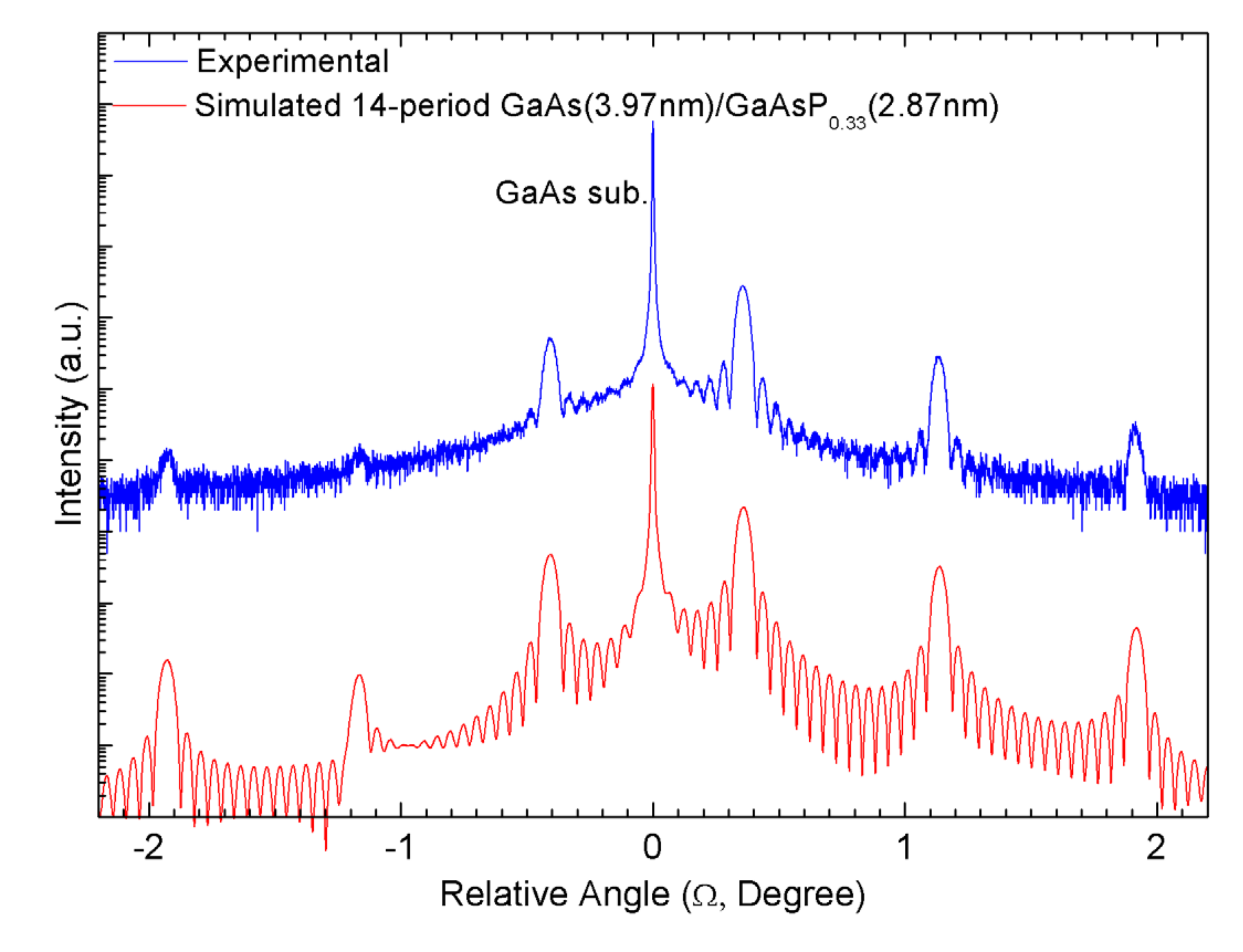
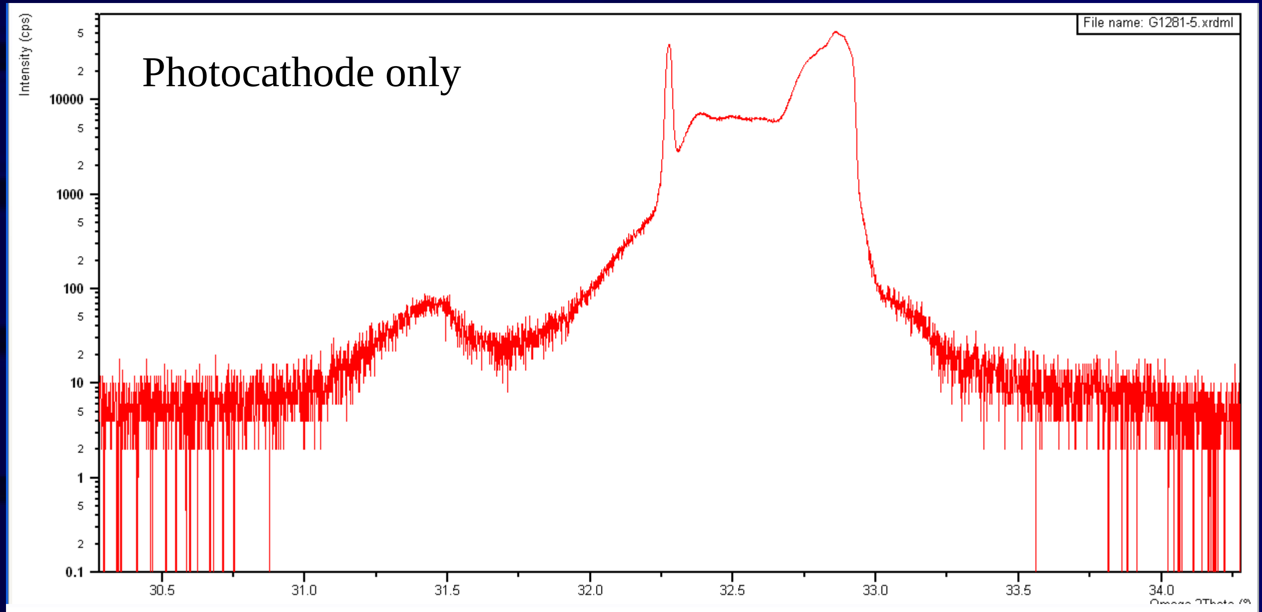
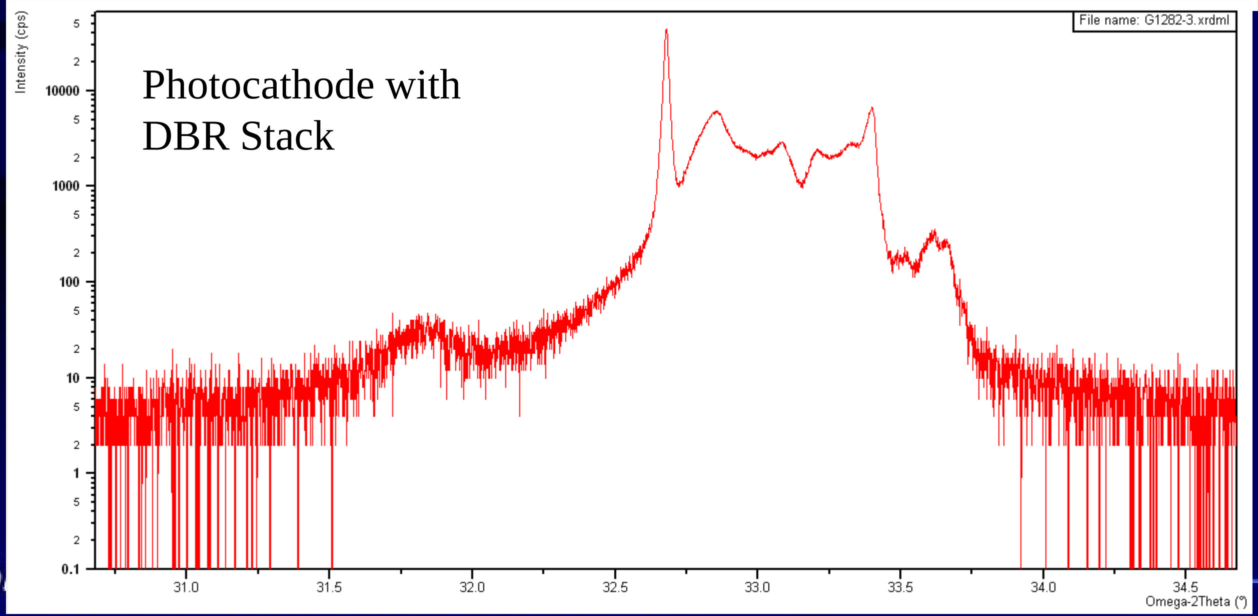


Structure of DBR Photocathode

emitter	GaAs	5nm
superlattice	GaAs/$GaAs_{0.64}P_{0.36}$ SL	3.8/2.9 nm x 14 pair
buffer	$GaAs_{0.64}P_{0.36}$ SL	2.5 um
DBR stack	$GaAs_{0.64}P_{0.36}$/AlGaAsP	1.4 um
grading layer	GaAsP composition grade	
	GaAs buffer	
	GaAs substrate	

X-Ray of Grown DBR Photocathodes





DBR Photocathodes Status

- Growth of two samples completed
    - One polarized photocathode structure only (control)
    - One polarized photocathode structure with DBR stack
- Awaiting polarization and QE data
- Optically measure DBR reflection of sample, compare with QE data
- Modify structure and produce new samples if needed

Conclusion

- Photocathodes with polarized emission
- Increased polarization and current -> faster collection of data
- GaAsP/GaAs SL structure already proven and in use
- Reflector integrated into photocathode
- Laser light inside Fabry-Perot cavity for increased absorption
- Modeling predicts up to an order of magnitude absorption increase
- Control and experimental samples grown, awaiting polarization and QE measurement.