GaAsSb/AlGaAs Superlattice High-Polarization Electron Source

Contract # DE-SC0007501

Principal Investigator: Yiqiao Chen, SVT Associates, MN 55344

Collaborator: DoE Jefferson Lab

DoE SBIR/STTR Exchange Meeting

Aug 6-7, 2015, Gaithersburg, Maryland

SVT Associates, Inc.

SVT Associates Company Overview

Founded in 1993 as Molecular Beam Epitaxy (MBE) equipment provider

  - Originated from Perkin Elmer Physical Electronics MBE Group
  - One of today's leading MBE suppliers by continual product development
  - Over 160 MBE systems now in the field

- Strong UHV hardware, epitaxial growth, and thin film expertise
- Technology Driven Company
  - >30% employees are PhD scientists (currently 30 employees total)
  - Key engineers > 25 years experience in MBE and UHV technology
- Diverse system product line spanning Molecular Beam Epitaxy (MBE), Thin Film Deposition (i.e. ALD, PVD, PLD and Solar), and In-situ Thin Film Monitoring
- Only MBE Company with System, Components, Process, In-situ Monitoring Expertise with our own Applications Laboratory and Characterization Facility

SVT Associates, Inc.

SVT Facilities and Capabilities

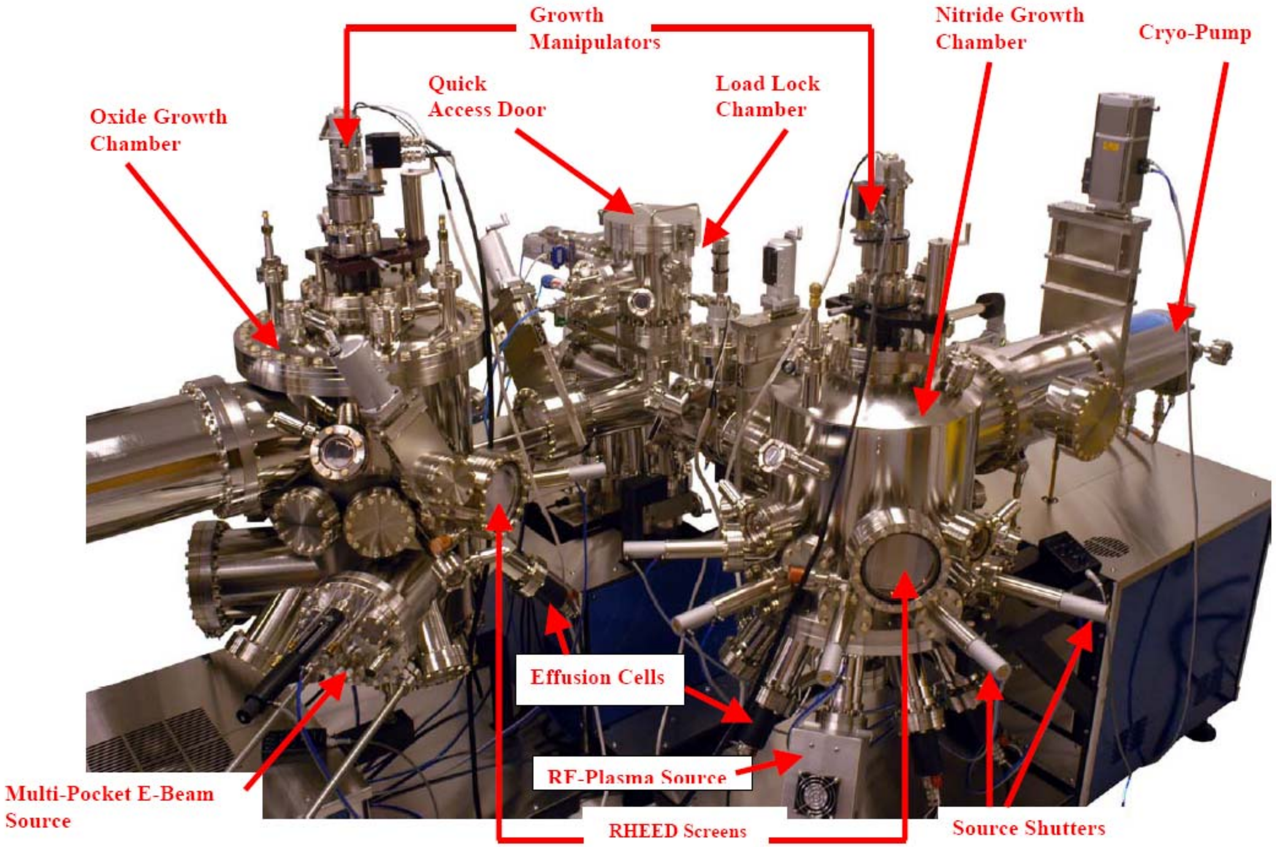
- Material deposition systems: MBE PLD, ALD

Established know-how:
8 Applications Laboratory MBE systems producing world class epitaxial growth, feeding requirements back to equipment designers

- Complete semiconductor material characterization facility: HR-XRD, FTIR, Hall, Low-temp probe station, Semiconductor parameter analyzer, ellipsometer.

- Device Fabrication

Class-100 clean room, ICP dry etcher.



Dual Oxide - Nitride MBE

Semiconductors Research at SVT

- US government, industrial research grants, and internal programs
- 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 Photodiode
  - Rainbow colored MgZnCdO

Program Overview

Program title: GaAsSb/AlGaAs Superlattice High-Polarization Electron Source

Ultimate goal:

cw polarized electron sources with >80% polarization and > 10 mA beam current

SVT-70%

- Photocathode Modeling/Design
- Material Growth

JLab-30%

- Photocathode Testing

Present Applications:

•DoE needs: high energy accelerators
•Spintronics

Potential Applications:

•Surface analysis
•Quantum computing
•Magnetic imaging

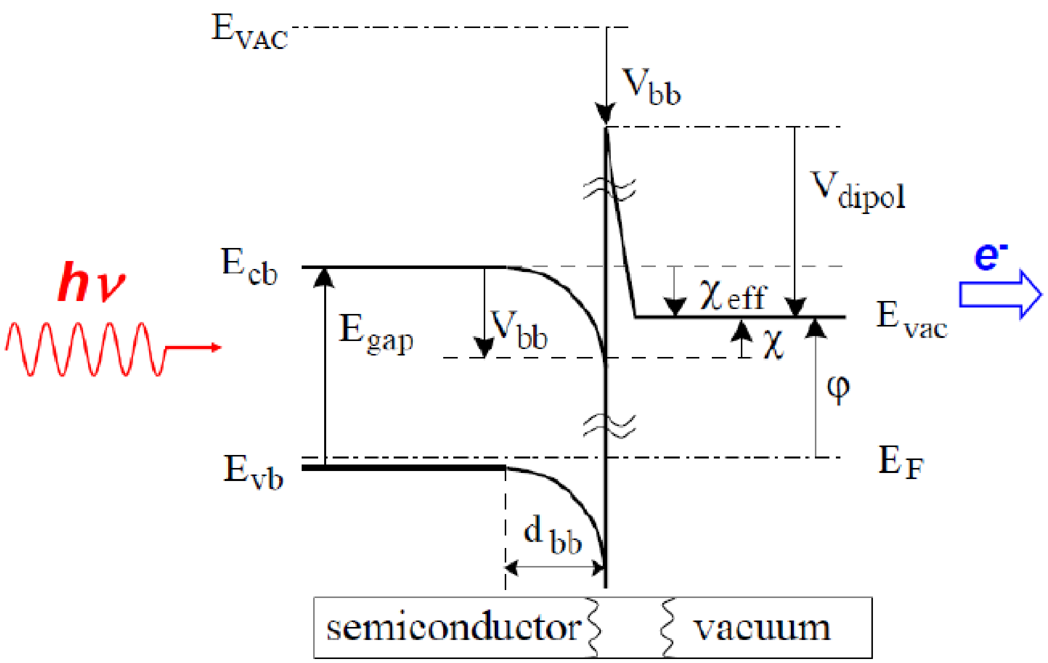
SVT Associates, Inc.

Photocathode - General Properties

Photons → free electrons in vacuum

1. **Optical absorption**
2. **Electron transport to surface**
3. **Escape from surface to vacuun**

Two aspects of emitted electrons in polarized photocathode: density and spins

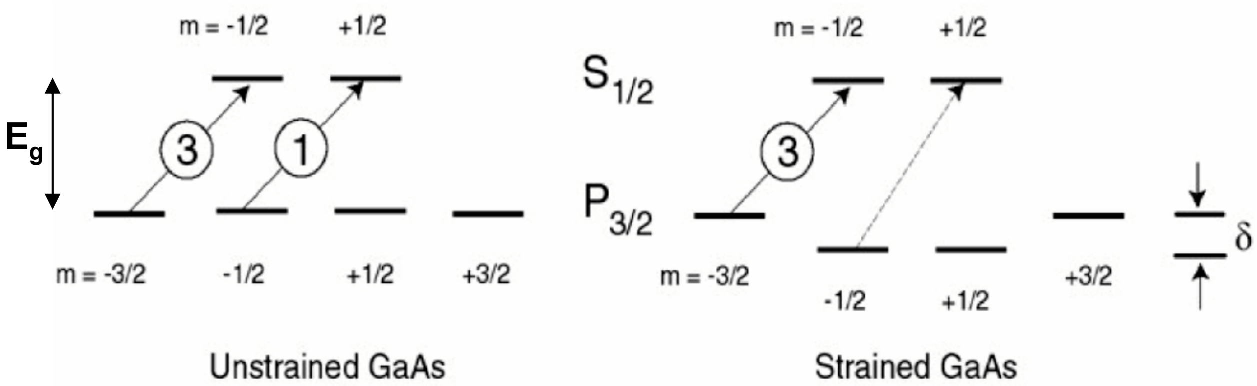


Improvement:
1. increase QE
2. increase polarization

Basics of polarized electron photocathode

Semiconductor: suitable material for polarized photocathodes

Non-zero transition matrix elements for semiconductors under circular-polarized light illumination



50% polarization **100% polarization**

Strained SL : highest polarization (HH-LH splitting further increased due to the quantum confinement by SL)

Initial polarization: $P_0 = (n_\uparrow - n_\downarrow)/(n_\uparrow + n_\downarrow)$

Why GaAsSb/AlGaAs SL?

Existing structures in literature

1. InGaAs/AlGaAs (strained well),70-80%, QE~0.7%
2. GaAs/GaAsP (strained well), 92%, measured, QE~1%
3. GaAs/AlInGaAs (strained barrier), 91%
4. AlInGaAs/GaAsP (strain-balanced), 84%
5. AlInGaAs/AlGaAs (strained well), 92% with QE~0.85%

} All HH-LH splittings<95meV

$GaAs/GaAs_{0.64}P_{0.36}$ SL:
Best overall performance thus far, HH-LH splitting δ~92 meV

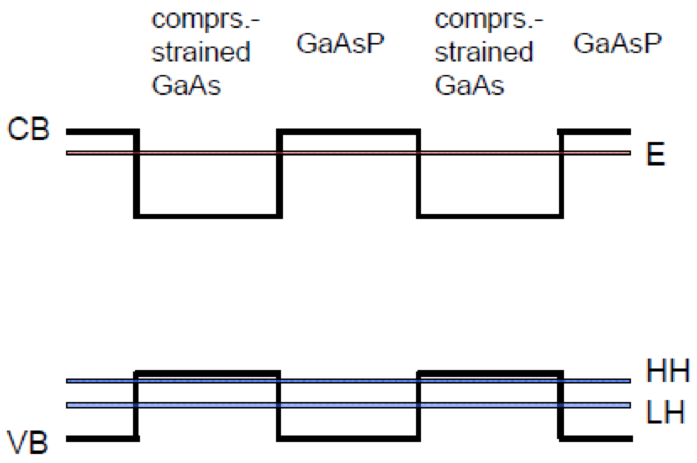
$GaAs_{0.85}Sb_{0.15}/Al_{0.4}Ga_{0.6}As$ SL:
•highest VB offset ⟹ Highest HH-LH splitting: δ~168 meV resulting in highest initial polarization and larger tolerance to γ
•Dislocation-free SL material since no strain relaxed layer required, boost QE
•No need to grow very thick metamorphic buffer (5-10 μm), cost-effective

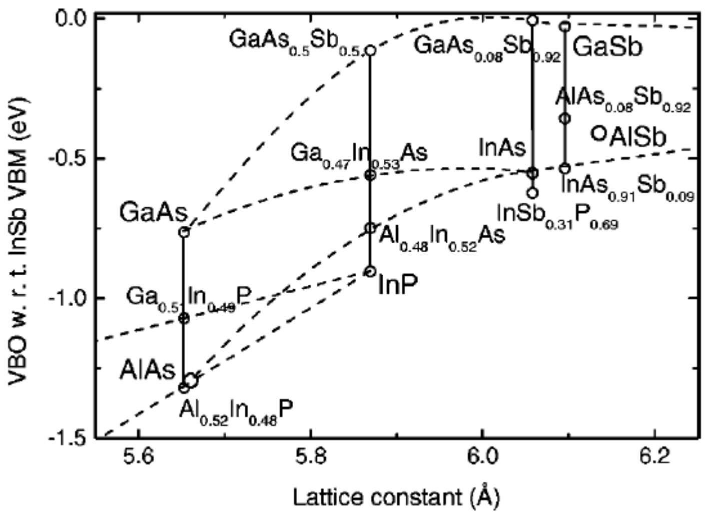
GaAsSb/AlGaAs SL Photocathode – High Polarization and High QE

SVT Associates, Inc.

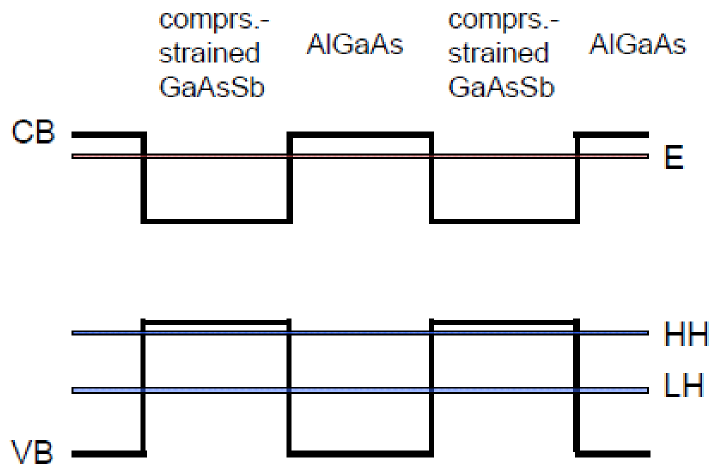
Very High VB offset in GaAsSb/AlGaAs Heterostructure

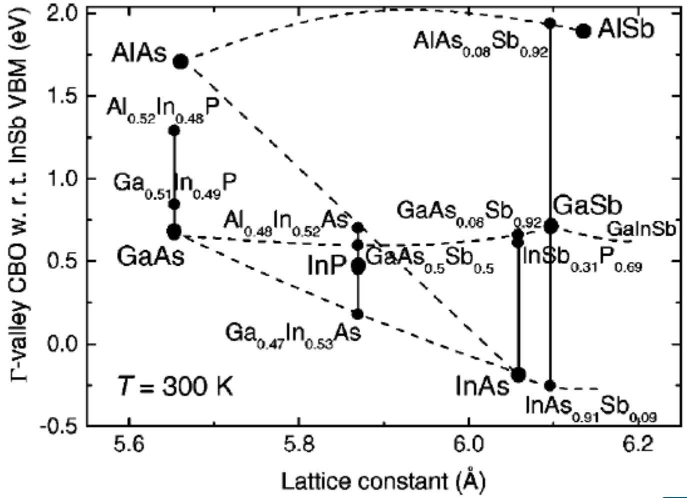
GaAs/GaAsP SL





GaAsSb/AlGaAs SL

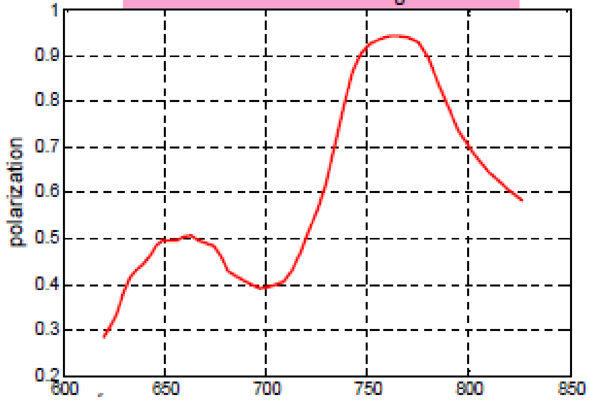




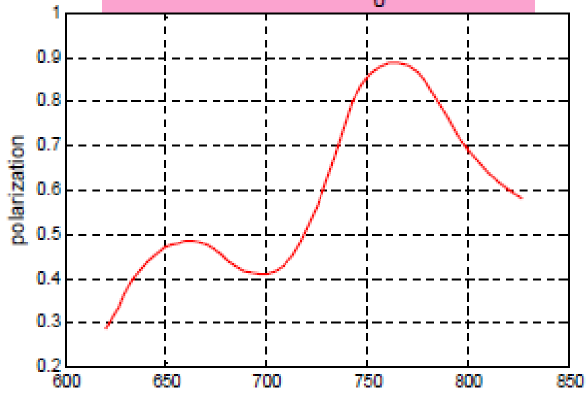
GaAsSb/AlGaAs SL: wider high P_0 range and larger tolerance to γ

$GaAs/GaAs_{0.64}P_{0.36}$ SL

Line width γ=10 meV,
Maximum initial P_0=95%

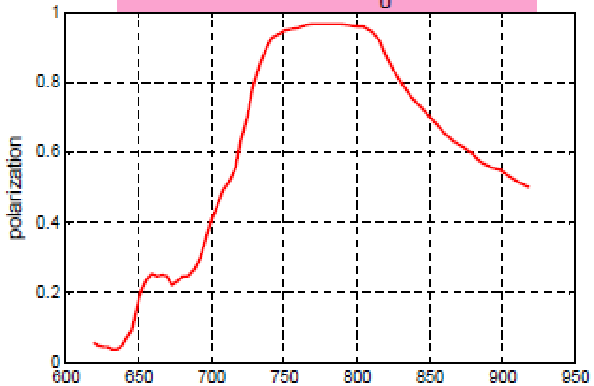


Line width γ=20 meV,
Maximum initial P_0=88.5%

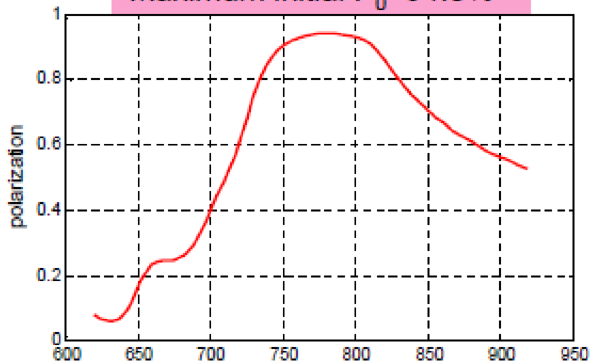


$GaAs_{0.85}Sb_{0.15}/AlGaAs$ SL

Line width γ=10 meV,
Maximum initial P_0=97.0%



Line width γ=20 meV,
Maximum initial P_0=94.0%

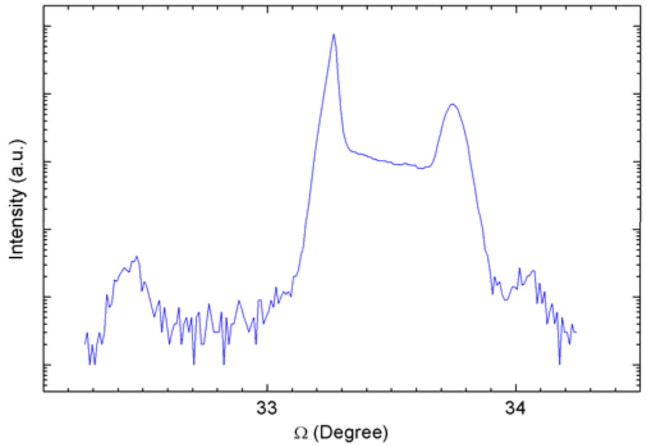


Broadening of band: $\delta(\omega_{nn'}(\vec{k}_\parallel,k_z)-\omega) \rightarrow \frac{1}{\pi}\mathrm{Im}\frac{1}{\omega-\omega_{nn'}(\vec{k}_\parallel,k_z)-i\gamma}$

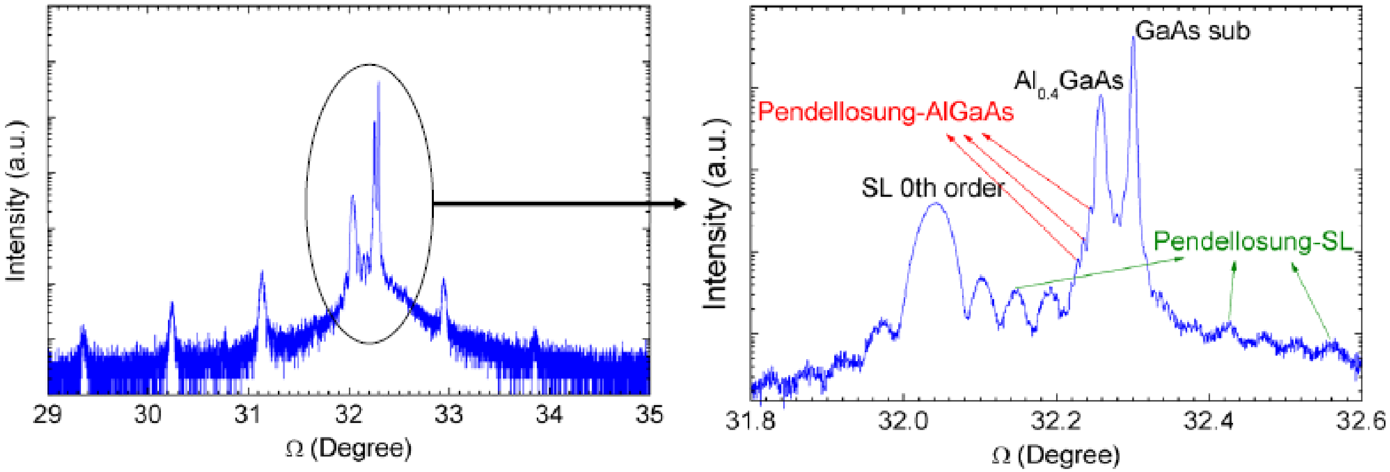
SVT Associates, Inc.

Much Better Crystalline Quality Material : GaAsSb/AlGaAs SL

Higher order satellite peaks and Pendellosung fringes observed indicate better quality SL materials.



(Left)
XRD rocking curve for GaAs/GaAsP SL on 5um GaAsP buffer grown on GaAs substrate.



XRD rocking curve for GaAsSb/AlGaAs SL grown on GaAs.

SVT Associates, Inc.

Engines for Thin Film Innovation

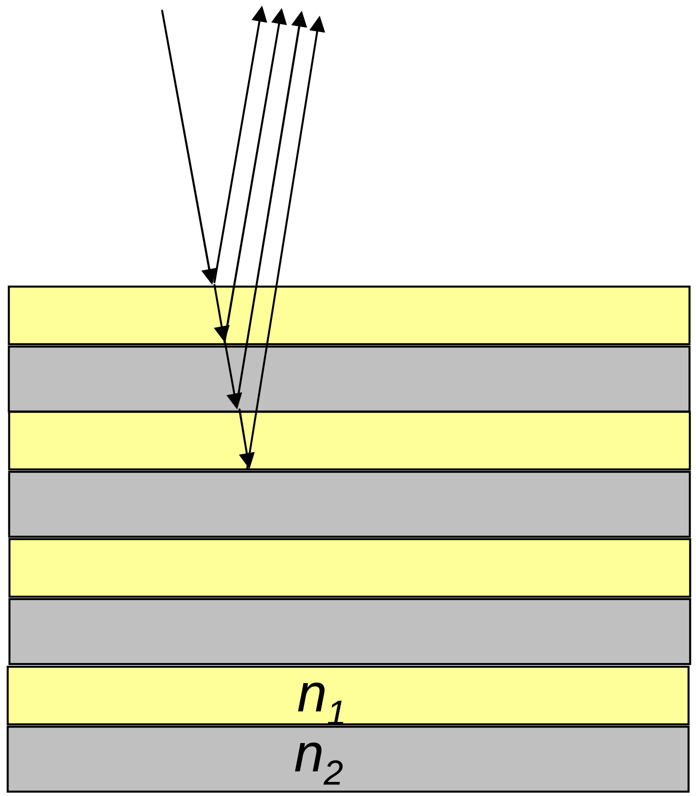
Distributed Bragg Reflector (DBR)

- Challenge of the epitaxial growth of high quality SL
- Slow transport of the photo-excited electrons
- The rapid spin relaxation

↓

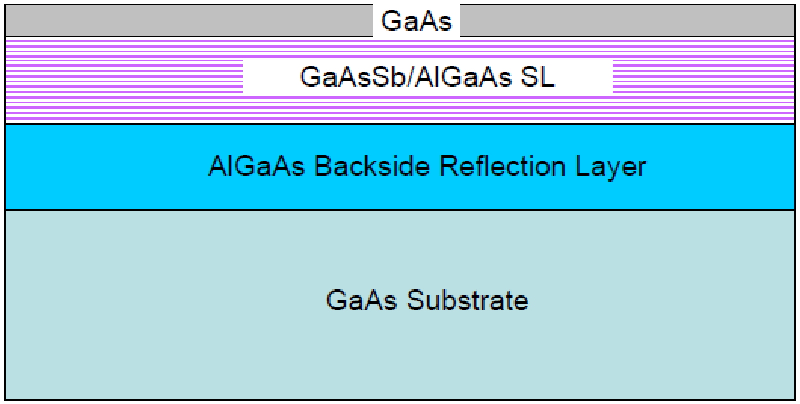
- The active layer of SL photocathode ~100 nm thick.
- Only a few percent of incident light absorbed at best.

$$R = \left[\frac{n_o(n_2)^{2N} - n_s(n_1)^{2N}}{n_o(n_2)^{2N} + n_s(n_1)^{2N}}\right]^2,$$

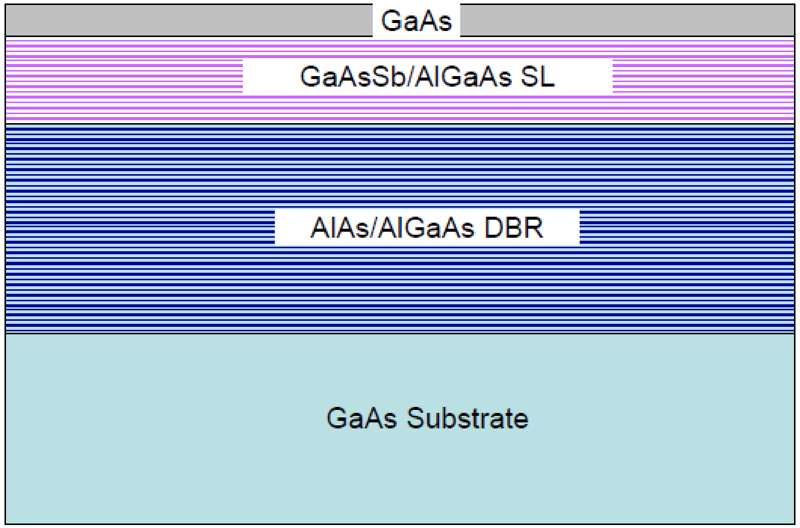


GaAsSb/AlGaAs SL Photocathode Wafer Structures

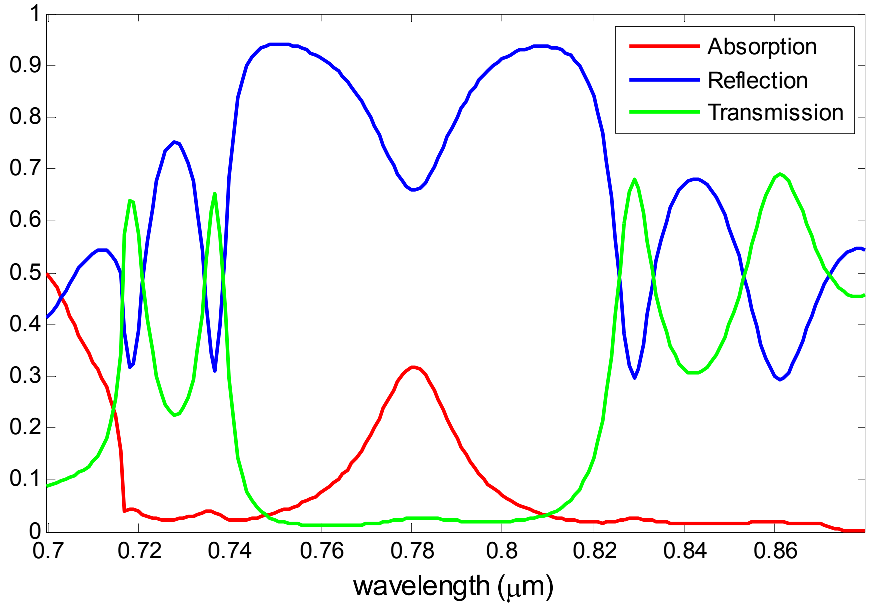
GaAsSb/AlGaAs SL photocathode w/o DBR



GaAsSb/AlGaAs SL photocathode w/ DBR



Absorption enhancement by DBR

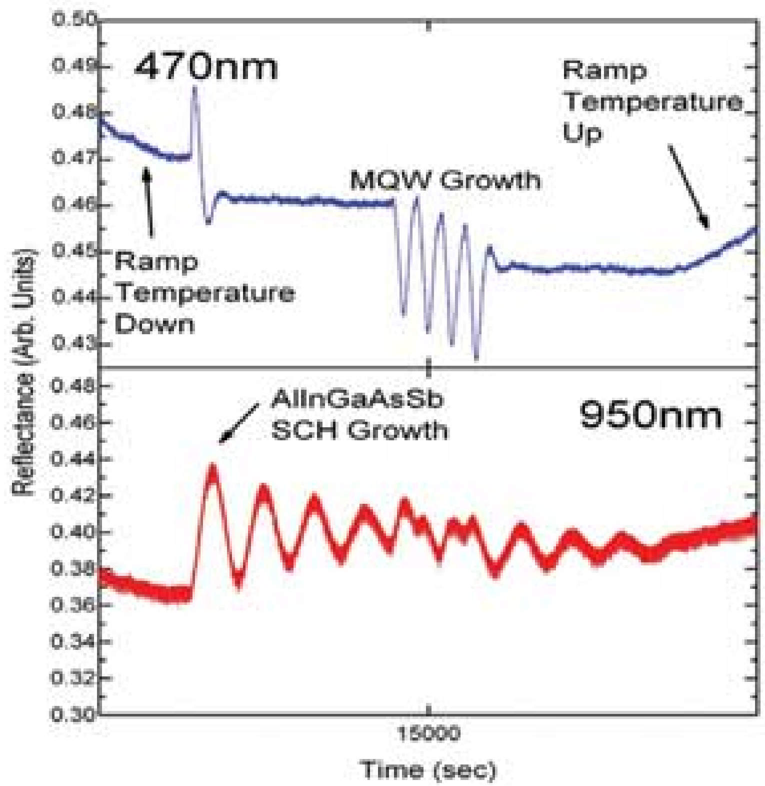


Absorption of the superlattice with DBR and Fabry-Perot cavity together with the surface reflection and transmission into GaAs substrate

Accurate Temperature Control for Mixed Group-V Materials

GaAsSb: As/Sb composition highly dependent on growth temperature

AccuTemp™ In-Situ 4000 Process Monitor

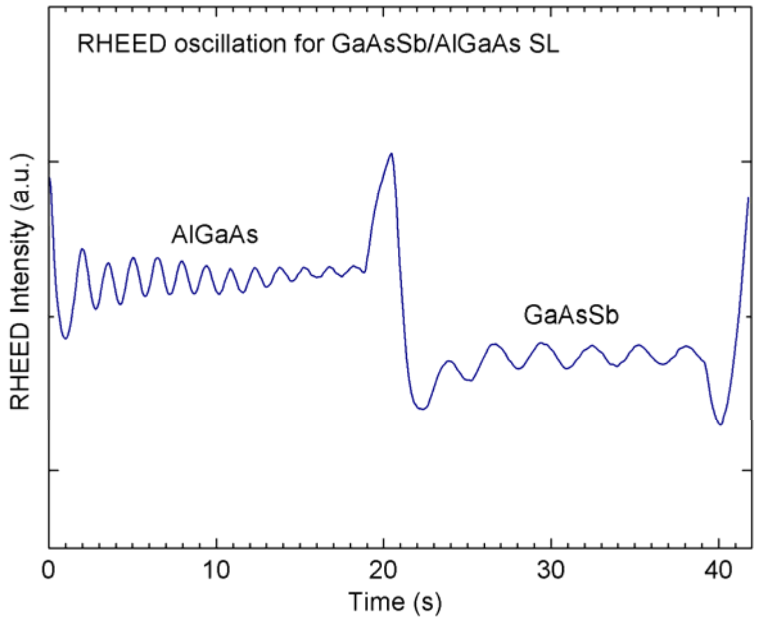


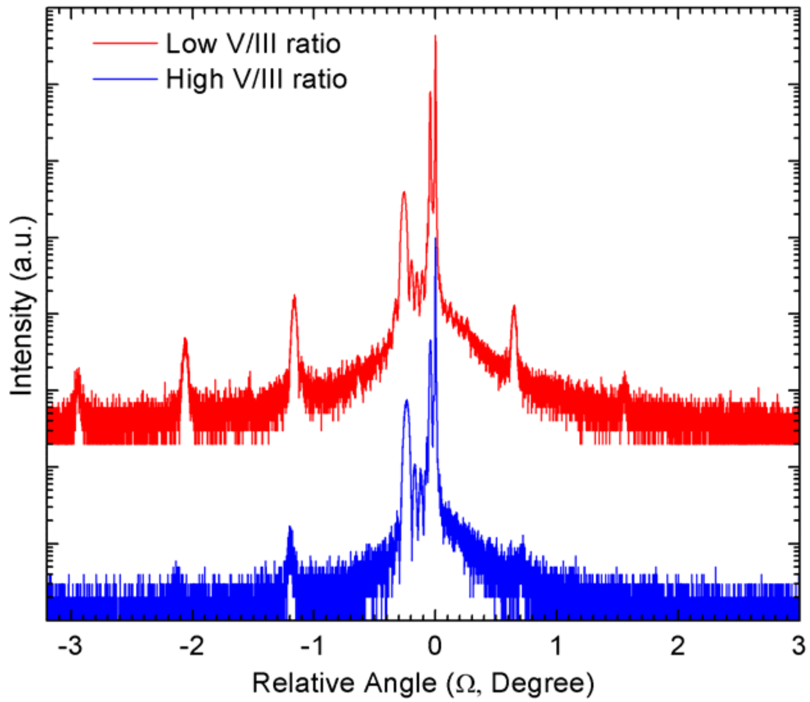
Temperature equivalent noise: <0.5C

Engines for Thin Film Innovation

High Quality GaAsSb/AlGaAs SL Grown by MBE

- Strong RHEED oscillations during whole process of MBE growth
- Up to 4th order satellite peaks observable in HRXRD rocking curves





SVT Associates, Inc.

Engines for Thin Film Innovation

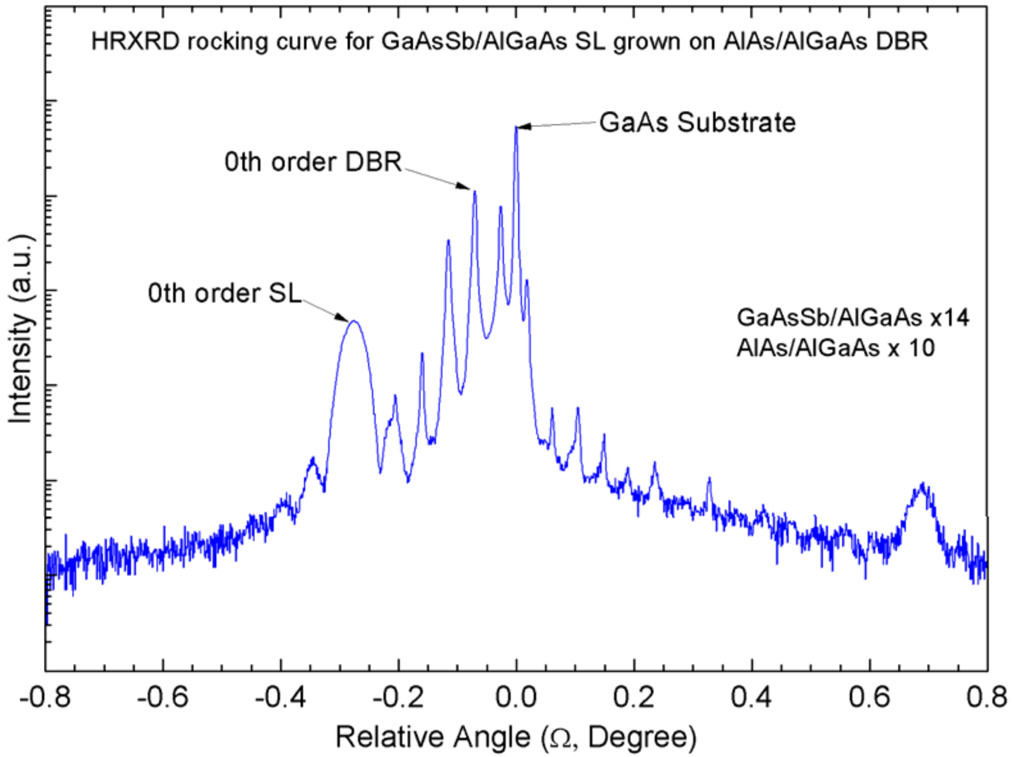
MBE Growth of AlAs/AlGaAs DBRs

Calibration of MBE growth of AlAs/AlGaAs DBR completed

Main challenge of growth of AlAs/AlGaAs DBR:

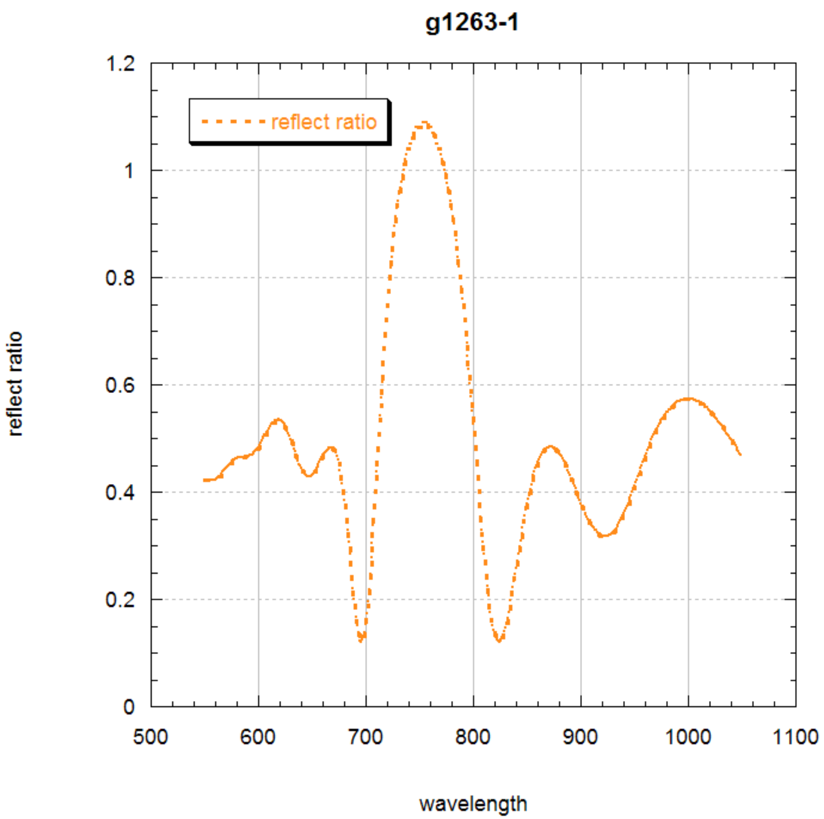
large growth temperature difference between AlAs (705 °C) and AlGaAs (615 °C).

A special recipe developed for MBE growth of AlAs/AlGaAs DBRs

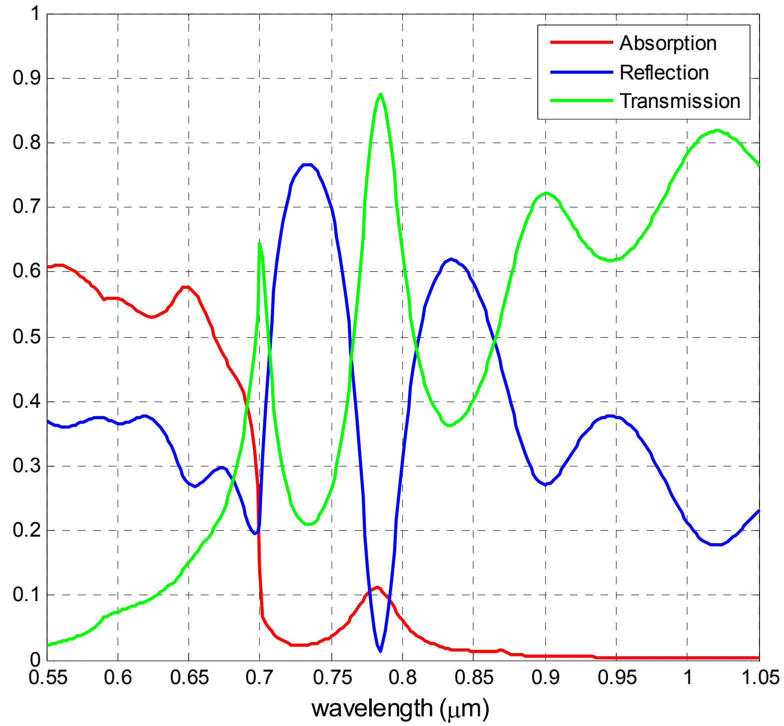


HRXRD rocking curve for $GaAs_{0.85}Sb_{0.15}/Al_{0.38}Ga_{0.62}As$ (x14) SL grown on $AlAs/Al_{0.25}Ga_{0.75}As$ (5.6nm/6.3nm x10) DBR on GaAs (100) substrate.

6-pair Al0.25GaAs/AlAs DBR



Measured surface reflection performed at SVT.

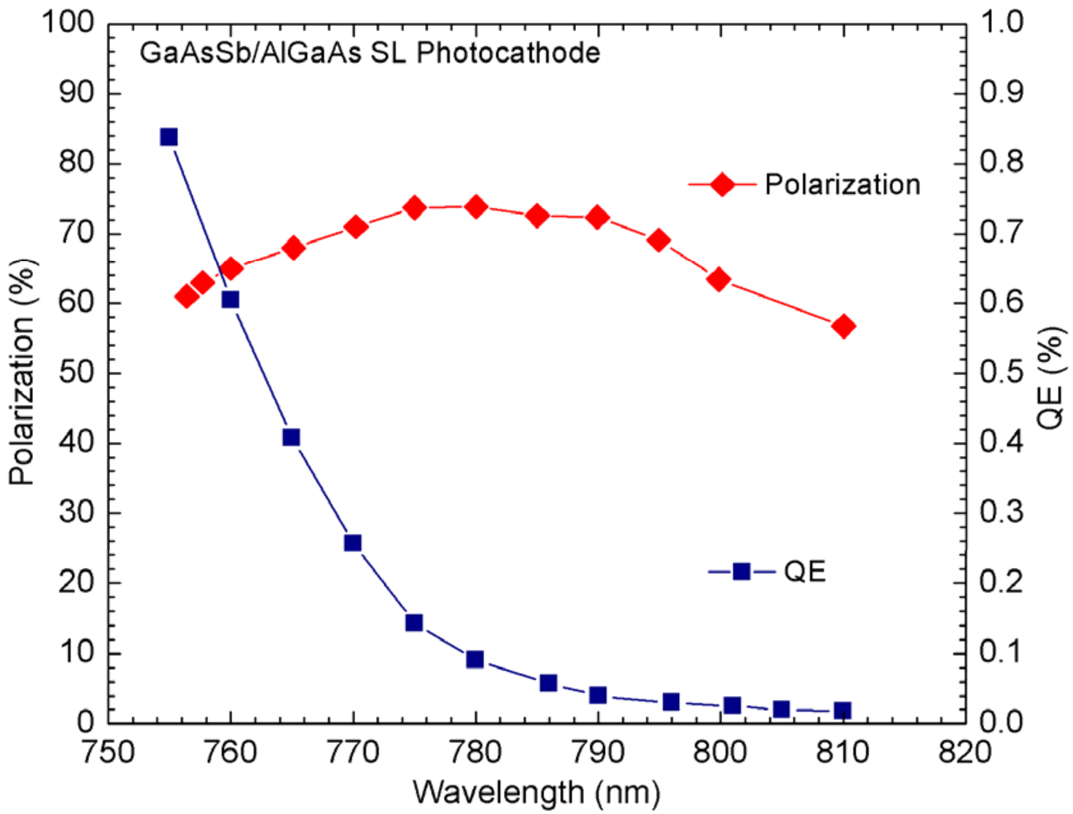


Modeling results of DBR with photocathode SL..

SVT Associates, Inc.

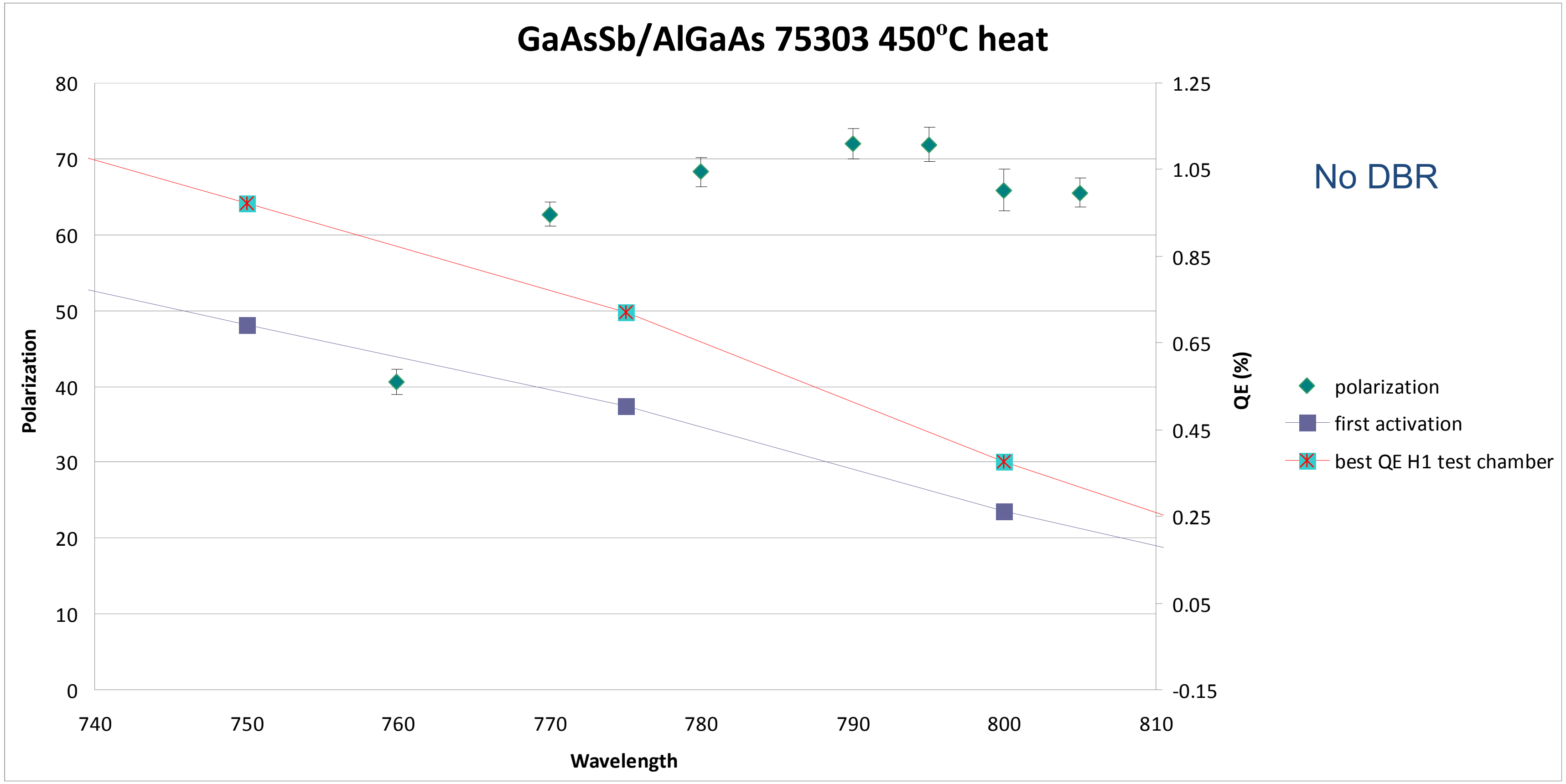
GaAsSb/AlGaAs SL Photocathode – Testing Results (1st batch)

- Up to 73% polarization achieved
- QE very low ~0.1%



Polarization and quantum efficiency for a fabricated GaAsSb/AlGaAs superlattice photocathode (w/o DBR).

GaAsSb/AlGaAs SL Photocathode – Testing Results (2nd batch)



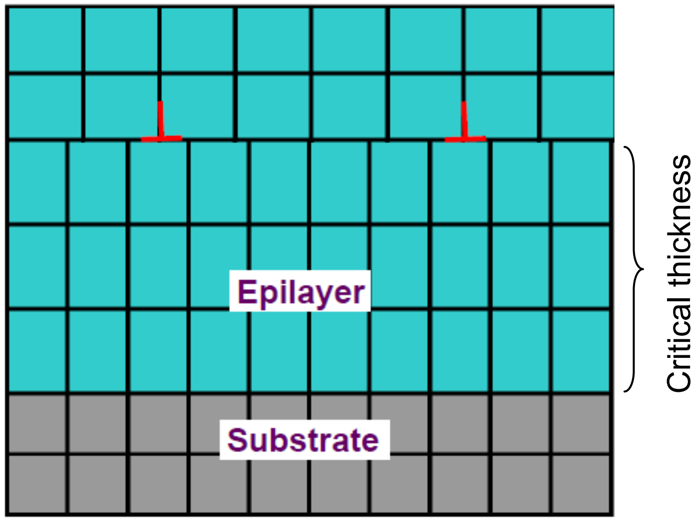
Better QE by improved As capping process.
The polarization is still below expected P_0.

Less Strain Tolerance for Antimonides

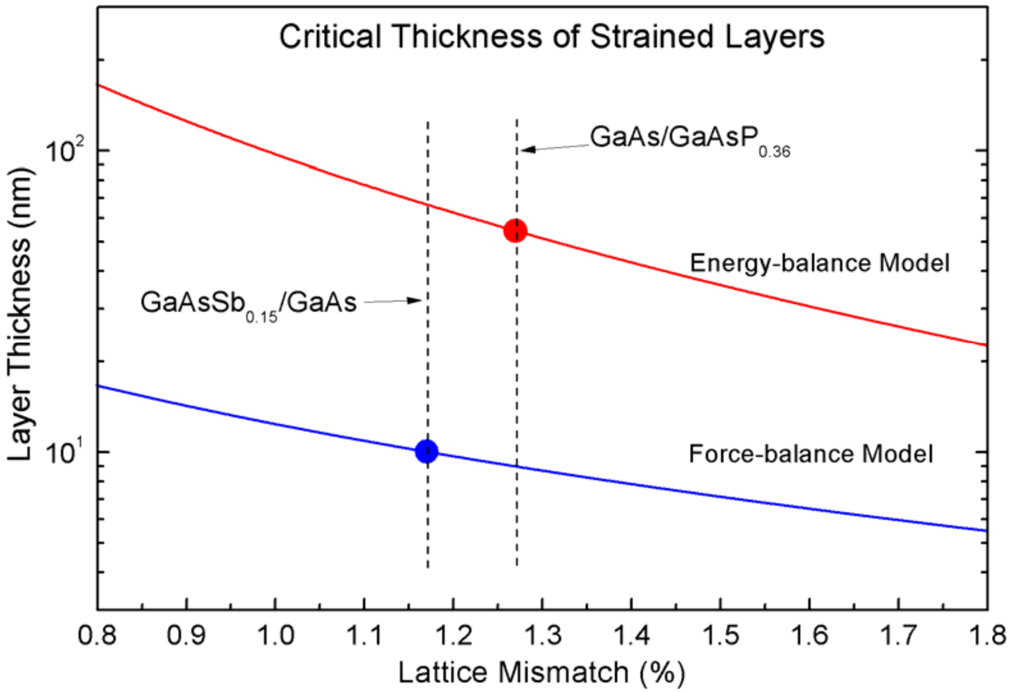
Strain Relaxation:

•Poor quality of single crystal material due to dislocations

•Loss of strain effect on bandstructure - low polarization



Compressively strained epilayers -> relaxed layers

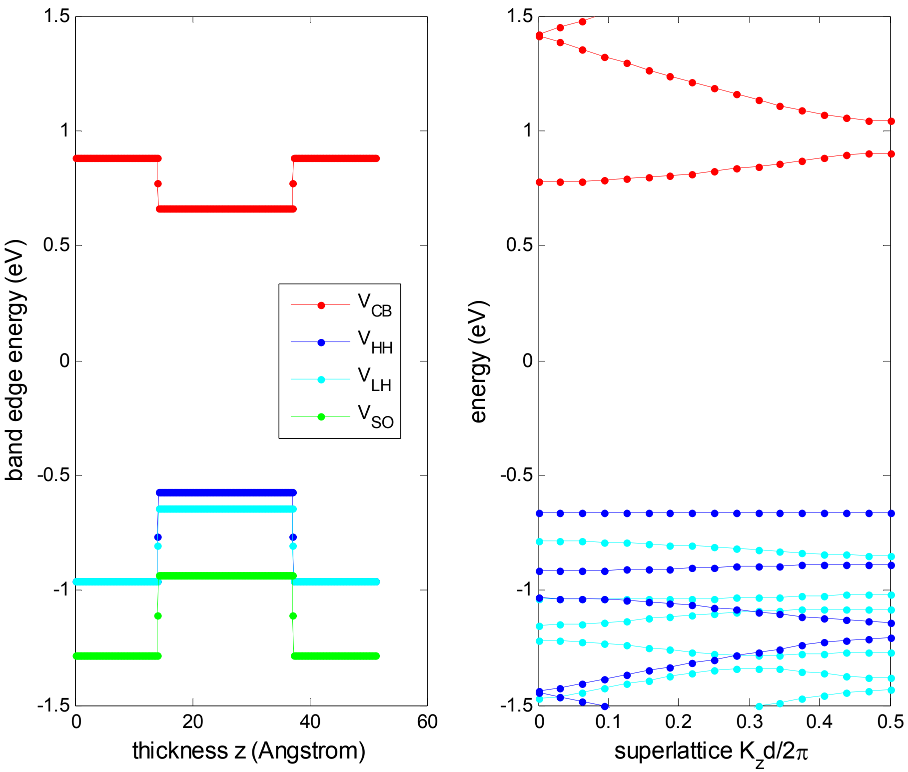


Modified GaAsSb/AlGaAs SL

- **Remove strain relaxation**
  1. More detailed analysis on GaAsSb/AlGaAs SL (Strain relaxation percentage, XRD reciprocal space mapping)
  2. Lower Sb composition in SL
- **Minimize transport loss**
  1. Thinner AlGaAs barrier and lower Al composition
  2. Further improvement of material quality
- **Reduce spin relaxation**
  Lower Sb and Al composition

Modified SL design (right)
Initial polarization:
~96% @ γ=10 meV
~93% @ γ=20 meV

$GaAsSb_{0.10}/Al_{0.30}GaAs$, 8-10 ML



HH-LH splitting = 123.56 meV
me* = 0.0755, electron mobility 3845.54

Summary

Progress

- SL structure design and DBR design completed.
- Two batch of GaAsSb/AlGaAs SL photocathode grown, fabricated, and tested.
- New GaAsSb/AlGaAs SL structure designed.
- Calibration of modified GaAsSb/AlGaAs SL completed
- Delay due to cryo-shroud leakage; leakage fixed and maintenance completed.

Next step

- Optimization of MBE growth of GaAsSb/AlGaAs SLs
- MBE growth and optical testing of DBRs
- MBE growth of GaAsSb/AlGaAs SL photocathodes
- Device fabrication and testing (JLab)