GaAsSb/AlGaAs Superlattice High-Polarization Electron Source

Contract # DE-SC0007501

Principal Investigator: Yiqiao Chen, SVT Associates, MN 55344

Subcontractor: DoE Jefferson Lab (Matt Poelker)

DoE SBIR/STTR Exchange Meeting

Aug 6-7, 2014, Washington D.C.

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 (Over 25 MBE Systems in Asia)

- Strong UHV hardware, epitaxial growth, and thin film expertise
- Technology Driven Company
  - >30% employees are PhD scientists (currently 35 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

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SVT Facilities and Capabilities

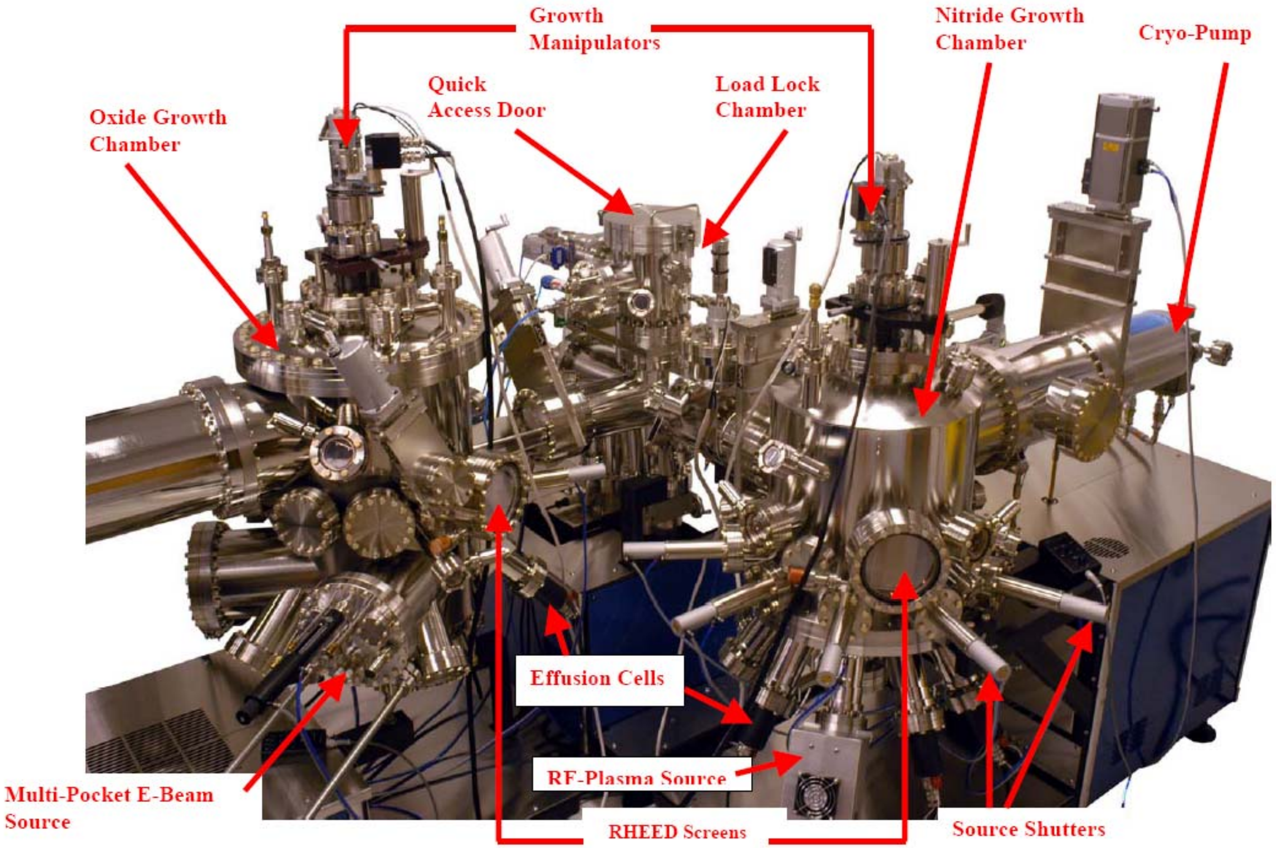
- Material deposition systems: MBE PLD, ALD

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

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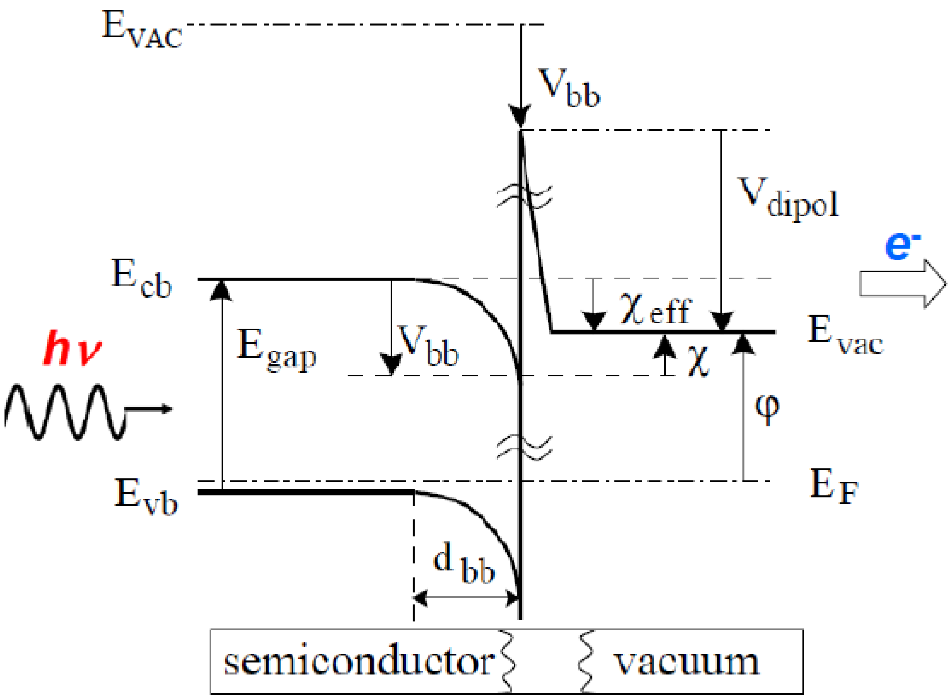
Photocathode - General Properties

Photons → free electrons in vacuum

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



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

Improvement:
1. increase QE
2. increase polarization

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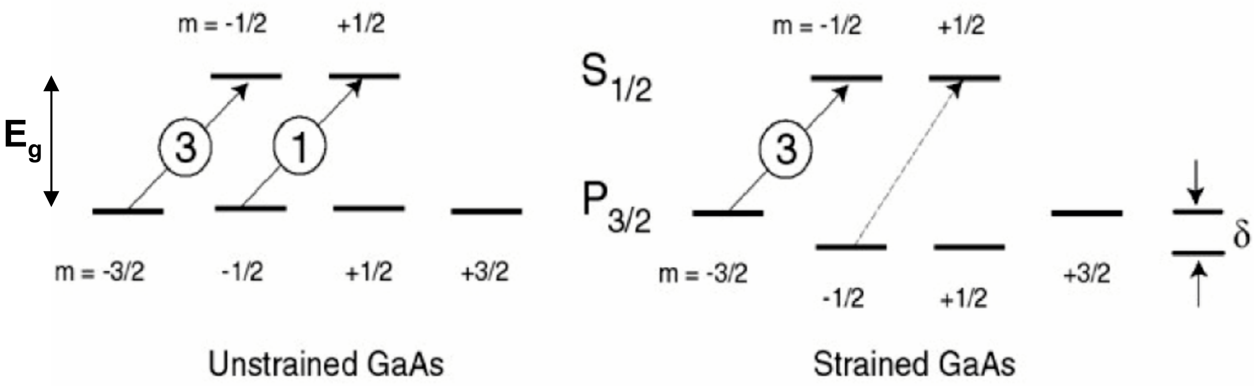
Basics of polarized electron photocathode

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

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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

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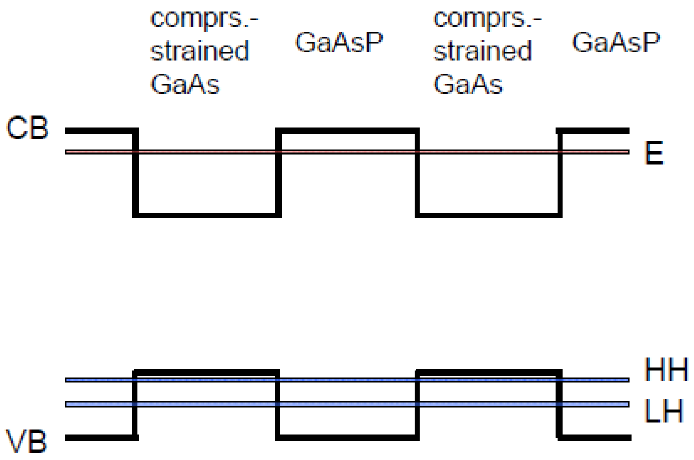
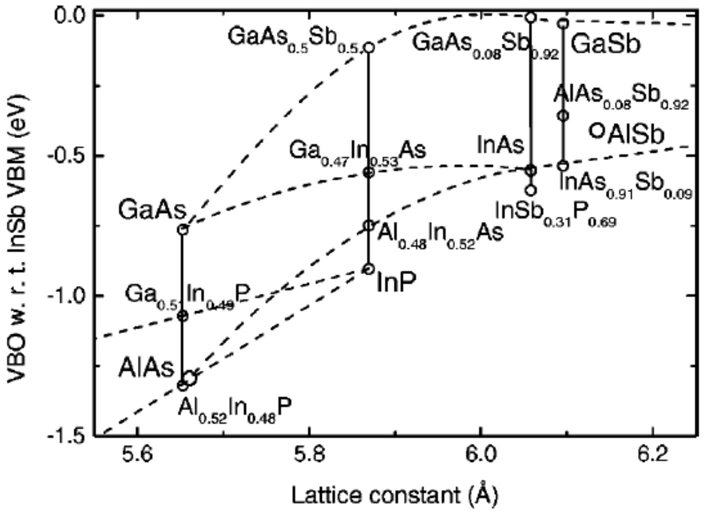
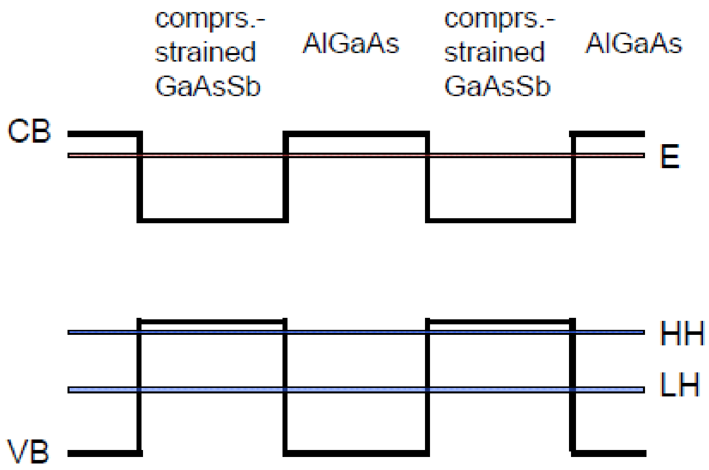
Very High VB offset in GaAsSb/AlGaAs Heterostructure

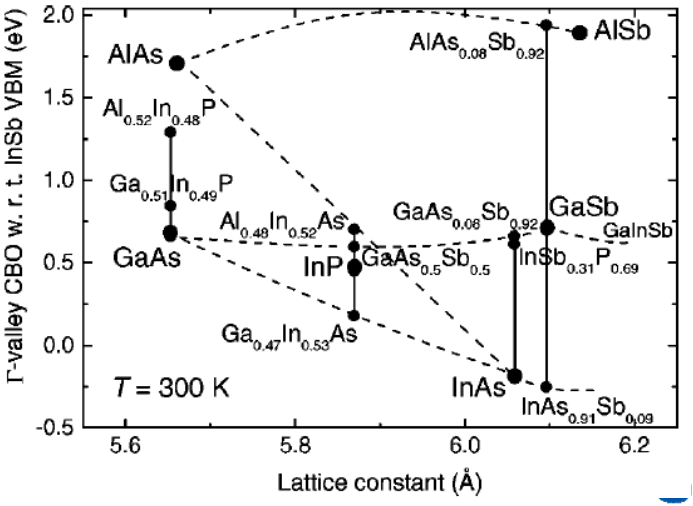
GaAs/GaAsP SL





GaAsSb/AlGaAs SL

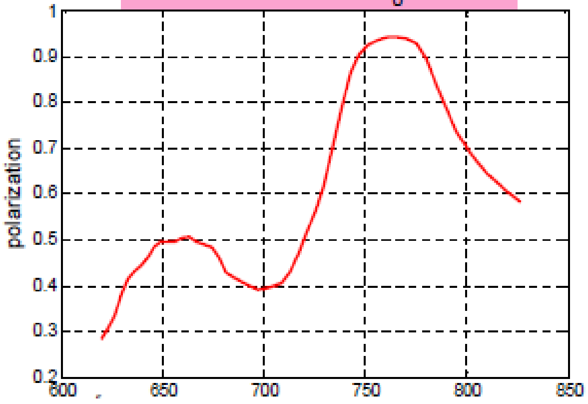




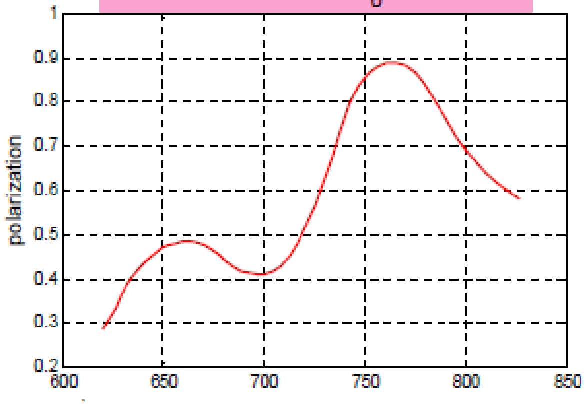
GaAsSb/AlGaAs SL: wider high P_0 range and larger tolerance to γ

GaAs/GaAs$_{0.64}$P$_{0.36}$ SL

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

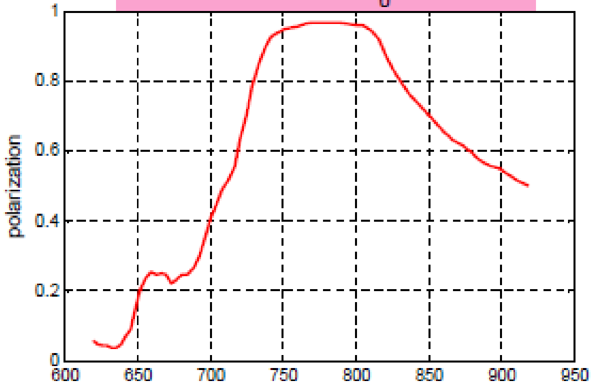


Line width γ=20 meV,
Maximum initial P_0=88.5%

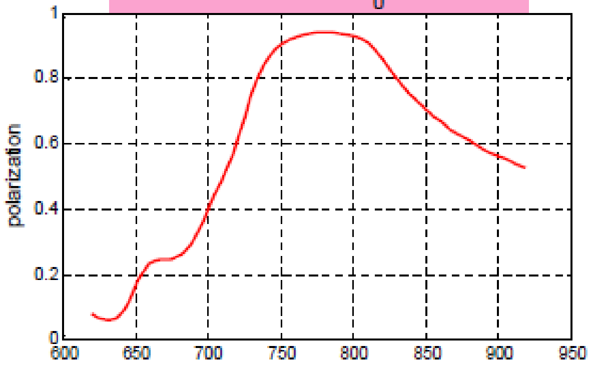


GaAs$_{0.85}$Sb$_{0.15}$/AlGaAs SL

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



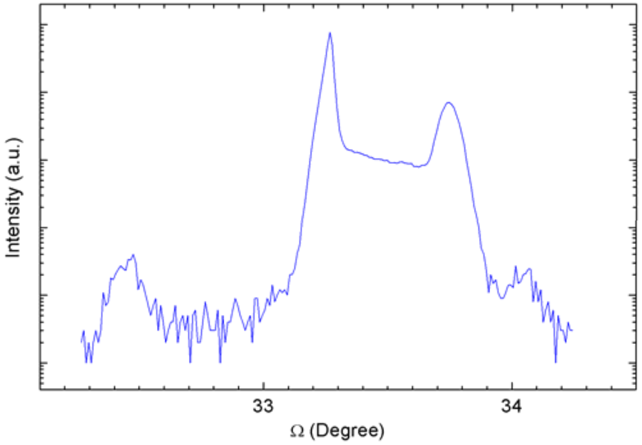
Line width γ=20 meV,
Maximum initial P_0=94.0%



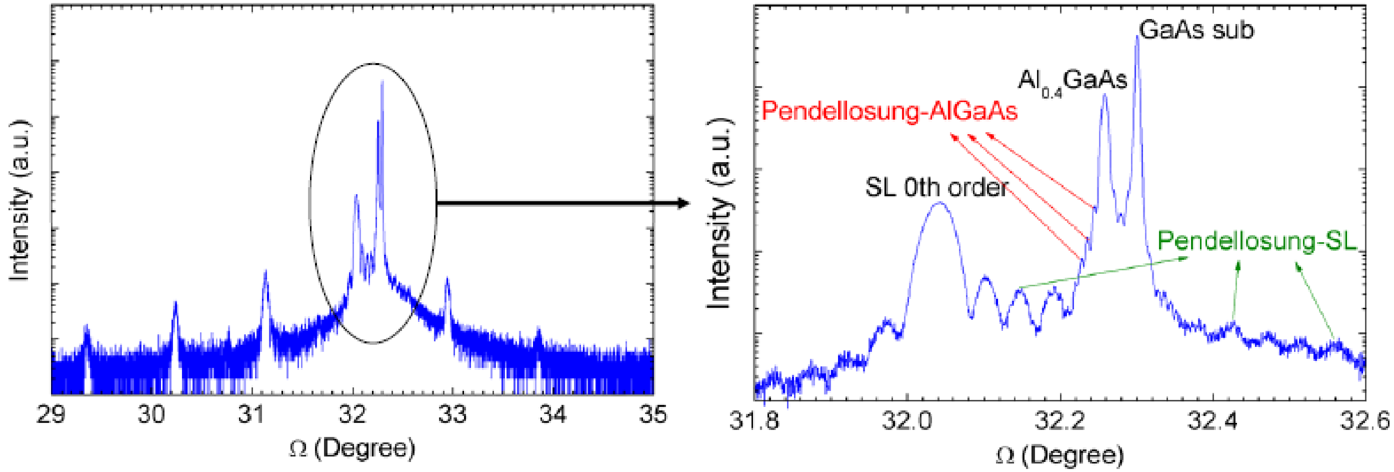
Broadening of band: $$\delta(\omega_{nn'}(\vec{k}_{\parallel},k_z)-\omega)\rightarrow\frac{1}{\pi}\mathrm{Im}\frac{1}{\omega-\omega_{nn'}(\vec{k}_{\parallel},k_z)-i\gamma}$$

Much Better Crystalline Quality Material : GaAsSb/AlGaAs SL

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

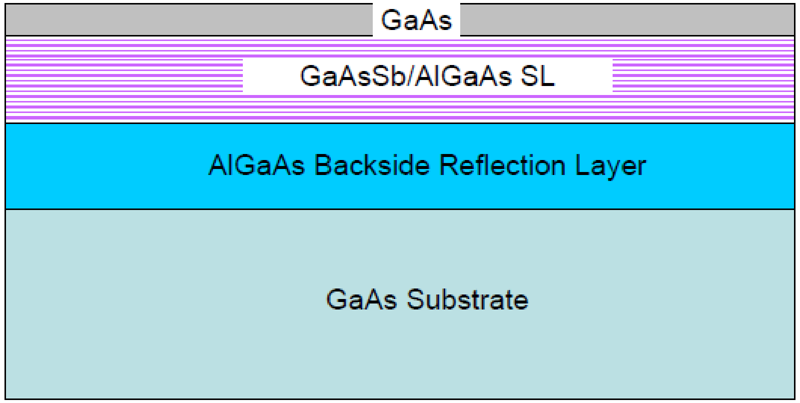


(Left)
XRD rocking curve for GaAs/GaAsP SL on 5um GaAsP buffer grown on GaAs substrate.

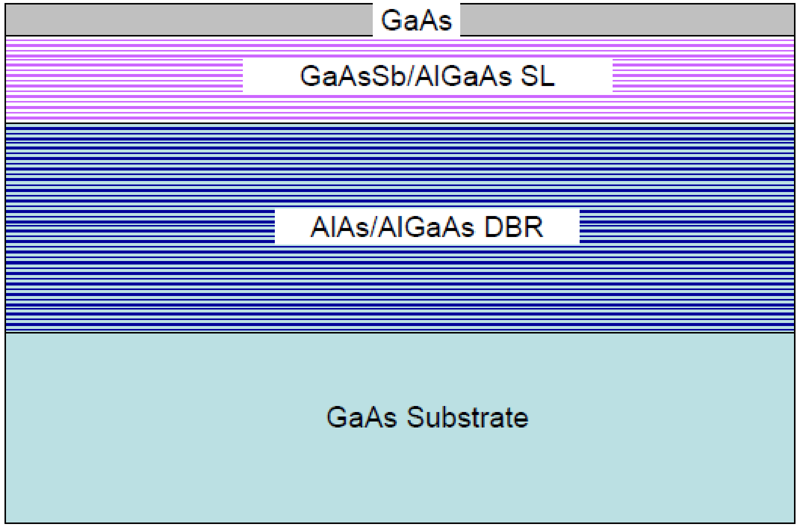


XRD rocking curve for GaAsSb/AlGaAs SL grown on GaAs.

GaAsSb/AlGaAs SL Photocathode Wafer Structures



GaAsSb/AlGaAs SL photocathode w/o DBR



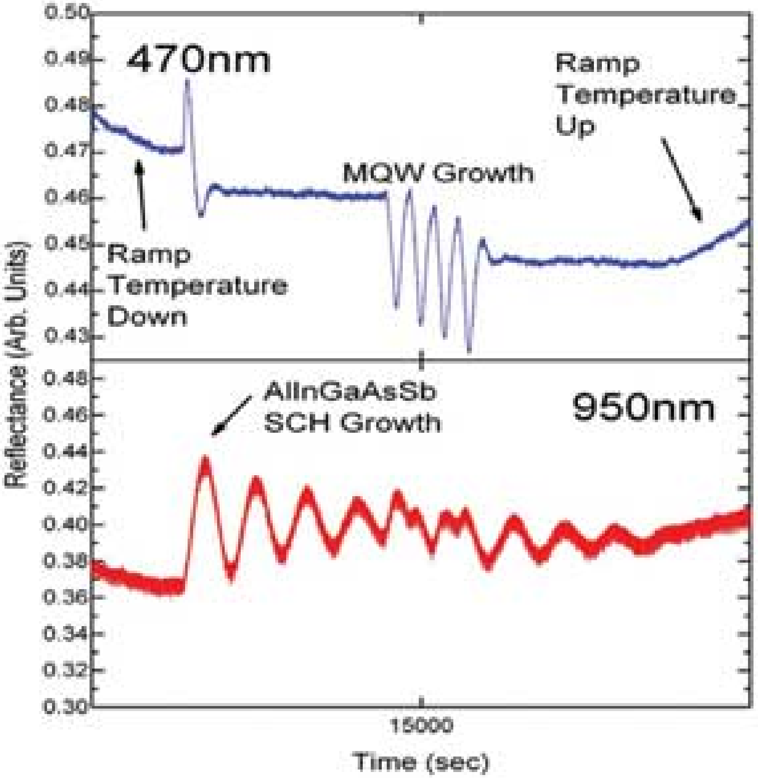
GaAsSb/AlGaAs SL photocathode w/ DBR

Accurate Temperature Control for Mixed Group-V Materials

GaAsSb: As/Sb composition highly dependent on growth temperature

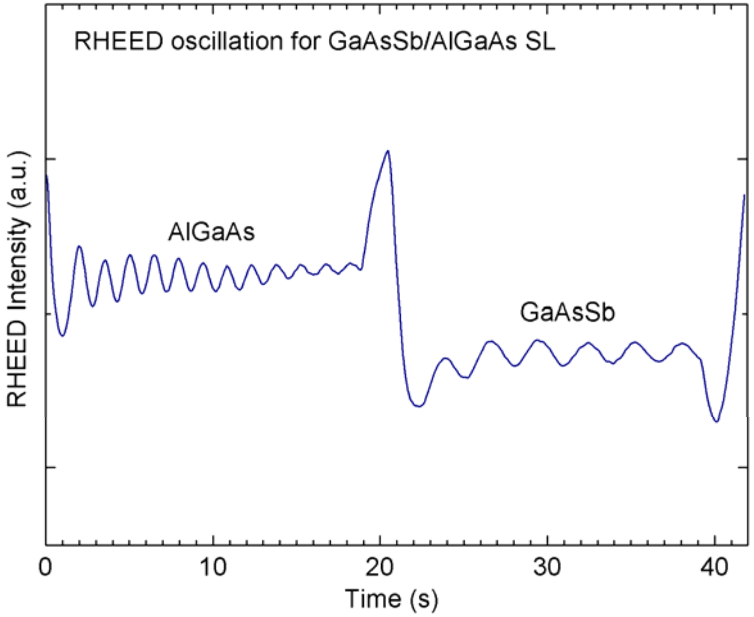
AccuTemp™ In-Situ 4000 Process Monitor

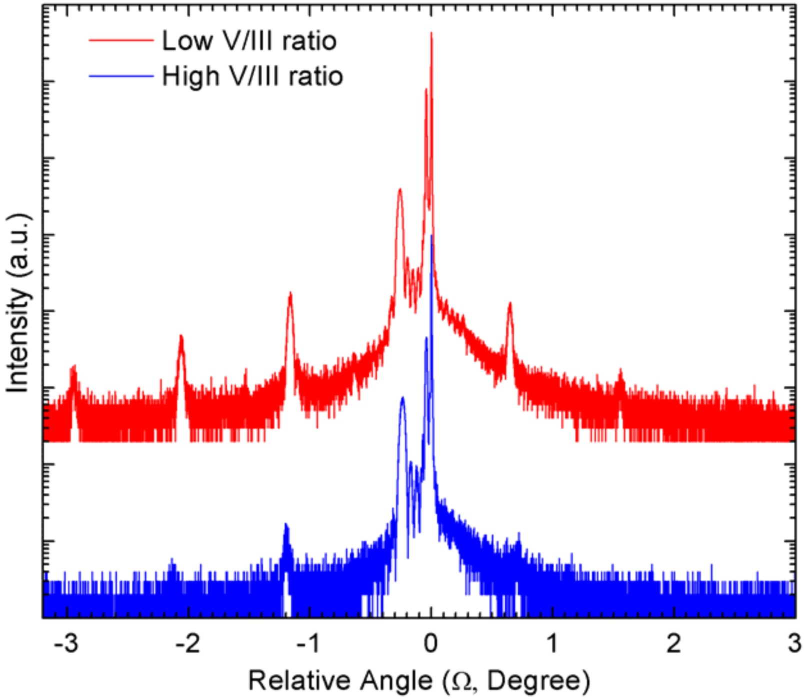
Temperature equivalent noise: <0.5C



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





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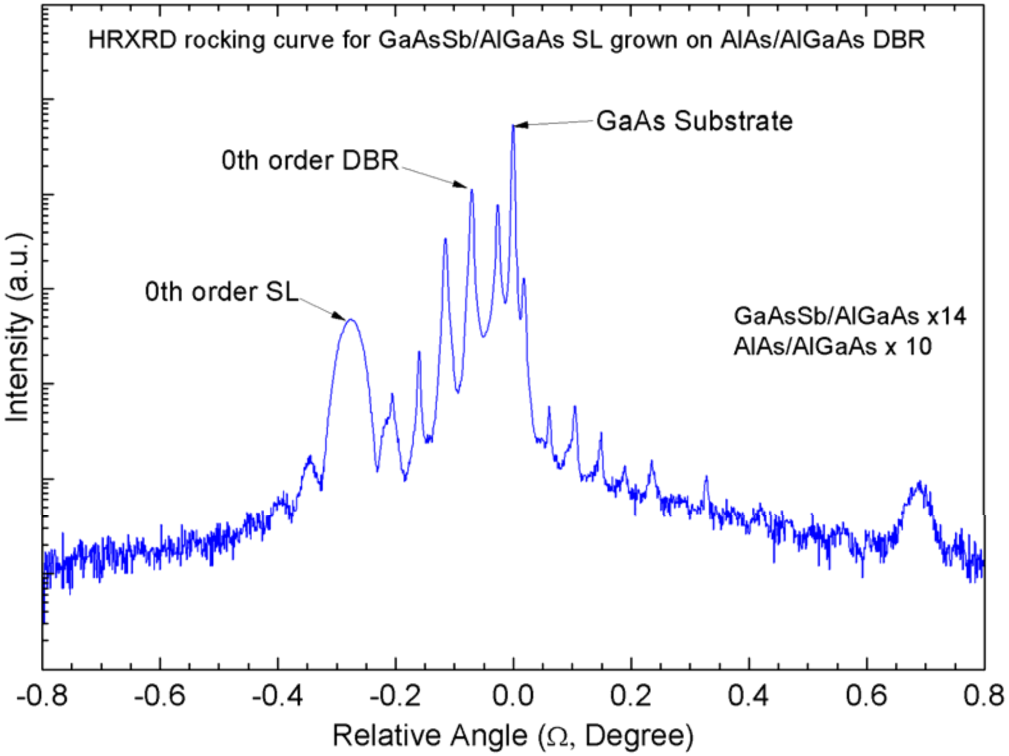
MBE Growth of AlAs/AlGaAs DBRs

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).

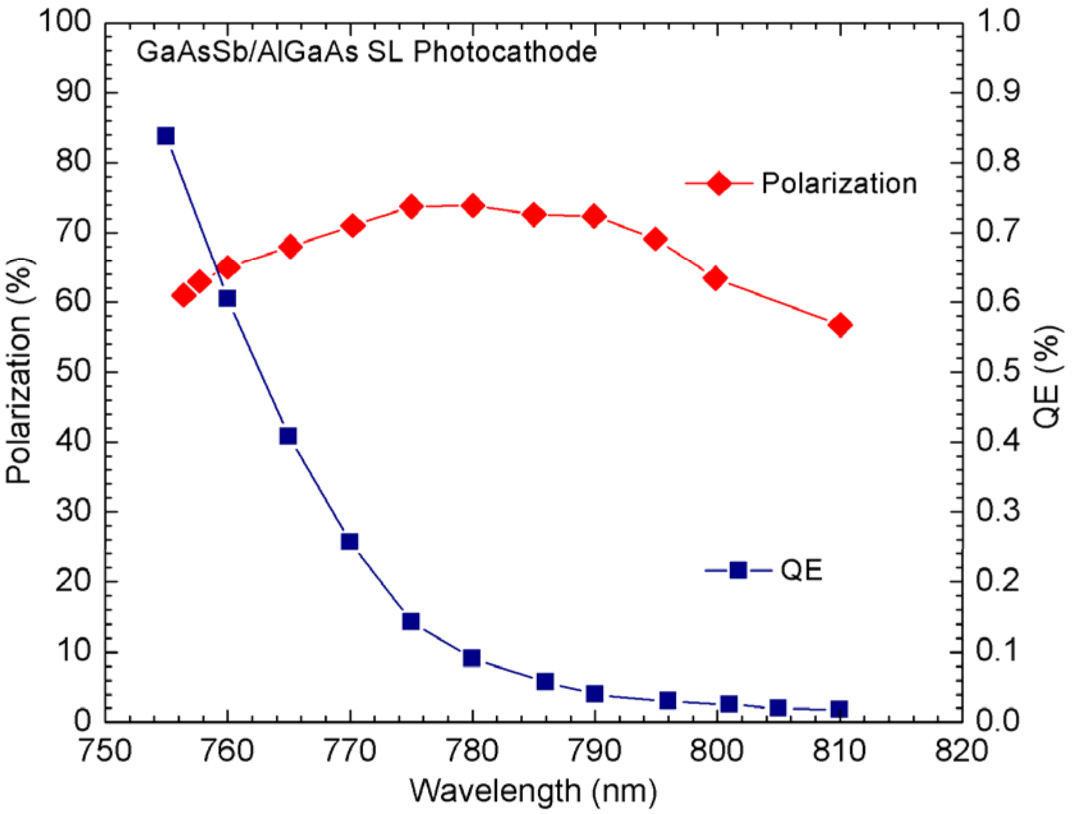
A special recipe developed for MBE growth of AlAs/AlGaAs DBRs



HRXRD rocking curve for GaAs0.$_{85}$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.

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).

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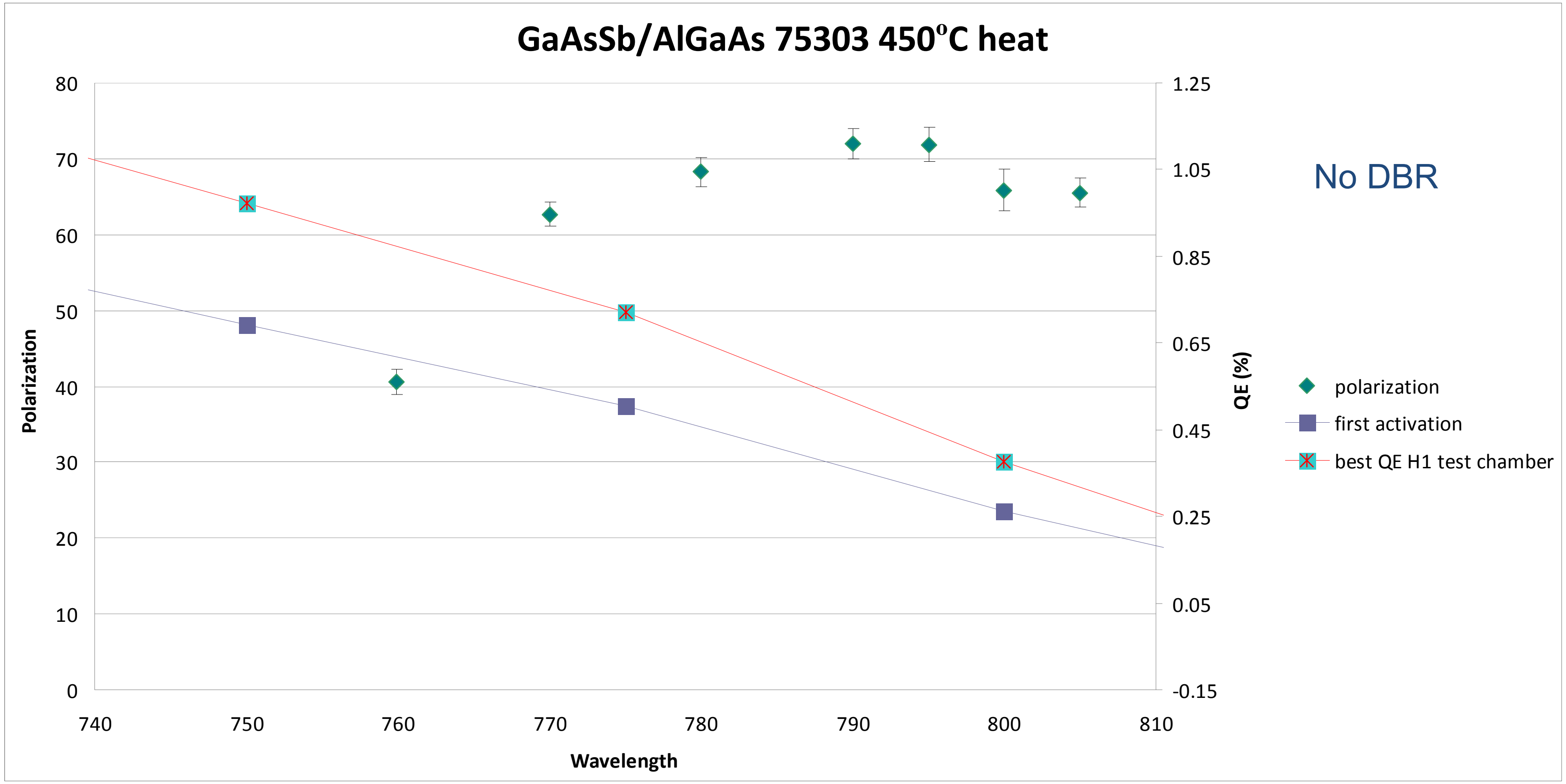
GaAsSb/AlGaAs SL Photocathode – Testing Results (2nd batch)



Better QE by improved As capping process.
The polarization is still below expected P_0. What’s the reason?

Possible Reasons for Low Polarization

Strain relaxation, transport loss, and spin relaxation

$$P = P_0 B_s \frac{\tau_s}{\tau_s + \tau_t}$$

Surface loss

Transport loss

τ_s: spin relaxation time, τ_t : the transport time.

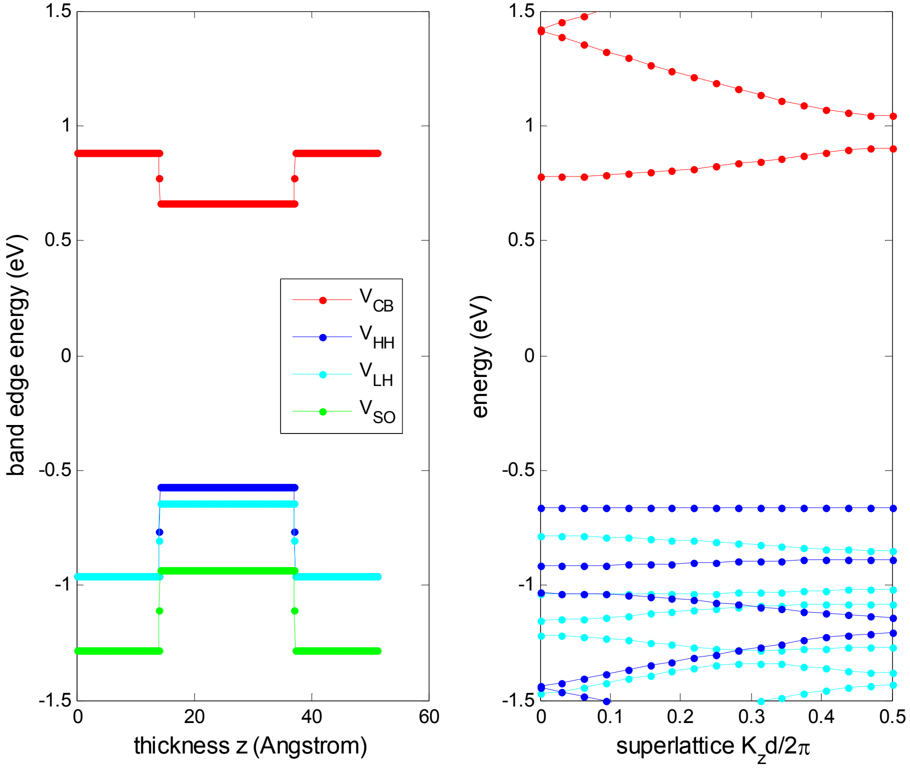
- Some SL layer might start to relax, especially the very top layers
- AlGaAs barrier might be too thick, resulting in lower electron mobility and shorter carrier lifetime
- Spin relaxation time in GaSb (~ 1ps) is shorter than that in GaAs (>7 ps)

Next Step

- **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=10 meV

GaAsSb0.12/Al0.30GaAs, 8-10 ML



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

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