GaAsSb/AlGaAsP Superlattice Polarized Electron Source

Contract # DE-SC0009516

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DoE SBIR/STTR Exchange Meeting

8/10/2016, Gaithersburg, Maryland

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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 Facilities and Capabilities

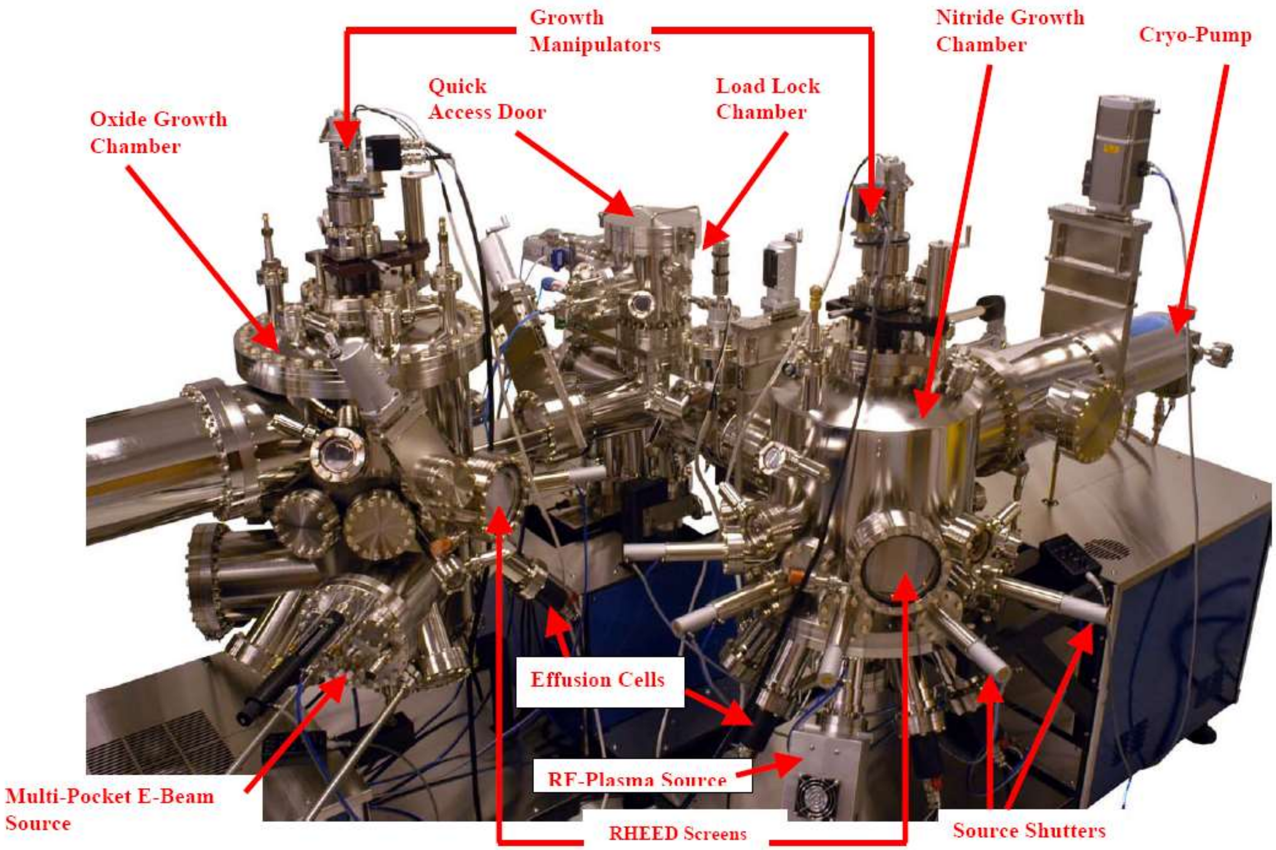
•Material deposition systems: MBE PLD, ALD, PECVD, ICP

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



Dual Oxide - Nitride MBE

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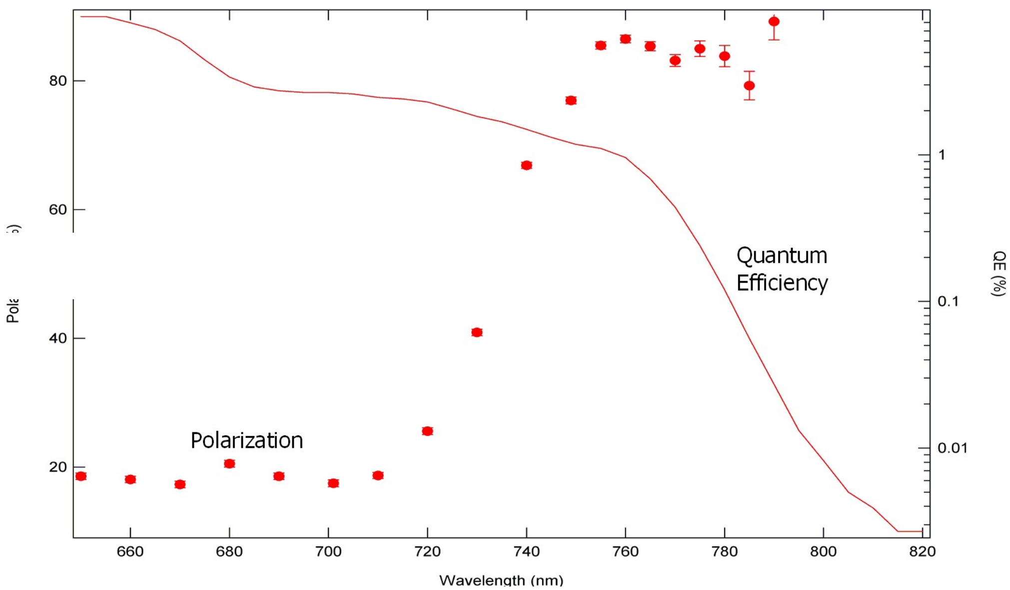
Engines for Thin Film Innovation

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

Polarized Photocathode

- More than10 year R&D on polarized photocathode
- Dedicated MBE system for material growth of polarized photocathode, equipped with As,P, crackers
- Over 90% polarization with 1% QE achieved by previous SBIR programs and collaborations with DoE labs (JLab, SLAC, and BNL)



Program Overview

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

Ultimate goal:

cw polarized electron sources with >85% 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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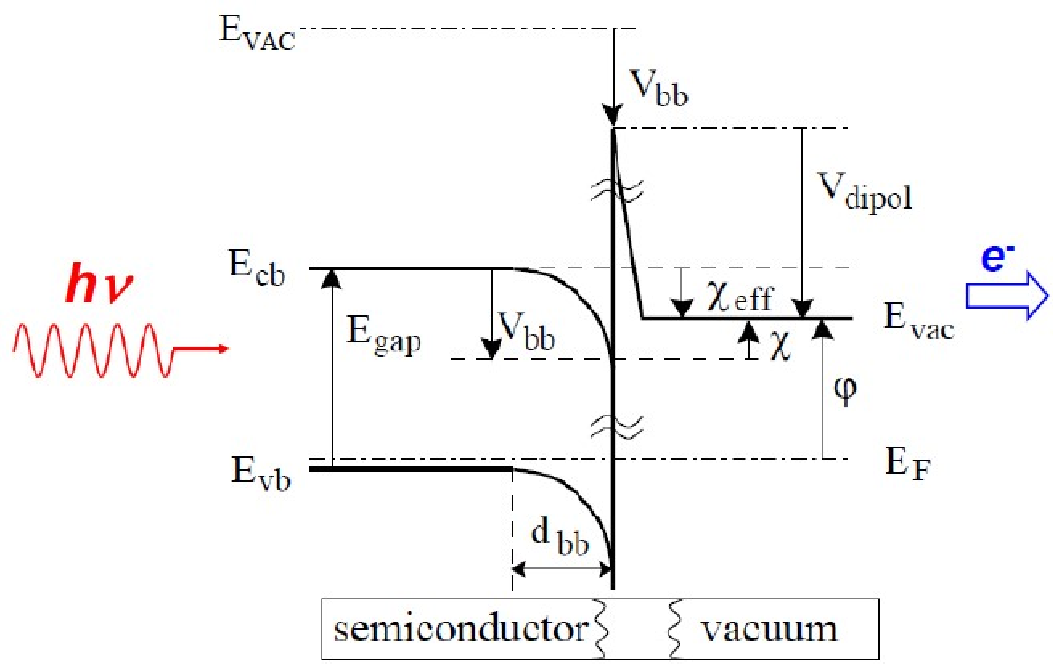
Photocathode - General Properties

Photons → free electrons in vacuum

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



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

Improvement:
1. increase QE
2. increase polarization

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Why Sb-based SL?

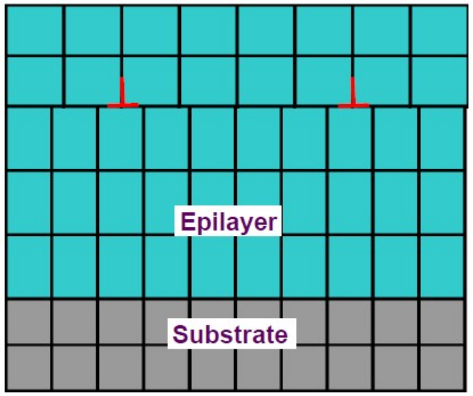
Existing structures in literature

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

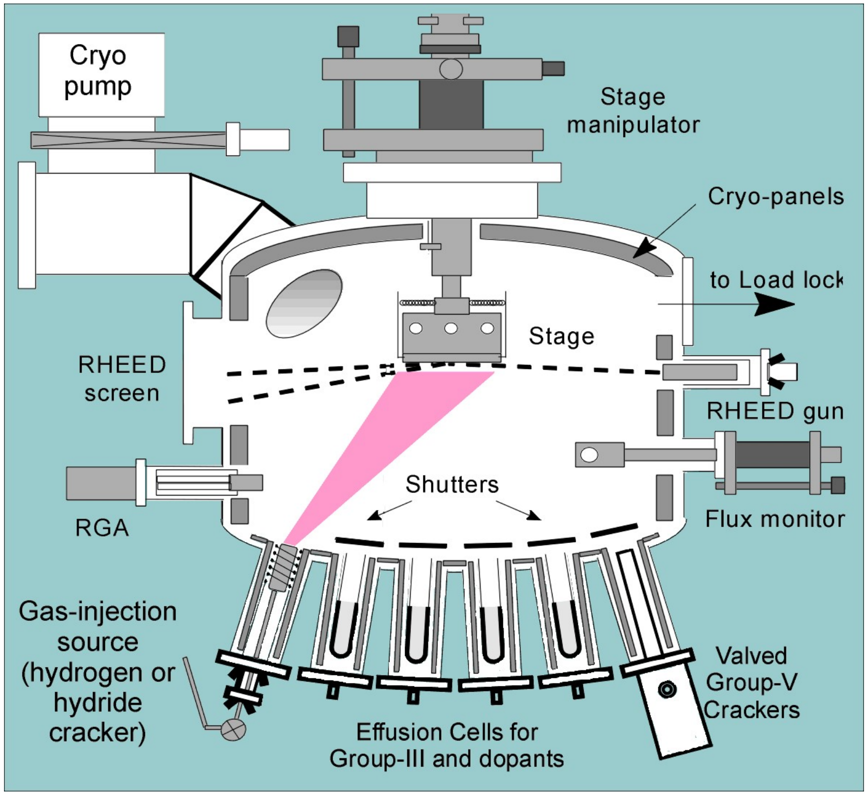
$GaAs_{0.85}Sb_{0.15}/Al_{0.25}GaAsP_{0.15}$ SL:
•highest VB offset ⟹ Highest HH-LH splitting: δ>150 meV resulting in highest initial polarization
•Dislocation-free SL material since no strain relaxed layer required, boost QE
•No need to grow very thick metamorphic buffer (5-10 μm), cost-effective

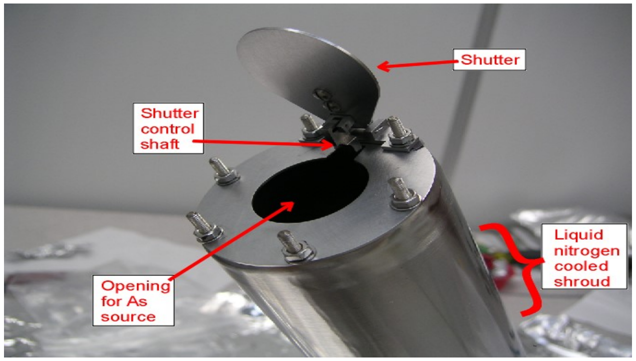


GaAsSb/AlGaAsP SL Photocathode – High Polarization and High QE

Cooled shutter for As/P/Sb material system

•As and P very volatile -> unwanted P into GaAsSb
•Instant flux shut off of P by cooled shutter -> sharp SL interfaces





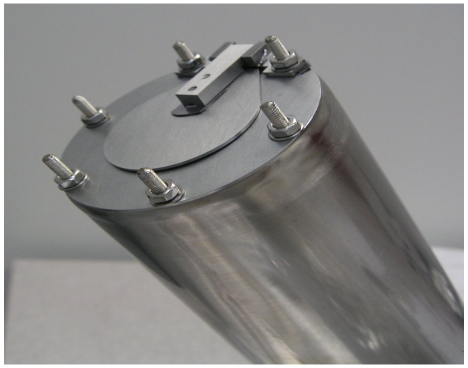
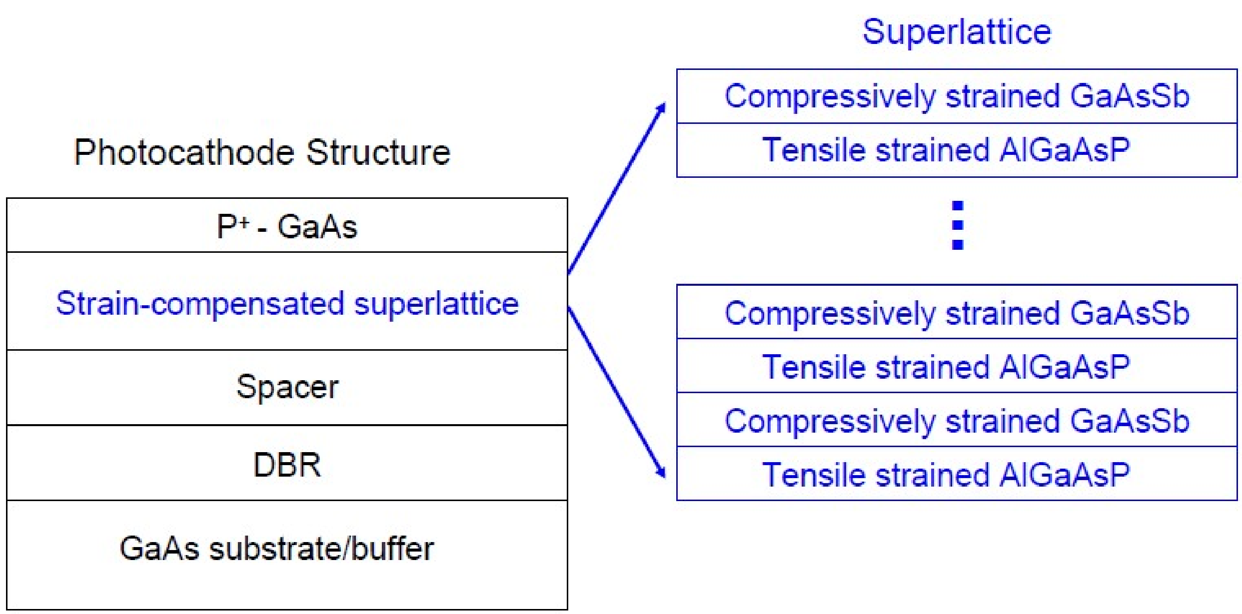


Photo of the output end of the independently cooled shroud/shutter assembly for phosphorus flux abatement. The shutter can change states in a sub-second time scale.

Key benefits of proposed approaches

- Improved polarization by large HH-LH splitting.
- Significantly improved material quality and thicker SL absorber region boosting QE by fully strain-compensated GaAsSb/AlGaAsP SL.
- An effective GaAs(P)/AlAs(P) DBR structure to enhance QE through more efficient photon absorption.
- Cooled shutter approach to improve interface quality of GaAsSb/AlGaAsP SLs.



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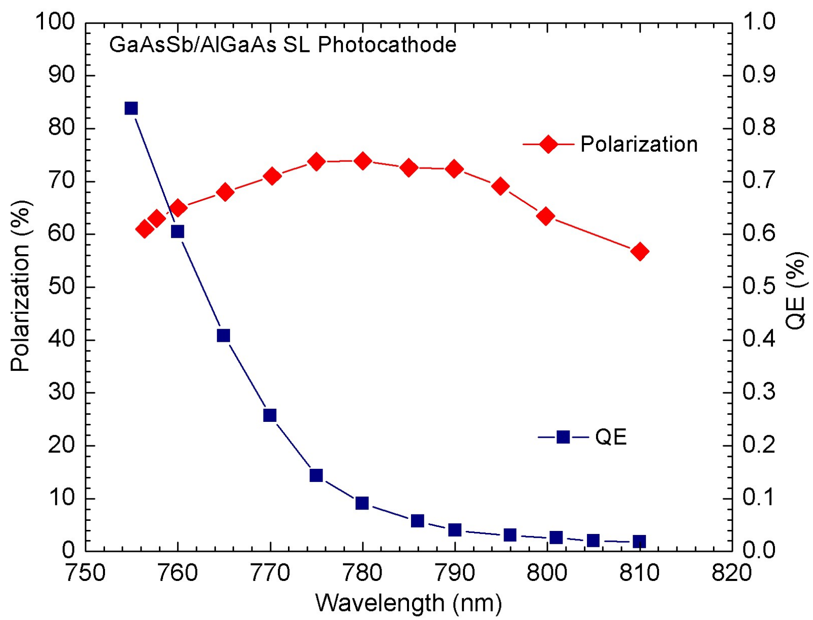
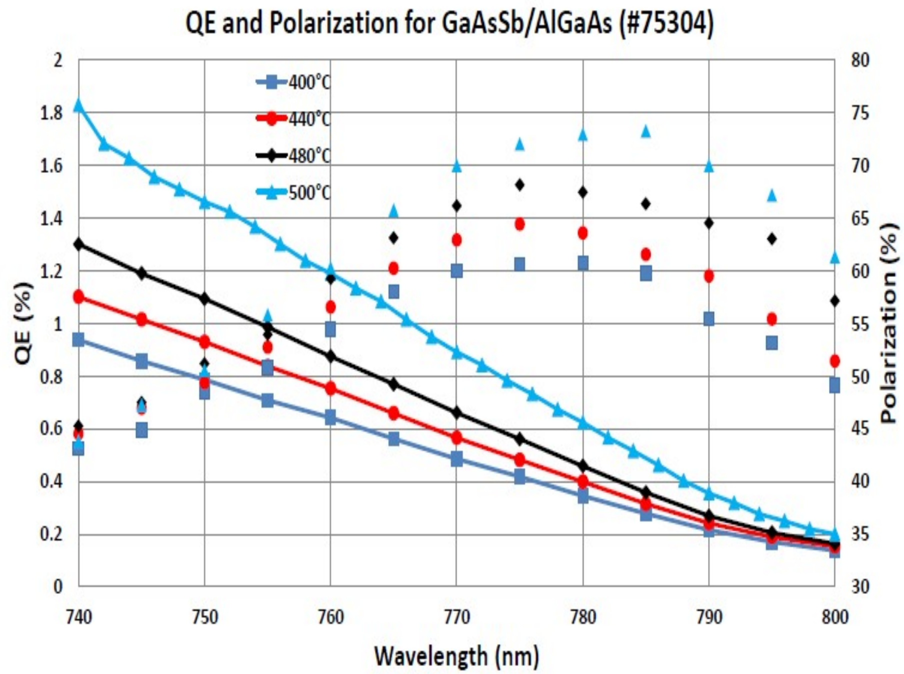
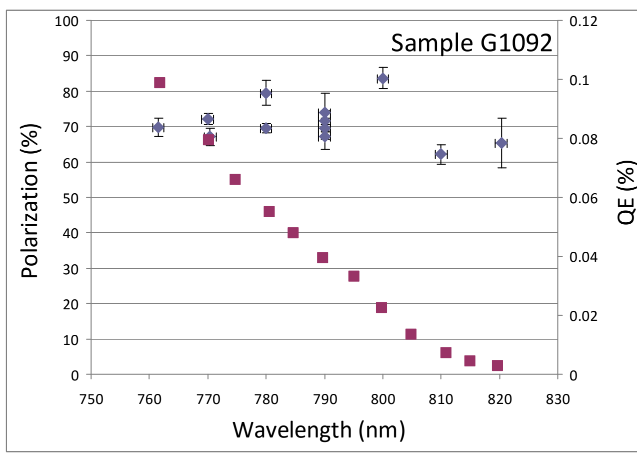
Polarization of Sb-based SL photocathodes

Best polarization for Sb-SL: 84%

Our goal: >92%







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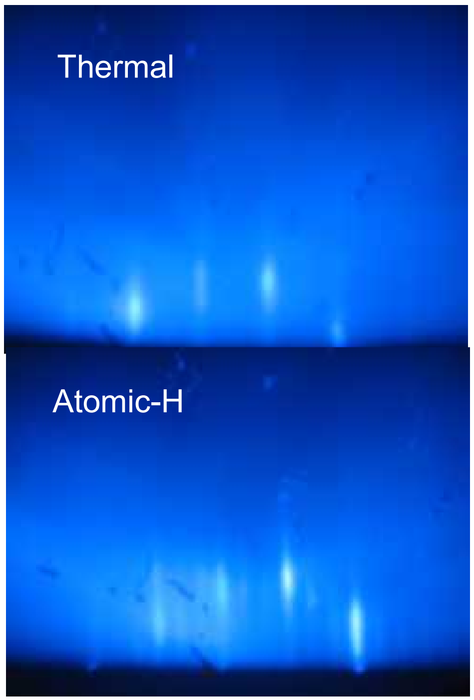
Polarization of Sb-based SL photocathodes

Thermal native oxide removal test under RHEED monitor performed

- 520C required to fully remove surface oxide even with As capping, SL growth temperature – 490C
- Structural damage of Sb-based SL due to heating

Nest step – two approaches

- Atomic hydrogen, native oxide on GaAs can be removed by atomic-H below 450C
- Other surface capping material : Sb



Oxide removal test - RHEED

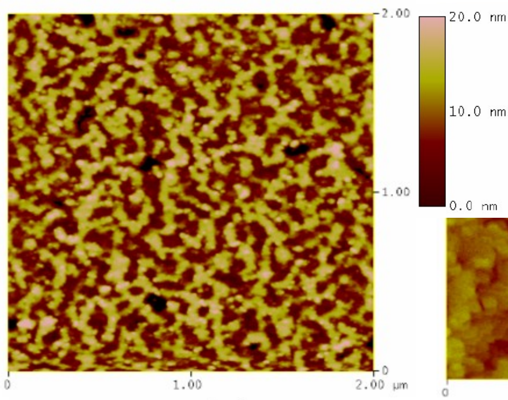


Image Statistics

Img. Z range	48.512 nm
Img. Rms (Rq)	4.669 nm
Img. Ra	3.851 nm
Img. Srf. area	4.252 µm²
Img. Prj. Srf. area	4.000 µm²
Img. Srf. area diff	6.295 %
Img. SAE	1.027

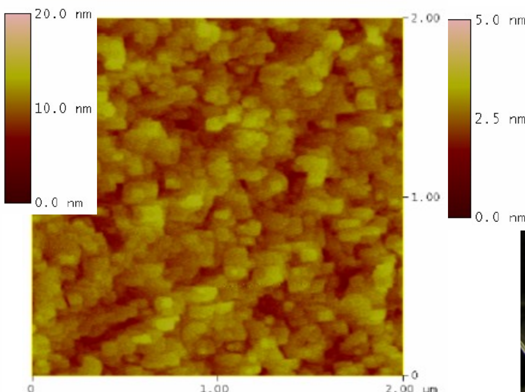
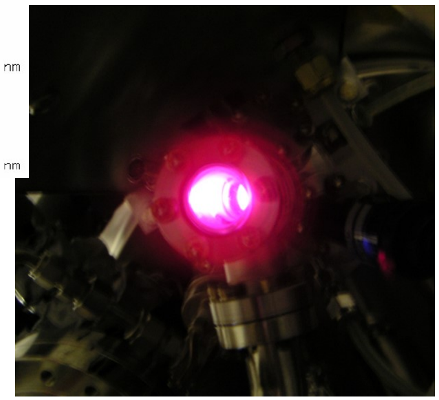


Image Statistics

Img. Z range	3.097 nm
Img. Rms (Rq)	0.374 nm
Img. Ra	0.296 nm
Img. Srf. area	4.003 µm²
Img. Prj. Srf. area	4.000 µm²
Img. Srf. area diff	0.063 %
Img. SAE	1.000

As: porous
Sb: better surface coverage



Atomic-H generated from an SVT RF-source

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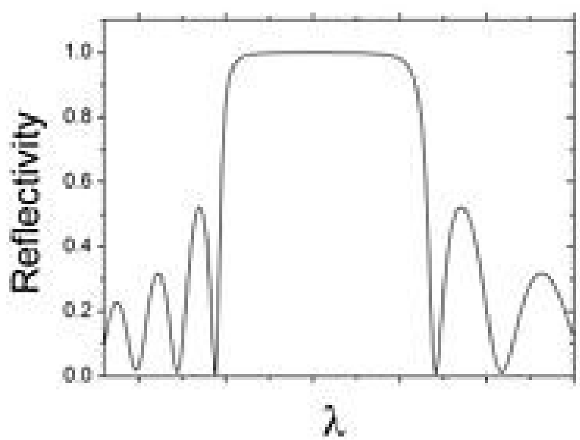
Distributed Bragg Reflector (DBR)

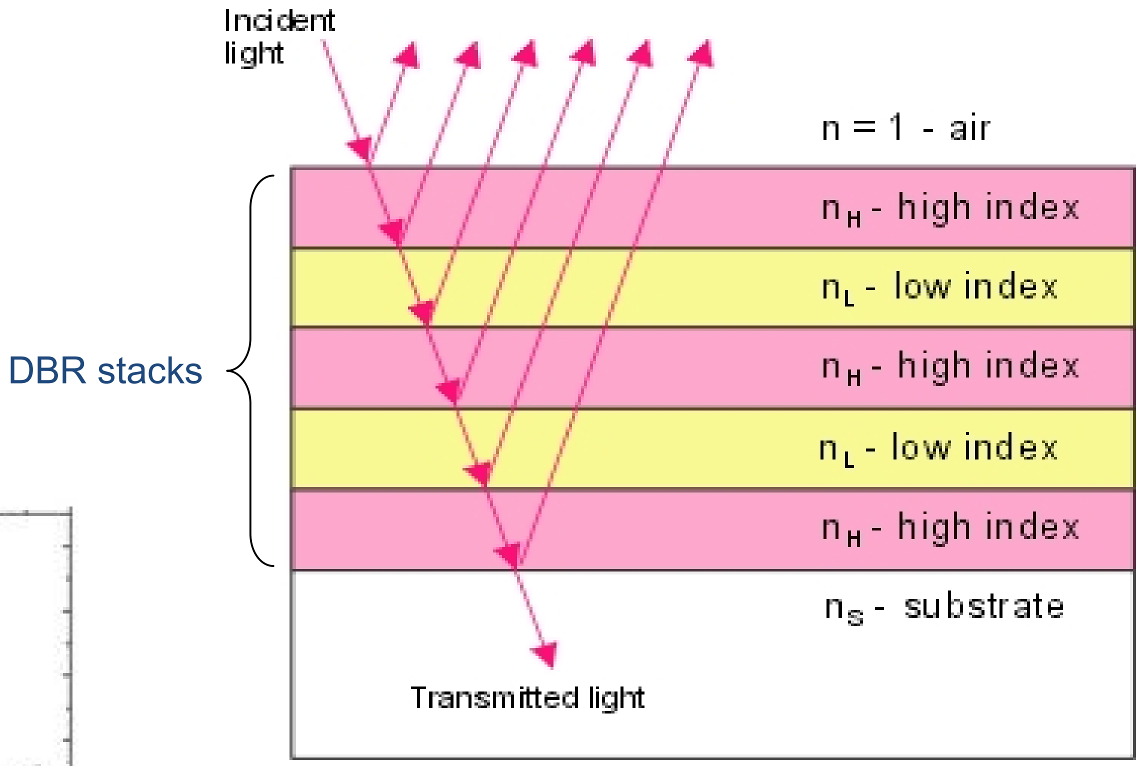
•Core SL layer very thin (~100-200nm) due to short spin relaxation time –very low absorption (a few percent) and hence low QE

•Perfect reflector

•Reflection ~99% for 20-period GaAs(P)/AlAs(P) DBR

DBR requirement:
•Abrupt interfaces
•Good periodicity

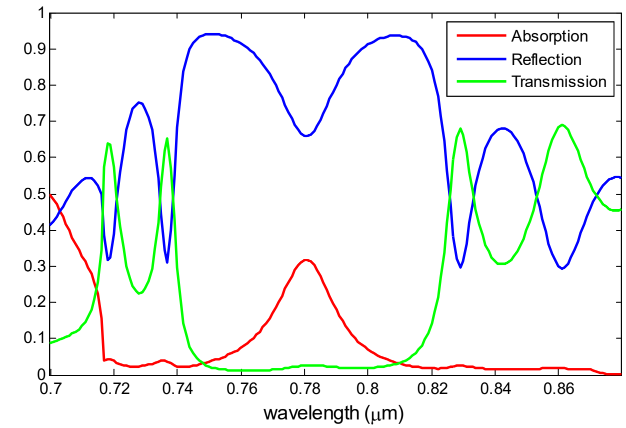


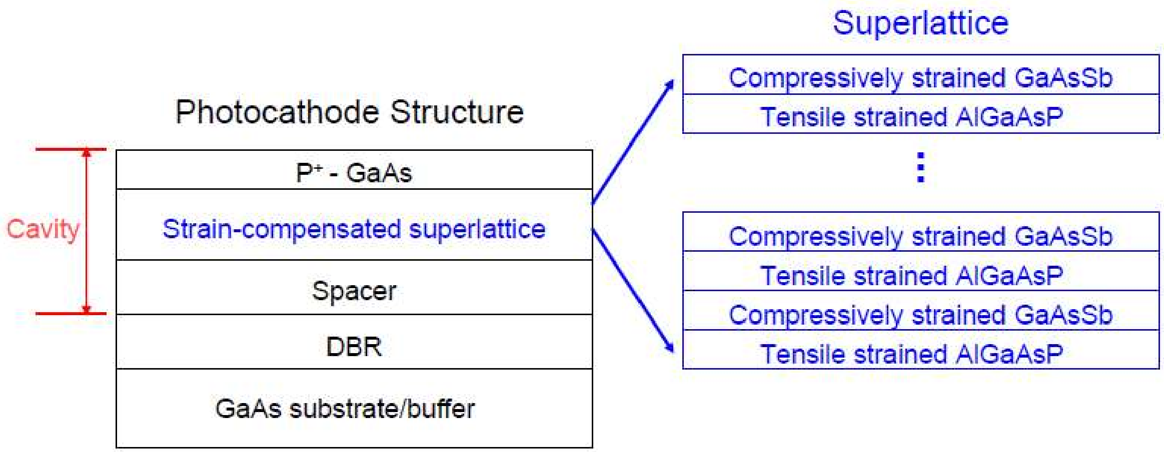


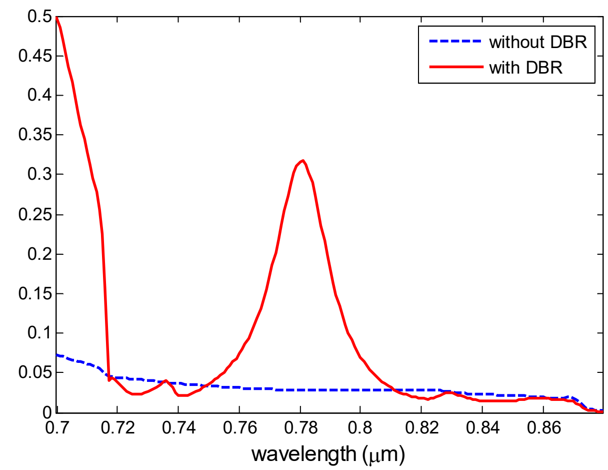
DBR with Fabry-Perot Cavity

- Fabry-Perot cavity formed between wafer/air interface and DBR/spacer interface
- Resonant light absorption in SL core layers due to F-P cavity
- Absorption resonant peaks very sensitive to cavity length – accurate layer thickness and composition control required

Calculated absorption of the superlattice with DBR and Fabry-Perot cavity (right). (8-pair DBRs)







Calculated absorption spectra for 12-pair DBR and w/o DBR

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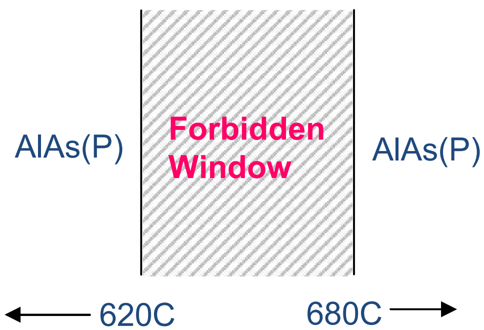
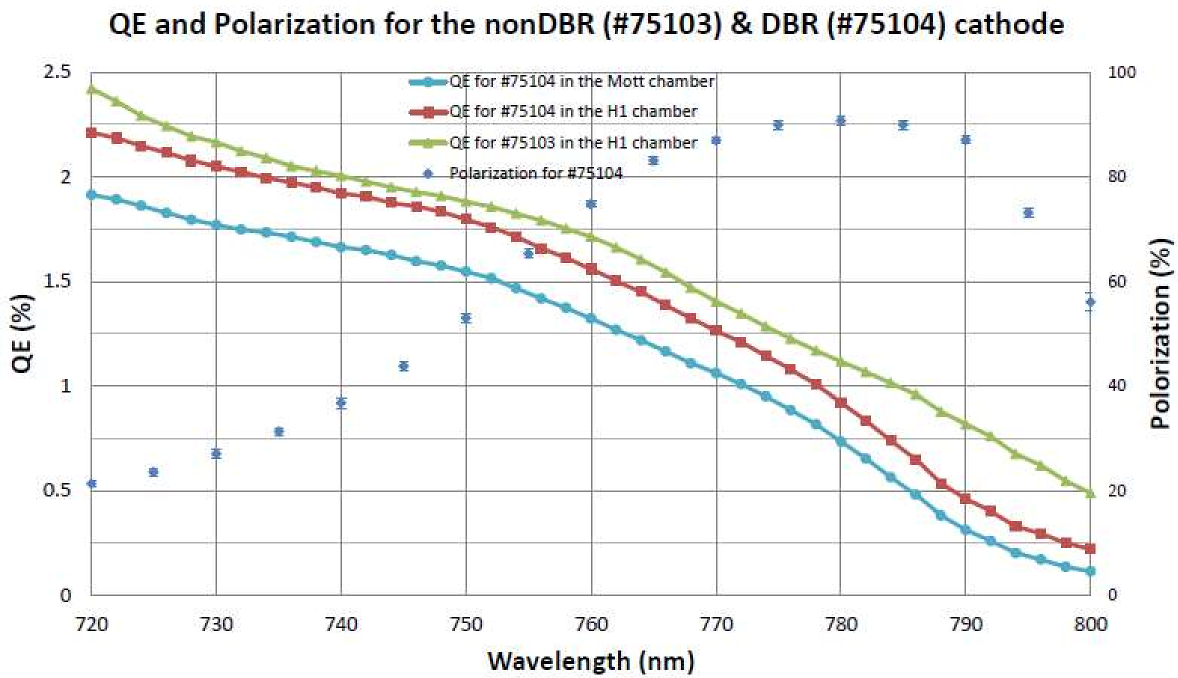
No QE Enhancement for Poor DBR

GaAsP/AlAsP DBR

•High growth temperature favorable to single-layer GaAsP and AlAsP
•For GaAsP/AlAsP multi-layer structure, high growth temperatures cause interface damage





Growth temperature: 680 C

Forbidden window for growth of AlAs(P) : 620-680 C

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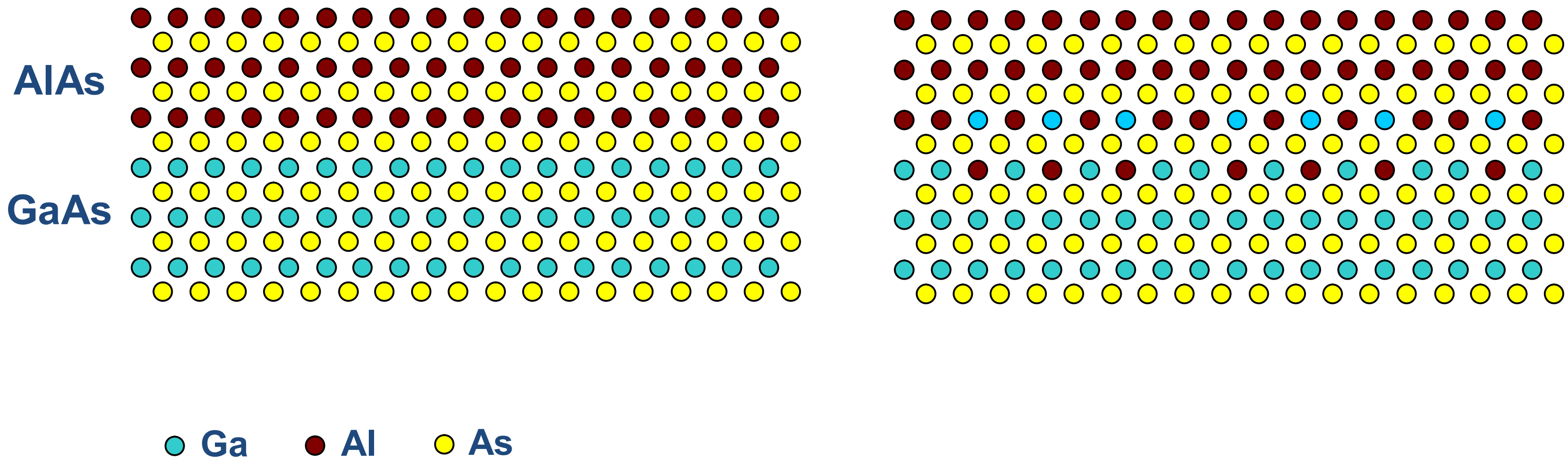
Structural Damage due to Ga Diffusion at High Temperatures

Ga atoms diffused at the interfaces
•Poor interface quality
•loss of periodicity of DBR



New Quantum Efficiency Milestone Achieved !

- Low growth temperature
- Very low growth rate for Al-containing layers

Important milestone:
Over 5% QE with 87% polarization for the first time!

Next goal: >10% QE

Preliminary results promising; still room to improve.

- Lack of data for optical parameters of AlAsP
- Best growth window for GaAs(P)/AlAs(P) unknown

Summary

- SL structure design and DBR design completed
- High quality GaAsP/AlAsP DBR material achieved
- MBE growth of GaAsSb/(Al)GaAsP SL
- Surface oxide removal test performed to investigate the cause of low polarization of Sb-based SL photocathodes
- Over 5% QE with 87% polarization achieved– New world record
- Substrate heater upgrade – temperature variation over 3-inch < 5 °C
- New surface capping material; Atomic-H assisted surface oxide removal

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