GaAsSb/AlGaAs Superlattice
High-Polarization Electron Source

Contract # DE-SC0007501

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Subcontractor: DoE Jefferson Lab (Matt Poelker)

DoE SBIR/STTR Exchange Meeting
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
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.
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

**Present Applications:**
• DoE needs: high energy accelerators
  • Spintronics

**Potential Applications:**
• Surface analysis
  • Quantum computing
  • Magnetic imaging

**SVT-70%**
- Photocathode Modeling/Design
- Material Growth

**JLab-30%**
- Photocathode Testing
Photocathode - General Properties

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
Basics of polarized electron photocathode

Semiconductor: suitable material for polarized photocathodes

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

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

Initial polarization: \[ P_0 = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \]
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 < 95 meV

GaAs/GaAs$_{0.64}$P$_{0.36}$ SL:
Best overall performance thus far, HH-LH splitting $\delta$~92 meV

GaAs$_{0.85}$Sb$_{0.15}$/Al$_{0.4}$Ga$_{0.6}$As SL:
- highest VB offset $\Leftrightarrow$ Highest HH-LH splitting: $\delta$~168 meV resulting in highest initial polarization and larger tolerance to $\gamma$
- 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
Very High VB offset in GaAsSb/AlGaAs Heterostructure

GaAs/GaAsP SL

compr.-strained GaAs    GaAsP    compr.-strained GaAs

CB

HH

VB

GaAsSb/AlGaAs SL

compr.-strained GaAsSb    AlGaAs    compr.-strained GaAsSb

CB

HH

VB

Graphs showing the Very High VB offset in GaAsSb/AlGaAs Heterostructure with respect to the conduction band (CB) and valence band (VB) for GaAs/GaAsP SL and GaAsSb/AlGaAs SL.
GaAsSb/AlGaAs SL: wider high $P_0$ range and larger tolerance to $\gamma$

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

- Line width $\gamma=10$ meV, Maximum initial $P_0=95\%$
- Line width $\gamma=20$ meV, Maximum initial $P_0=88.5\%$

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

- Line width $\gamma=10$ meV, Maximum initial $P_0=97.0\%$
- Line width $\gamma=20$ meV, Maximum initial $P_0=94.0\%$

**Broadening of band:**

$$\delta(\omega_m(k,\omega) - \omega) \rightarrow \frac{1}{\pi} \text{Im} \frac{1}{\omega - \omega_m(k,\omega) - i\gamma}$$
Much Better Crystalline Quality Material: GaAsSb/AlGaAs SL

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

(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: <0.5°C
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
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/AlGaAs 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).
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 \quad \text{Transport loss}

\( \tau_s \): spin relaxation time, \( \tau_t \): 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% @ $\gamma=10$ meV
~93% @ $\gamma=10$ meV

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

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