GaAsSb/AlGaAsP Superlattice Polarized Electron Source

Contract # DE-SC0009516

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Collaborator: Shukui Zhang, Wei Liu, and Matt Poelker, DoE Jefferson Lab

DoE SBIR/STTR Exchange Meeting
8/10/2016, Gaithersburg, Maryland
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
• 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
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
• More than 10 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

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

**Potential Applications:**
• Surface analysis
• Quantum computing
• Magnetic imaging
Photocathode - General Properties

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

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

Improvement:
1. increase QE
2. increase polarization

Photon → free electrons in vacuum
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<sub>0.64</sub>P<sub>0.36</sub> SL:
Best overall performance thus far, HH-LH splitting δ~92 meV

GaAs<sub>0.85</sub>Sb<sub>0.15</sub>/Al<sub>0.25</sub>GaAsP<sub>0.15</sub> 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.
• 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.

### Key benefits of proposed approaches

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<tr>
<th>Photocathode Structure</th>
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<td>P⁺ - GaAs</td>
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<td>Spacer</td>
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<tr>
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### Superlattice

- Compressively strained GaAsSb
- Tensile strained AlGaAsP
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Polarization of Sb-based SL photocathodes

Best polarization for Sb-SL: 84%
Our goal: >92%
Polarization of Sb-based SL photocathodes

Thermal native oxide removal test under RHEED monitor performed
• 520°C required to fully remove surface oxide even with As capping, SL growth temperature – 490°C
• Structural damage of Sb-based SL due to heating

Next step – two approaches
• Atomic hydrogen, native oxide on GaAs can be removed by atomic-H below 450°C
• Other surface capping material: Sb

Atomic-H generated from an SVT RF-source

As: porous
Sb: better surface coverage
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 stacks

DBR requirement:
• Abrupt interfaces
• Good periodicity

反射率 

n = 1 - air

n_H - high index

n_L - low index

n_H - high index

n_L - low index

n_H - high index

n_S - substrate

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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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Engines for Thin Film Innovation
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

Forbidden window for growth of AlAs(P) : 620-680 C
Structural Damage due to Ga Diffusion at High Temperatures

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

AlAs
GaAs

Ga Al As
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
• 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