Intersubband Absorption in MOCVD Grown Nitride Superlattices

Yu Song\textsuperscript{1}, Arjun Vijayakumar\textsuperscript{1,2}, Claire Gmachl\textsuperscript{1}
\textsuperscript{1} Princeton University, Princeton, NJ 08544, USA
\textsuperscript{2} Schlumberger Incorporation, Houston, TX 77054, USA

email: yusong@princeton.edu
Motivation

- <3.5μm Quantum Cascade Lasers (QCLs)
- InGaAs/AlInAs system:
  - QCLs lasing at wavelengths longer than 3.5 μm.
- What is physically limiting the wavelength range?
  - QCLs rely on inter-subband (ISB) transitions
  - Band offset!
Band Gap of Semiconductors

- **Conduction Band Offsets (CBOs):**

<table>
<thead>
<tr>
<th>Material System</th>
<th>CBO (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>InGaAs/AlInAs</td>
<td>~ 0.52</td>
</tr>
<tr>
<td>InAs/AlSb</td>
<td>~ 1 (Effective)</td>
</tr>
<tr>
<td>II-VI material</td>
<td>~ 1.2</td>
</tr>
<tr>
<td>GaN/Al(Ga)N</td>
<td>~ 2</td>
</tr>
</tbody>
</table>

- Nitride system ISB transition wavelength covers the telecommunication band (1.3-1.55 μm).
Facts of III-Nitrides

- Hexagonal crystal structure
- Material growth challenging
  - Lack of good substrate
  - GaN on Sapphire: 13.9% mismatch (30° rotation)
  - GaN / AlN / InN lattice constant are different
- Spontaneous and piezoelectric polarization
  - Tilted band profile – changes selection rule
- High electron effective mass (~ 0.2m₀ in GaN)
  - Better confinement
  - Higher density of states
  - Not good for transport

(From: http://web.tiscali.it/decartes/phd_html/III-Vms-latgap-gan.png)
Inter-subband Absorption Experiment

- First step of fabricating QCLs in a new material:
  - Inter-subband absorption measurements

- 45° incident transmission measurement

Diagram:
- Lenses: CaF2
- Beam splitter: CaF2
- Detector: cryogenic temperature InSb
Sample Geometry

- Sample geometry

Absorption measurement and inter-subband transition

\[-\ln \left( \frac{T_{TM}}{T_{TE}} \right) = C \times \frac{L_{sub}}{D_{sub}} \cdot N \cdot \alpha_{2D} \cdot \sin \theta \]

*C Coupling Strength, \(L\) length, \(D\) thickness, \(N\) number of QWs, \(\theta\) Incident Angle*

\[\alpha_{2D} = \frac{n_e e^2 \hbar}{2\varepsilon_0 c n^* \varepsilon_m} f_{12} \frac{\Gamma}{(E_2 - E_1 - \hbar \omega)^2 + \Gamma^2} \]

\[f_{12} = \frac{2m^* \alpha_{12}}{\hbar} \left| \langle 1 | z | 2 \rangle \right|^2 \]

\(n_e\) doping, \(f_{12}\) oscillator strength, \(\Gamma\) linewidth
Design (Calculation) Tool

- Different parameters
  - Crystal field splitting
  - Uncertainty

- Polarizations
  - Spontaneous (Sp) polarization
    - Strong bowing in Sp polarization
      \[ P_{AN}^{sp} x + P_{BN}^{sp} (1-x) + b_{ABN}^{sp} x (1-x) \]
  - Piezoelectric (Pz) polarization
    - Weak bowing in coefficients; strong nonlinearity
      \[ P_{pz} = 2 \left( e_{31} - \frac{C_{31}}{C_{33}} e_{33} \right) \times \varepsilon_{||} + \alpha \varepsilon_{||}^2, \varepsilon_{||} = \frac{(a - a_0)}{a_0} \]
      \[ P_{AN}^{pz} x + P_{BN}^{pz} (1-x) + b_{ABN}^{pz} x (1-x) \]

- Boundary condition uncertainty
  - Equal field / flat-band
Design (Calculation) Tool

- Effective mass
  - Model based on k·p theory
  - Effective mass depend on energy and position

\[
\frac{m_0}{m^*_c} = 1 + 2F + \frac{2m_0}{\hbar^2} P^2 \left( \frac{E_q + E_g + 2\Delta_2}{(E_q + E_g + \Delta_1 + \Delta_2)(E_q + E_g + 2\Delta_2) - 2\Delta_3^2} \right)
\]

\[\Delta_1 = \Delta_{cr}, \Delta_2 = \Delta_3 = 1 / 3\Delta_{SO}, P_1 = \frac{\hbar}{m_0} \langle S | P | Z \rangle, P_2 = \frac{\hbar}{m_0} \langle S | P | X \rangle, E_g = E_c - E_{hh}\]

- Calculated conduction subbands

<table>
<thead>
<tr>
<th>Materials</th>
<th>GaN / AlN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thicknesses</td>
<td>2nm / 1.5nm</td>
</tr>
<tr>
<td>P_{Pz} (Barrier)</td>
<td>4.24MV/cm</td>
</tr>
<tr>
<td>P_{Sp} (Barrier)</td>
<td>7.26MV/cm</td>
</tr>
<tr>
<td>P_{Sp} (Well)</td>
<td>3.96MV/cm</td>
</tr>
<tr>
<td>E_{12}</td>
<td>652meV</td>
</tr>
<tr>
<td>\lambda_{12}</td>
<td>1.93\mu m</td>
</tr>
</tbody>
</table>
Sample Set #1

<table>
<thead>
<tr>
<th>Sample</th>
<th>GaN / AlN Thickness (nm)</th>
<th>Doping (cm⁻³)</th>
<th>Periods</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1498(A)</td>
<td>1.5 / 1.5</td>
<td>6 X 10^17</td>
<td>60</td>
<td>2.2 µm GaN buffer on Sapphire</td>
</tr>
<tr>
<td>L1550(B)</td>
<td>1.5 / 0.7</td>
<td>6 X 10^17</td>
<td>60</td>
<td>2.2 µm GaN buffer on Sapphire</td>
</tr>
<tr>
<td>L1551(C)</td>
<td>1.5 / 0.7</td>
<td>4 X 10^18</td>
<td>60</td>
<td>2.2 µm GaN buffer on Sapphire</td>
</tr>
</tbody>
</table>

Expected absorption:

- \( E_{41} \approx 0.96 \, \mu m \)
- \( E_{31} \approx 1.14 \, \mu m \)
- \( E_{21} \approx 1.27 \, \mu m \)

* Sample grown by Prof. Nelson Tansu’s group
Sample Set #1 Results

- Interference patterns
  - $n_{\text{sapphire}} \approx 1.71$ (at 3 µm)
  - $n_{\text{epilayer}} \approx 2.28$ (at 3 µm)

- Absorption at 2960 cm\(^{-1}\)
  - In both TE and TM

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**P1498**

- WL Absorption

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**P1550**

- P1550B WL (non-metal)

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**P1551**

- Non-Metal

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**P1550A Spectra**

- Intensity (a. u.)

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**Wavenumber (cm\(^{-1}\))**
Coating Metal

- Fields near surface of samples:
  - For air–epilayer interface, reflected wave partially cancel incident field
  - For metal–epilayer interface, field strength could be high

(From H. C. Liu, etc. *Intersubband Transitions in Quantum wells*, Academic Press, 2000)
Sample Set #1 (Coated Metal)

- Shifted interference pattern
  - Due to phase change on the boundary
- Still no obvious ISB absorption
Sample Set #2

- Modification:
  - $\text{Al}_{0.84}\text{In}_{0.16}\text{N} / \text{GaN}$ (Lattice matched)
  - Grown on sapphire and GaN
  - Increased doping

- Expected transition:
  - $E_{41} \sim 1.88 \mu m$
  - $E_{31} \sim 2.34 \mu m$
  - $E_{21} \sim 3.35 \mu m$

<table>
<thead>
<tr>
<th>Sample</th>
<th>GaN/AllN Thickness (Å)</th>
<th>Periods</th>
<th>Doping (cm^-3)</th>
<th>Substrate</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2257</td>
<td>20 / 30</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>Sapphire</td>
</tr>
<tr>
<td>AG2257</td>
<td>20 / 30</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>GaN</td>
</tr>
<tr>
<td>L2270</td>
<td>25 / 20</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>Sapphire</td>
</tr>
<tr>
<td>AG2270</td>
<td>25 / 30</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>GaN</td>
</tr>
<tr>
<td>L2272</td>
<td>20 / 25</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>Sapphire</td>
</tr>
<tr>
<td>AG2272</td>
<td>20 / 25</td>
<td>60</td>
<td>7.8 X 10^19</td>
<td>GaN</td>
</tr>
</tbody>
</table>
Sample Set #2 (on Sapphire)

- For samples grown on sapphire:
  - Possible broad peak adding to interference pattern
  - Need further verification
For sample AG2257A we found possible absorption at around 2800 cm\(^{-1}\)
- Lorentzian

In other samples no obvious absorption
Sample AG2257

- Repeatability
  - AG2257B
  - Possible broad peak adding around 3000 cm\(^{-1}\)

- Coat metal and apply voltage tuning
  - Peak at 2800 cm\(^{-1}\) still discernable
  - Sharp peak at 2960 cm\(^{-1}\) suppressed
Conclusion and Future work

- Conducted optical absorption measurement
  - Modified design considering lattice mismatch
  - Characterized samples grown on both sapphire and GaN
- Possible ISB absorption observed
  - Further verification needed
- Future work: measure resonant tunneling transport, design lasers, etc.

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*Sample grown by Prof. Nelson Tansu, Lehigh University; Substrates from Kyma Technologies*