Semiconductor Mid-IR Interband Cascade Lasers for Trace Gas Monitoring

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**Detection Limits Using Laser Spectroscopy**

<table>
<thead>
<tr>
<th>Molecule</th>
<th>ppb</th>
<th>mid-IR ((\lambda))</th>
<th>ppb</th>
<th>Near-IR ((\lambda))</th>
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<td>H2O</td>
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<td>5.25 (\mu)m</td>
<td>60000</td>
<td>1.8 (\mu)m</td>
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<td>CH4</td>
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<td>3.4 (\mu)m</td>
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<td>1.5 (\mu)m</td>
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</table>


**Mid-IR lasers can improve detection sensitivity by orders of magnitude**

Major advantages of semiconductor laser spectrometers:
- high sensitivity and selectivity
- fast response & remote sensing capability
- low-power consumption & high efficiency

However, the development of efficient mid-IR diode lasers has been very challenging
Interband Cascade (IC) Lasers – Promising Approach

A schematic band diagram of two cascade stages based on InAs/GaSb/AlSb system

- Cascade process ⇒ high efficiency, large output power, & uniform injection of carriers over every cascade stage
- Suppressing Auger recombination in type-II QWs through band-structure engineering
- Wide wavelength tailoring range particularly in short wavelength side due to large band-gap
- Band-gap blocking feature ⇒ excellent carrier confinement with significant flexibility

→ low threshold current, high efficiency, high output power
JPL’s New Sb MBE System

The IC laser structure is very complicated, comprising ~2000 or more layers, some as thin as a few atomic layer, requiring not only careful design of quantum engineering in sub-nanometer scale, but also sophisticated growth technology with good controls.

A new MBE system was delivered to JPL and installed in July, 2002. We have since worked to bring it to operation and recently produced two IC laser samples with 15 & 23 cascade stages, respectively. The two samples have good crystal structural quality examined by x-ray spectra.
Gain-guide metal stripe lasers

- Lasers made from each sample lased at ~2.8 µm and ~4 µm, respectively
- The 2.8-µm laser had significant high threshold current due to substantial deviations (~12%) of layer thickness from the design
- At 81 K, 4-µm laser had peak power > 100 mW/f, external quantum efficiency of ~400%
- Under pulsed conditions, 4-µm laser lased at temperatures up to ~200 K
- Threshold currents were high due to significant current spreading over the lateral direction without confinement
Using mesa to suppress the current spreading, the threshold current was remarkably reduced ($J_{th}$ is as low as 58 A/cm$^2$ at 80 K)

- under pulsed conditions, 4-μm laser could lase at temperatures up to ~210 K and the maximum operation temperature was limited by the damage with high current and voltage

- cw operation was achieved in these mesa stripe lasers at temperatures up to ~86 K

- the output power and quantum efficiency are much lower than what observed from gain-guided metal stripe lasers (?! -- surprise and question)
un-flat facet particles & dirt

undercut during mesa processing metal hand over the edge of mesa

devices were damaged under high current pulses with burned hole and metal
Considering Sb-based materials and device structures are much less explored and we just had short time with the facilities at JPL, the results on mid-IR type-II IC lasers are very encouraging, indicating significant room for improvement and more efforts are needed.

- For gas sensing application, single-mode lasers are needed – one solution is to incorporate distributed feedback (DFB) gratings into IC lasers (*Laterally coupled DFB laser structure* – avoids need for crystal regrowth on top of gratings)

- Improve MBE growth and device design
  » optimize crystal growth conditions with reduced interface roughness
  » suppression of various loss mechanisms at high temperatures ⇒ challenging in design
  » better understanding of underlying physics

- Material quality and processing
  » defects ⇒ substrate quality, polishing, cleaning, MBE growth
  » etched surfaces ⇒ leakage, recombination loss
  » small-area ridge lasers ⇒ processing, passivation

- Improvement of device thermal management and packaging
  » epilayer side down mounting (care needs to minimize mechanical stress)
  » facet coating (for preventing oxidation and obtaining high output power)
Back-up
This is an Sb-based wide mesa stripe (0.3 mm x 1.58 mm) laser made about 3 years ago [laser sample ICL3 reported in Yang, et al, Physica E 7, 69 (2000)] and has been exposed to ambient conditions since that time. Nevertheless, the device performance did not show any observable degradation over time even after many thermal cycles.
Bipolar Cascade Lasers based on InGaAs/InP

- InGaAs bipolar cascade laser, grown by MOCVD, has been demonstrated at wavelengths near 2 μm.
- Threshold current density was ~20A/cm² at 80 K, but increased rapidly at the higher temperatures with large threshold voltage (>7 V at 230 K).
- Series resistance is large even after lasing, which is speculated due to the tunnel junction and can be reduced by improving the design.
- The results were just very preliminary (the first try). More work need to be done on device fabrication and characterization before next design iteration.
Laser Diode Operating Ranges & Absorption Lines of Gases

**Diode Sources**
- AlGaAs/GaAs
- InGaAsP/InP
- InGaAsSb/GaSb
- Type-II ICLs
- Quantum Cascade

**Atmospheric Gases**
- O₂
- HCl
- CO₂
- CH₄
- NH₃
- HF
- H₂O
- NO₂
- HNO₃
- O₃
- ClO

**Planetary Gases**
- CO₂
- H₂O
- CO
- C₂H₆
- ¹³CO₂
- HDO
- CH₄
- CH₃O
- NH₃
- HCN
- C₂H₂

**WAVELENGTH (μm)**
- 0.25
- 0.5
- 1
- 2
- 4
- 6
- 8
- 10
- 12
- 14
- 16
- 18