MBE Growth of Terahertz Quantum Cascade Lasers

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Presentation Outline

- Introduction
- Issues associated with growth
- Robustness of Active Region designs
- Minor tweaks to Active Region
- Transfer of structures between growth reactors
- Summary
“materials by design”: band structure engineering through molecular beam epitaxy


What Grower Sees


4.4THz chirped superlattice QCL AR

x104 Repeats

$\text{Al}_{0.15} \text{Ga}_{0.85} \text{As/GaAs}$
What Grower Sees

**Final QCL device:**
- 90-250 periods active region
- 12-18µm thick
- 1200 - 1500 layers
- Some barriers ~6Å (~2MLs)
- 12-18hrs growth duration
What Grower Sees

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- 12-18\(\mu\)m thick
- 1200 - 1500 layers
- Some barriers \(~6\AA\) (~2MLs)
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PUSHING BOUNDARIES OF GROWTH TECHNIQUES

- growth rate calibration
- growth rate stability
- interface roughness

\{ accuracy of layer thickness \}
Molecular Beam Epitaxy

Precise semiconductor growth technique

- extensive range of source materials
- layer thickness to monolayer accuracy
- high degree of control on layer composition & doping level
- abrupt interfaces
- little interface diffusion
Theoretical growth rate tolerances

GaAs growth rate within +2% and −1%
AlAs growth rate within +10% and −5%

Beere et al., J Cryst Growth 278, p756 (2005)
X-ray spectra of THz laser

- Clear satellite structure in good agreement with simulation
- Confirms excellent growth stability over 12 hour growth duration
- Thickness variation across 2” wafer is less than 2%
Terahertz Quantum Cascade Laser

- Single-mode emission from a Fabry-Perot Cavity
- Emission at 18.4meV: 4.44THz - Good agreement with design
Structure Reproducibility

- Good agreement design thickness and measured value (-1% to +2%)
Structure Reproducibility

- Single-mode emission from a Fabry-Perot Cavity
- Emission at ~18.2meV: 4.4THz - Good agreement with design
Robustness of Active Region Design


2.9 THz bound-to-continuum QCL AR

Energy (meV)

Distance (nm)

x90 Repeats

Injection barrier

17 meV

~12 meV

16 meV

Al_{0.15}Ga_{0.85}As/GaAs

ITQW07
Active Region Robustness

- Calculated emission frequency vs total AR thickness
- Again ±0.5meV emission energy equates ~ ±2% thickness
Active Region Robustness

PULSED OPERATION
3mm x 0.25mm ridge

- Single plasmon waveguide $V_{\text{align}} \sim 2V$: $T_{\text{max}} \sim 95K$: $P_{\text{max}} \sim 90mW$
- Series structure growths -5% to +5%

ITQW07
Active Region Robustness

- Actual range (-3%, +5%) ⇒ ~0.4THz (~2.5meV)
- Systematic route to tuning emission frequency
- Could possibly extend frequency range further (>5%)?
Active Region Robustness II

Worrall et al., Optics Express, 14, 171 (2006)

2.0 THz bound-to-continuum QCL AR

\[ F = 1.5 \text{ kV/cm} \]

\[ \text{Al}_{0.1}\text{Ga}_{0.8}\text{As/GaAs} \]

Energy (meV) vs Distance (nm)

Injection barrier

1. 14 meV
2. \( \sim 8 \text{ meV} \)
3. 16 meV

Active Region Robustness II
Active Region Robustness II

- Single plasmon waveguide 3mm x 0.25mm ridge waveguide
- $J_{th} \ 103 \ A/cm^2$ – $V_{align} \sim 1.8v$ : $T_{max} = 67K$  
  Output Power $\sim 22mW$  
  $f \sim 2.00THz$
Active Region Robustness II

- Similar ‘linear’ trend emission frequency against AR thickness
- Limited range (~3%) explored to date ⇒ ~0.06THz span
- Investigate extending frequency further!
Active Region Robustness II

- Bound-to-continuum design very robust!

- Possible systematic route to tuning frequency
  
  *how far can we realistically exploit this method?*
Minor Structure Variations

V305 3mm x 250mm 2.0THz Reference

\[ J_{th} = 103 \text{ A cm}^{-2} \quad V_{\text{align}} \approx 1.8 \text{ V} \]

\[ T_{\text{max}} = 67 \text{ K} \quad \text{Output Power} \approx 22 \text{ mW} \quad f \approx 2.00 \text{ THz} \]
Minor Structure Variations

V309 3mm x 250µm 2.0THz Thicker Injection Barrier

- Reduced Leakage, lower threshold (increased useable current)
- Similar dynamic range compared to reference
- Same temperature of operation as reference

(12% thicker injector: 6Å)

\[ \text{J}_\text{th} \ 90 \ \text{Acm}^{-2} \quad - \quad V_{\text{align}} \sim 1.7\text{v} \quad : \quad T_{\text{max}} = 67K \quad \text{Output Power} \sim 22\text{mW} \]
Minor Structure Variations

V309 (Thick Barrier) Laser Emission Spectra

1.99THz (8.25meV) – Singlemode (Frequency identical to Reference)
Minor Structure Variations

V308 3mm x 250 μm 2.0THz Thinner Injection Barrier

Increased leakage, higher threshold current
Device performance lower
(12% thinner injector : 6Å)

\( J_{th} \ 133 \text{ A cm}^{-2} (V_{align} \sim 1.9\text{A}) \): \( T_{max} = 47\text{K} \)  Output Power \( \sim 7\text{mW} \)
Minor Structure Variations

2.0THz Thin Injector Structure

Laser Emission Spectra

Emission (Norm Arb)

Energy (meV)

V308 (Thick Inj)

1.88THz (7.79meV) – lower frequency compared 2.0THz reference
Minor Structure Variations

Overlap strength between lower state and upper, injector

Thinner injector barrier no longer produces isolated upper and injector states

STRUCTURE LASES FROM INJECTOR TO LOWER STATE $\Rightarrow$ LOWER FREQUENCY
Minor Structure Variations

V307 3mm x 250μm 2.0THz Higher Doping

Laser Action Two Terminal ONLY
38% increase in doping

Device worked to 10K - IVs to 20K shown

- Device operation severely degraded
Minor Structure Variations

V307 (High Doped) Laser Emission Spectra

1.94THz (8.04meV) – Multimode: just above threshold
1.96THz (8.10meV) – Multimode: just before NDR
Minor Structure Variations

2.0THz Higher Doping & Reference (3mm x 250µm)

- 38% doping increase
- 92% current increase

Reference V305
(1.3 x 10^16)

Higher Doping V307
(1.8 x 10^16)

Killed by doping?

3 Terminal

• Higher current kills device operation
Minor Structure Variations

2THz Reference (V305) double-metal THz QCL devices

Pulsed LIVs - V305 DM
1.35mm, 50μm

\[ T_{\text{max}} = 89K \]

- Single plasmon waveguide \( T_{\text{max}} \sim 67K \)

1350 μm x 50 μm device
Minor Structure Variations

High doping (V307) double-metal THz QCL devices

- Slightly degraded performance compared to single plasmon

$T_{\text{max}} = 73K$

1000 $\mu$m x 50 $\mu$m device
Minor Structure Variations

- QCL performance sensitive to structure
  - doping level critical (especially single plasmon waveguide)
  - ensure variations does not completely change design

- Growth needs to be accurate!
Transfer of QCLs between growth systems

Veeco (V305) 3mm x 250mm 2.0THz Reference

Current (A)

Voltage (V)

Current Density (A/cm²)

Frequency

Energy (meV)

Emission (Norm Arb)

4K

67K

\( J_{th} \ 103 \ \text{Acm}^{-2} \quad V_{align} \sim 1.8v \quad T_{max} = 67K \quad \text{Output Power} \sim 22\text{mW} \quad f \sim 2.00\text{THz} \)
Transfer of QCLs between growth systems

VG (A3847) 3mm x 250mm 2.0THz Reference

![Graph showing current density vs. voltage and power output.]

- $J_{th} = 82 \text{ A cm}^{-2}$ – $V_{align} \approx 1.6 \text{ v}$
- $T_{max} = 57K$
- Output Power $\approx 10 \text{ mW}$
- $f \approx 1.99 \text{ THz}$
Transfer of QCLs between growth systems

- Active regions different by 27Å (~2%) ⇒ 0.05THz
- Variation due to growth or fabrication?
Transfer of QCLs between growth systems

- VG wafers consistently lower frequency (~0.05THz)
Transfer of QCLs between growth systems

- VG wafers consistently higher frequency (~0.1THz)
- Observed frequency differences
  - *Barrier profile/thickness*
  - *Growth interfaces*
Transfer of QCLs between growth systems

- Successful transfer of multiple AR designs
- Similar performance levels ($P$, $T$, $J_{th}$)
- Different frequency observed for same AR thickness
  - under investigation
• Over 60 working QCLs, incorporating in excess 30 different ARs
• Since 2002 frequency spans 0.95THz – 4.8THz (300µm – 62µm)
Summary

- Highlighted issues associated with growth
- Study of Active Region robustness presented
- Minor tweaks to Active Region
- Transfer of structures between growth reactors
- Span of frequencies so far