Deep-Well GaAs-InGaAs-AlGaAs Quantum Cascade Laser Design for Room Temperature Operation at 6.7 μm

Mithun D'Souza, Xujiao Gao, Irena Knezevic and Dan Botez

Department of Electrical and Computer Engineering, University of Wisconsin-Madison, Madison, WI 53706

THE UNIVERSITY of WISCONSIN MADISON

ABSTRACT

Design and simulation of a GaAs-based quantum cascade lasers (QCLs) emitting at 6.7 μm.

– Introduction of compressively strained $In_{0.1}Ga_{0.9}As$ **only** in the active quantum wells, where the optical transition occurs

– Monte-Carlo simulation including **both** Γ- and X-valley transport

– Proposed QCLs can achieve room-temperature lasing at threshold-current densities in the 9.5 to 14 kA/cm² range, lower than those of the conventional 9.4 μm GaAs-based QCLs[1]

Background : $GaAs/Al_{0.45}Ga_{0.55}As$ based QCLs

9.4 μm QCL by Page et. al.[1]

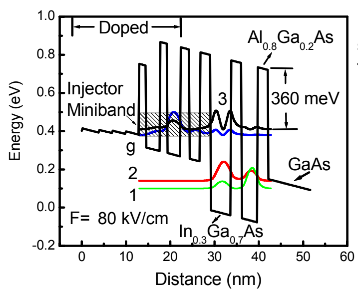
– Γ-point conduction band offset: 370 meV

– Pulsed room-temperature operation and CW operation up to 150 K from 36-stage devices

– Pulsed: J_{th}(77 K) = 4 kA/cm², J_{th}(300 K) = 16.7 kA/cm²

• Lasing wavelength limited to above 8 μm due to intervalley electron transfer when the upper lasing level is aligned with the lowest X-valley state of the injection barrier[2]

• Lowest wavelength achieved: 7.3 μm using a double-injection-barrier design, but only lased at cryogenic temperatures[2]

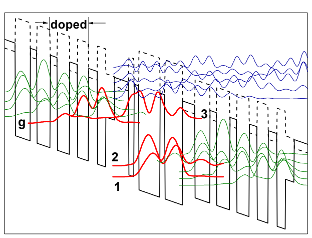


Deep-well compressively strained intersubband-transition devices

– Quantum wells in the active region are lower in energy than the quantum wells in the injector region

– Achieved, for GaAs-based based devices, *first* mid-IR (λ=4.7 μm) emission from single-stage devices[3]

Deep-well $GaAs/Al_{0.45}Ga_{0.55}As/In_{0.1}Ga_{0.9}As$ QCL design



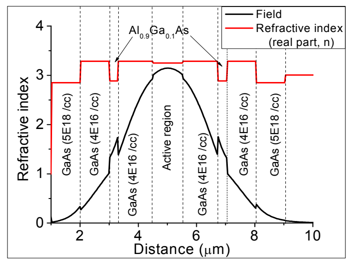
• Deep compressively strained $In_{0.1}Ga_{0.9}As$ active wells

• $GaAs_{0.6}P_{0.4}$ layer used just before the injection barrier to partially compensate strain (net compressive strain = 0.07%) => 25-stage QCL

• Conduction-band offset of the active region increases by 45 meV. Transition energy increases by 54 meV

• Lifetimes: τ_3=1.5 ps, τ_{21}=0.3 ps. Transition matrix element: $|z_{32}|$=1.5 nm

Waveguide design



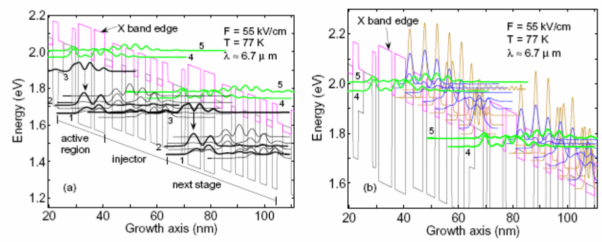
Use of $Al_{0.9}Ga_{0.1}As$ cladding increases the optical confinement factor (Γ) to compensate for the reduced number of stages

Γ = 32%

Waveguide loss, α_w = 15 cm⁻¹

Similar Γ and α_w values as for the $GaAs/Al_{0.45}Ga_{0.55}As$ structure[1]

Monte-Carlo simulation



• Γ-states are solved for using the **k.p** method, and the X-valley states are solved within the effective-mass framework[4,5]

• Both Γ- and X-valley transport are taken into account

• Includes all relevant scattering mechanisms within the same stage and between adjacent stages (stage ≡ active region + injector region):

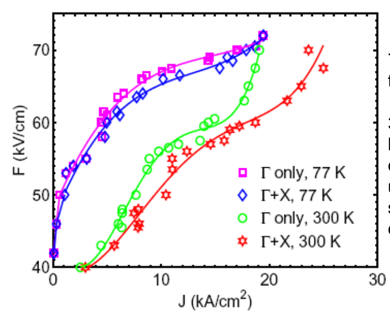
– electron-LO phonon

– electron-electron

– intervalley scattering

• Dominant leakage => Interstage scattering from the Γ-bound states (black) to the Γ-continuum states (green)

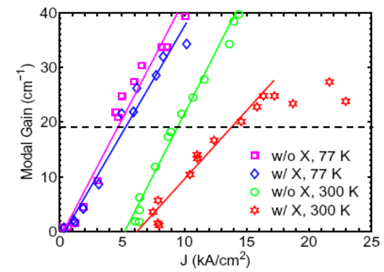
• Intrastage scattering then happens between the Γ-continuum states (green) to the X-valley bound states (blue and brown), and leads to interstage X-to-X leakage current



77 K: Almost no leakage to the X-valleys

300 K: Significant X-valley leakage due to increased electron population of the upper injector states and scattering to the Γ-continuum states

Modal gain vs. Current density

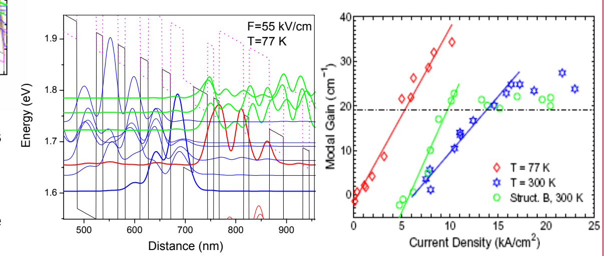


At 77 K and 300 K, with and without the inclusion of X-valley transport:

– Inclusion of X-valley transport causes the gain to saturate at ~25 cm⁻¹ (lasing can be achieved with up to 25 cm⁻¹ total losses)

– Total losses: $\alpha_w + \alpha_m$ = 19 cm⁻¹ => estimated thresholds at 77 K and 300 K are 5 kA/cm² and 14 kA/cm², respectively

Modified structure for low J_{th} at 300 K



• **J_{th} = 9.5 kA/cm² at 300 K** (structure B, green line)

Thicker injector well before the injection barrier:

▪ Reduced leakage to the continuum

▪ Larger energy separation between the injector ground state and the upper lasing level

– weaker coupling between the two states at 77K => no lasing at 77K

– active phonons distribute electrons to higher Γ-subbands at 300 K => *lasing can occur at 300K*

CONCLUSIONS

▪ Deep-well approach can be used to reduce the emission wavelength in GaAs-based devices to 6.7 μm at *no penalty* in device performance

- J_{th} = 5 kA/cm² at 77K and 14 kA/cm² at 300 K
- Alternate structure: J_{th} = 9.5 kA/cm² at 300 K

▪ Deep-well approach can be applied to lattice-matched InP-based devices to lower their emission wavelength below 7μm

Compared to InP-based devices *with all wells/barriers strained*

- simpler to implement as strain is only in the active wells
- potentially more reliable

References

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2. Wilson et. al. Appl. Phys. Lett. vol. 81, p.3178 (2002)
3. D.P. Xu et. al. Appl. Phys. Lett. vol. 85, p.4573 (2004)
4. X. Gao et. al. Appl. Phys. Lett vol. 89, 191119 (2006)
5. X. Gao et. al. J. Appl. Phys. vol. 101, 063101 (2007)