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

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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

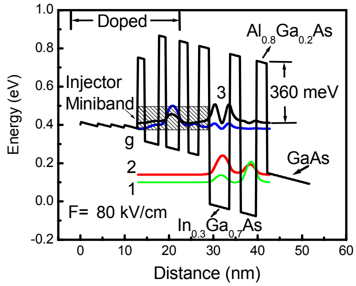
– Proposed QCLs can achieve room-temperature lasing at threshold-current densities in the 9.5 to 14 kA/cm² range, lower than those of the conventional 9.4 μm GaAs-based QCLs[1]

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

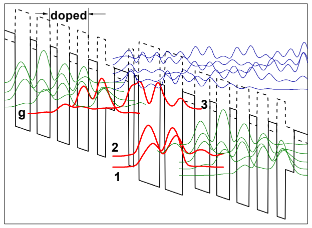
- Lasing wavelength limited to above 8 μm due to intervalley electron transfer when the upper lasing level is aligned with the lowest X-valley state of the injection barrier[2]
- Lowest wavelength achieved: 7.3 μm using a double-injection-barrier design, but only lased at cryogenic temperatures[2]



Deep-well compressively strained intersubband-transition devices

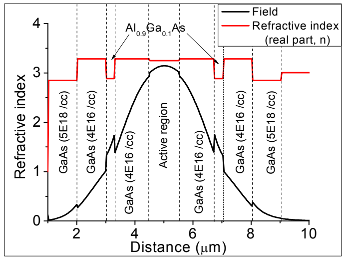
- Quantum wells in the active region are lower in energy than the quantum wells in the injector region
- Achieved, for GaAs-based based devices, *first* mid-IR (λ=4.7 μm) emission from single-stage devices[3]

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



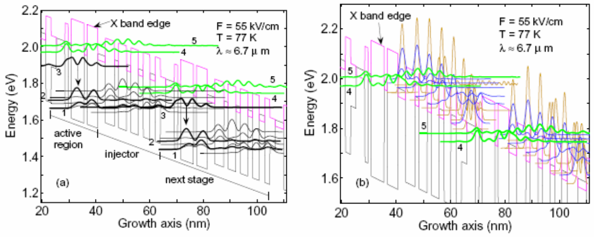
Use of $Al_{0.9}Ga_{0.1}As$ cladding increases the optical confinement factor (Γ) to compensate for the reduced number of stages

Γ = 32%

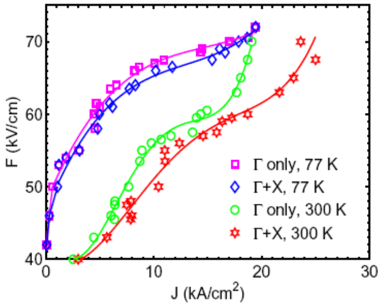
Waveguide loss, α_w = 15 cm^{-1}

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

Monte-Carlo simulation



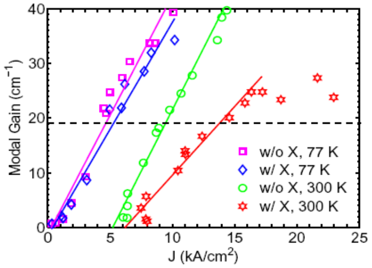
- Γ-states are solved for using the **k.p** method, and the X-valley states are solved within the effective-mass framework[4,5]
- Both Γ- and X-valley transport are taken into account
- Includes all relevant scattering mechanisms within the same stage and between adjacent stages (stage $\equiv$ active 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

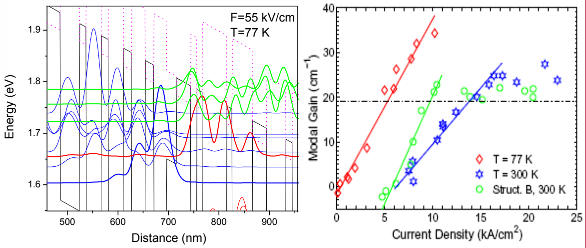


At 77 K and 300 K, with and without the inclusion of X-valley transport:

– 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: α_w + α_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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4. X. Gao et. al. Appl. Phys. Lett vol. 89, 191119 (2006)
5. X. Gao et. al. J. Appl. Phys. vol. 101, 063101 (2007)