Quantum Cascade Laser with a Vertical Transition and an Electron Bragg Reflector

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Conventional semiconductor lasers rely on the recombination of electrons from the conduction band with holes in the valence band. We have recently developed a radically different type of semiconductor laser, called the quantum cascade (QC) laser.[1, 2] In the QC laser, light is emitted when electrons make transitions between bound states created by quantum confinement in a multiple-quantum well heterostructure. The InGaAs/AlInAs structure, grown lattice-matched to InP by molecular beam epitaxy, consists of 25 periods cladded by high confinement ($\Gamma = 0.5$) waveguiding layers. As shown in Figure 1, each period consists of a superlattice electron injector which "feeds" electrons in the third state of the active coupled-quantum well active region. The lifetimes were engineered to maintain population inversion between state n=3 and n=2. Approximately one phonon energy separates the n=2 and n=1 states. The resonant nature of the optical phonon emission between these two states shortens the lifetime of the n=2 state, preventing any significant population build-up on the latter and maintaining the population inversion. In the first devices,[1] the laser transition was diagonal in real space between states with reduced spatial overlap. This increased the lifetime of the upper n=3 state and decreased the escape rate of electrons into the continuum. However, being less sensitive to interface roughness and impurity fluctuations, a laser structure based on a vertical transition, *i.e.*, with the initial and final states centered in the same well, exhibits a narrower gain spectrum and thus a lower threshold.[3] To prevent electron escape in the continuum, the vertical transition structure's superlattice injector region is designed such that, under bias, a miniband faces the lower states of the active region for efficient carrier escape from the ground state of the lasing transition, and a minigap faces the upper state for efficient carrier confinement (see Fig.1).

The inset of Figure 1 shows the peak optical power versus injected current characteristic of a 2.4 mm long device patterned in a 15 μm wide stripe operating at 4.6 μm wavelength. The threshold density in pulsed mode is J_{th} = 1.7 kA/cm^{-2} at 10K and 3kA/cm^{-2} at 100K, which is two to three times lower than the threshold density of the original structure based on a diagonal transition.[1, 2] The measured slope efficiency (for uncoated devices) is 300 mW/A per facet with a maximum peak power above 60 mW.

In another set of experiments, devices were designed using the same InGaAs/AlInAs heterostructure material at λ=8.4 μm. Threshold densities of 2.1 kA/cm^2 at 10K and 2.8 kA/cm^2 at 100K, with a maximum power of 40 mW at 10K and 25 mW at 100K were obtained in pulsed operation.[4]

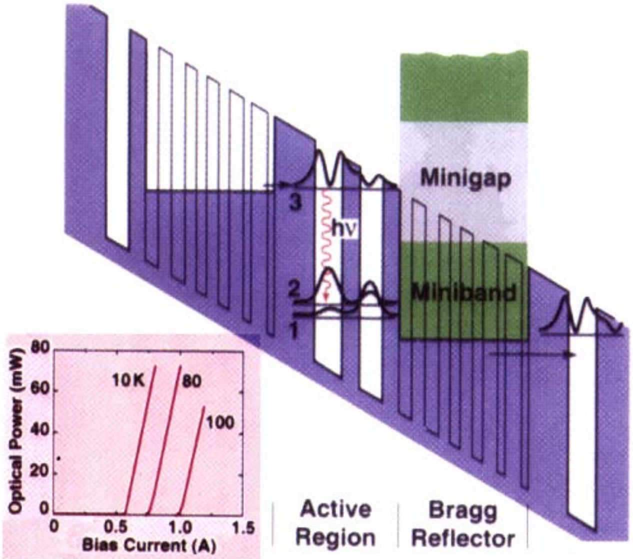

Figure 1. a) Schematic conduction band diagram of a portion of the QC laser under operating conditions. As shown, the superlattice electron injector is designed as an electron Bragg reflector to create a minigap that blocks the electron escape from level 3. Electrons are tunnel-injected via a 6.5 nm AlInAs barrier into the n = 3 subband of the active region. The wavy line indicates the 4.6 μm wavelength transition responsible for laser action. Inset: Peak optical output power from a single facet versus injection current for the structure. The pulse length is 70 nsec. The heat sink temperature is 10K (solid line), 80K (dashed) and 100K (dotted).

References

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Absorption Lineshape and Propagation Effects in Multiple Quantum Well Structures

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In homogeneous structures the experimentally measured absorption, *i.e.*, the ratio of transmitted and input intensity, is directly related to the imaginary part