Vertical transition quantum cascade laser with Bragg confined excited state

Jérôme Faist, Federico Capasso, a) Carlo Sirtori, Deborah L. Sivco, Albert L. Hutchinson, and Alfred Y. Cho

AT&T Bell Laboratories, Murray Hill, New Jersey 07974

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A new midinfrared (λ≈4.5 μm) intersubband quantum cascade laser based on a vertical transition is reported. A superlattice graded gap region was incorporated in the design to provide strong electron confinement in the upper state using a Bragg reflector. Pulsed operation at 100 K is reported with a threshold current density of Jth=3 kA/cm² and a measured slope efficiency of 300 mW/A. © 1995 American Institute of Physics.

We recently demonstrated laser action 1 in a unipolar intersubband laser. In these first devices, 1 population inversion was obtained through two design features. First the laser transition is diagonal in real space, i.e., between states with reduced spatial overlap. This increases the lifetime of the upper state and also decreases the escape rate (τesc)⁻¹ of electrons into the continuum. Second, a third state, located approximately one phonon energy below the lower state of the lasing transition, is added. The resonant nature of the optical phonon emission between these two states reduces the lifetime of the lower one to about 0.6 ps.

However, being less sensitive to interface roughness and impurity fluctuations, 2 a laser structure based on a vertical transition, i.e., with the initial and final states centered in the same well, would exhibit a narrower gain spectrum and thus a lower threshold, provided that the resonant phonon emission scheme is sufficient to obtain a population inversion and that electrons in the upper state can be prevented from escaping into the continuum.

The schematic band diagram of a portion of an InGaAs/AlInAs heterostructure which fulfills the above requirements is displayed in Fig. 1. As in the previous devices, 1 the structure, grown lattice matched on an n⁺ InP substrate by molecular beam epitaxy, consists of 25 stages, each one comprising an active region followed by a graded-gap superlattice. To ensure charge neutrality under strong electron injection in each period of the structure, seven layers in the center of the graded-gap superlattice regions were doped with Si (n=3×10¹⁷ cm⁻²), yielding a sheet density per period n₃=4×10¹¹ cm⁻². To minimize broadening of the lasing transition, the active region, consisting of a 4.5 nm InGaAs well coupled to a 3.6 nm well by a 2.8 nm AlInAs barrier, is left undoped. 2 Being associated with a large momentum transfer, the calculated optical phonon limited scattering time 3 between levels 3 and 2 of the 4.5 nm center well is τ₂₃=1.8 ps. This allows population inversion since electrons in level 2 relax to level 1 through optical phonon emission with near-zero momentum transfer in a time τ₁₂=0.6 ps. Tunneling injection from the superlattice into the active region is through a 6.5 nm AlInAs barrier and electrons escape out of the n=1 state through a 3.0 nm AlInAs barrier.

To enhance the confinement of the upper state in a structure based on vertical transitions and to facilitate electron escape from the n=1 state, we choose to keep the effective conduction band edge of the graded gap superlattice flat under the applied field, as was done in the previous devices, 1 while now requiring that each well and barrier pair satisfy the Bragg reflection condition at an injection energy corresponding to the n=3 state. In mathematical terms, we require that the effective conduction band potential V(xj)

![FIG. 1. Schematic conduction band diagram of a portion of the Ga₀.₄In₀.₆As/Al₀.₄In₀.₆As structure under positive bias condition and an electric field of 8.5×10⁷ V/cm. The dashed lines are the effective conduction band edges of the 20.8 nm thick superlattice graded gap electron injector. As shown, this superlattice is also designed as to create a minigap that blocks the electron escape from level 3. The wavy line indicates the transition responsible for laser action. The moduli squared of the relevant wave functions are shown. (b) Calculated transmission of the superlattice graded gap as a function of energy. The position of the relevant energy states E₁, E₂, and E₃ are also indicated. The energy level differences are E₁−E₂=271 meV, E₂−E₁=30 meV.](image-url)
of the graded gap at the position $x_j$ of the $j$th period, be approximated by

$$V(x_j) = \Delta E_c \frac{l_{b,j}}{l_{w,j} + l_{b,j}},$$

(1)

where $\Delta E_c$ is the conduction band discontinuity between the barrier and well material ($\approx 0.52$ eV), creates a quasielectric field which cancels the applied field at threshold $F_{th}$:

$$\frac{V(x_j) - V(x_{j-1})}{(l_{b,j} + l_{w,j})} = -F_{th}.$$

(2)

Also for each layer pair we have $l_{w,j}, l_{b,j}$ the Bragg reflection condition

$$k_{w,j} l_{w,j} + k_{b,j} l_{b,j} = \pi,$$

(3)

where $k_{w,j}$ and $k_{b,j}$ are the wave numbers in the well and barrier materials. This condition ensures that constructive interference of the electronic waves reflected by all the periods. It was recently shown that electronic quarter-wave stacks can be designed to confine an electronic state in the classical continuum.4,5

For our given upper state energy, this set of equations is solved iteratively for each consecutive layer pair $l_{b,j}$ and $l_{w,j}$ of the graded gap superlattice. This procedure yields successive values of $l_{w,j} = 2.1, 2.1, 1.6, 1.7, 1.3,$ and $1.0$ nm and $l_{b,j} = 2.1$, $1.9, 2.0, 2.3,$ and $2.7$ nm, right-to-left in Fig. 1. A region is created that has, under an electric field, an electronic spectrum similar to the one of a regular superlattice, with a miniband facing the lower states of the active region for efficient carrier escape from the ground state of the lasing transition, and a minigap facing the upper state for efficient carrier confinement [Fig. 1(a)]. This confinement is clearly apparent in Fig. 1(b), where the calculated transmission of the graded gap is plotted versus electron energy at the field $F_{th} = 85$ kV/cm corresponding to the laser threshold. The transmission is very small ($\sim 10^{-4}$) at the energy $E_3$ corresponding to the upper state $n = 3$ while remaining sufficiently large ($>10^{-1}$) at the energy $E_1$ [Fig. 1(b)] to insure a short escape time ($<0.6$ ps) from the $n = 1$ state into the superlattice.

In this structure, the waveguide cladding regions consist of the $n$-InP substrate followed by a 0.7 $\mu$m thick AlInAs $n$-type doped ($1.5 \times 10^{17}$ cm$^{-3}$) buffer layer and, on the opposite side of the core, of a 1 $\mu$m thick AlInAs layer doped to $n = 1.5 \times 10^{17}$ cm$^{-3}$, followed by a 0.6 $\mu$m thick $n$-type ($n = 4 \times 10^{15}$ cm$^{-3}$) AlInAs layer. Between the multistage graded gap coupled well portion of the core and the top cladding region three other regions are inserted. The first is a 14.6 nm AlInGaAs graded region, $n$-type doped to $n = 2 \times 10^{17}$ cm$^{-3}$ with, on top, a 300 nm $n = 1 \times 10^{15}$ cm$^{-3}$ GaInAs layer. The purpose of the latter is to enhance the optical confinement by increasing the difference between the average refractive index of the core and the one of the cladding.3 Between this layer and the cladding an AlInGaAs graded gap region is present to ensure a smooth conduction band edge in the transition region. An $n$-type doped ($2 \times 10^{17}$ cm$^{-3}$), 35.4 nm thick AlInGaAs graded gap region followed by an $n$-type doped ($1 \times 10^{17}$ cm$^{-3}$), 300 nm thick GaInAs layer is also inserted between the bottom AlInAs cladding and the multistage graded gap. Since the polarization selection rules for intersubband transitions require a transverse magnetic (TM) mode, to decouple the guided laser mode from the high loss ($\alpha = 140$ cm$^{-1}$) surface plasmon mode propagating at the metal contact/semiconductor interface, the 10 nm InGaAs contact layer, Sn doped to $2 \times 10^{20}$ cm$^{-3}$ is grown on a 0.7 $\mu$m thick, heavily ($n = 7 \times 10^{18}$ cm$^{-3}$) doped AlInAs layer grown above the top AlInAs cladding, with an intermediate 30 nm thick AlInGaAs region to insure a smooth conduction band profile. The free-carrier contribution to the refractive index of this AlInAs layer reduces the latter$^6$ from $n = 3.198$ to $n = 2.92$, shifting the effective refractive index of the plasmon mode by about the same amount. We computed a confinement factor $\Gamma_p = 2.1\%$ for each of the $N_p = 25$ stages of the active region, an effective index $n_{eff} = 3.22$, and a waveguide loss $\alpha_{wg} = 5$ cm$^{-1}$ for the fundamental guided mode.

The samples were processed into mesa etched ridge waveguides of width $14$ $\mu$m by wet chemical etching. A SiO$_2$ layer, 250 nm thick was then grown by chemical vapor deposition to provide an insulation between the contact pads and the doped InP substrate. Windows were etched through the SiO$_2$ via plasma etching in CF$_4$ gas, exposing the top of the mesas. Nonalloyed Ti/Au Ohmic contacts were provided to the top layer and the substrate. After processing, the samples were cleaved in $L_{cv} = 2.4\sim 3$ mm long bars and soldered with In to a ceramic holder, wire bonded, and mounted in a He flow cryostat. Current pulses of 30 ns duration were then injected in the device with a 20 kHz repetition rate. Figure 2 displays the peak optical power versus drive current obtained by focusing the light with an $f/0.8$ optics on a fast, calibrated, room-temperature HgCdTe detector. At a temperature of $T = 10$ K (solid line), and above a drive current of $I_{th} = 1.0$ A, the signal increases abruptly from microwatts levels to about 10 mW at $I = 1.5$ A. This is a direct manifestation of laser action corresponding to a threshold density of $J_{th} = 2.4$ kA/cm$^2$. The measured threshold bias of 8.5 V corresponding to an electrical field in the active region $F_{th} = 85$ kV/cm is in good agreement with the calculated one (0.5 cm$^{-1}$).
agreement with the value calculated for resonant tunneling injection. In fact, a detailed study of the $I$–$V$ curves of a shorter, nonlasing device shows that for biases around 9 V, a negative differential region appears in the latter, accompanied by quenching of light emission corresponding to the 3–2 transition. This gives strong indication that injection occurs in our devices through resonant tunneling. In the lasing structure, negative resistance is not observed because the electron density in the upper state remains essentially locked at the threshold value. The same peak optical power versus drive current measurements repeated at $T=50$ K (dashed lines) and $T=62$ K (dotted lines) show a relatively strong increase in the laser threshold with increasing temperature, along with a decrease of the differential quantum efficiency. A rate equation analysis showed this large sensitivity of the threshold and relatively low slope efficiencies to originate from backfilling of the carriers from the graded gap region into the state $n=2$ by thermal activation.\(^7\)

In an otherwise identical second sample, we increased therefore the separation $\Delta$ between this state and the quasi-Fermi level in the graded superlattice from $\Delta=50$ meV to $\sim80$ meV by adding a well/barrier pair to the graded-gap superlattice, which consists of wells of lengths $l_w=2.1, 2.1, 1.6, 1.7, 1.3$, and $1.0$ nm and barriers of lengths $l_b=2.1, 2.1, 1.9, 2.0, 2.3, 2.7$ nm. The transmissivity of this improved superlattice is not significantly modified and remains close to the one displayed in Fig. 1(b). As shown in Fig. 3, this modification to the structure strongly improved both the high-temperature performance of the device and the differential quantum efficiency. The threshold density has now a value $J_{th}=1.7$ kA/cm\(^2\) at 10 K and 3 kA/cm\(^2\) at 100 K. The threshold current density $J_{th}$ can be expressed as (in MKSA units and in the low-temperature limit, i.e., $kT/\Delta<1$)

$$J_{th} = \frac{e_0 n_p L_p}{4\pi q N_p} \frac{(\gamma_{32})^2}{(\alpha_m + \alpha_n)} \left[ \frac{\eta_m \tau_3}{1 - \eta_m(1 - \tau_3/\tau_{32})} \right] t_3,$$

where $L_p=45$ nm is the length of each stage, $\lambda=4.6$ $\mu$m the emission wavelength, $\gamma_{32}=1.4$ nm the transition matrix element,\(^6\) \((\tau_{32} + \tau_1)^{-1} = 1.25$ ps the lifetime of level 3, \(\tau_2=0.6$ ps the lifetime of level 2, \(\alpha_m = -\ln(R)/L_{cav} = 5.6$ cm\(^{-1}\) the mirror losses (for $L_{cav}=2.4$ mm); $n=3.22$ is the mode refractive index, $e_0$ the vacuum permittivity. The full-width at half-maximum of the luminescence line $2\gamma_{32}=12.4$ meV is as expected, significantly smaller than the width of the diagonal transitions (22 meV) in the previous QC lasers.\(^1,2\)

In deriving Eq. (4), we assumed that a fraction of the electrons ($1-\eta_m$), where $\eta_m$ is the injection efficiency, are injected into the $n=2$ subband rather than the $n=3$ subband due to elastic/inelastic scattering accompanying the tunneling process. Equation (4) reduces to the expression given in Ref. 1(c) in the limit of $\tau_2$ significantly larger than $\tau_3$. Note that the threshold density is very sensitive to $\eta_m$: the predicted $J_{th}$ is 719 A/cm\(^2\) for ideal injection ($\eta_m=1$), it increases to 1100 A/cm\(^2\) for $\eta_m=0.8$ and no lasing is possible if $\eta_m<0.45$. The discrepancy between the measured and calculated $J_{th}$ can be assigned to heating effects during the pulse, or other physical mechanisms such as intervalley scattering into the L valleys.\(^1\)

Our calculations show that at 100 K, the threshold density is still limited by backfilling, i.e., a further increase in $\Delta$ should lead to a concomitant decrease in the threshold density.

The measured slope efficiency of 300 mW/A per facet corresponds to a differential quantum efficiency per period $\eta_d=4.5\times10^{-2}$ when corrected for the collection efficiency of 0.8. The expression for $\eta_d$ reads

$$\eta_d = \frac{1}{2} \left[ \frac{\alpha_m}{J_{th}} + \frac{\alpha_n}{\eta_m} \right] \left[ 1 - \frac{\tau_2}{\tau_3} \left( \frac{1}{\eta_m} - 1 \right) + \frac{\tau_2}{\tau_{32}} \right].$$

This equation for the slope efficiency deviates from $\eta_d = (1/2)(\alpha_m/\alpha_m + \alpha_n)$ due to the non-negligible value of $\tau_2/\tau_3$ which is significantly larger than in lasers with diagonal transitions.\(^1\) We have for $\eta_m=0.8$, $\eta_d=0.13$. This value is significantly higher than the measured one. This discrepancy is attributed to a variety of causes including parallel current paths (e.g., injection into the L valley) and spatial hole burning.


\(^7\) This effect is weaker for comparable values of $\Delta$ in the quantum cascade laser with diagonal transition due to the longer upper state lifetime.