CHAPTER V

CONCLUSIONS AND OPEN QUESTIONS

In this dissertation we have investigated the possible intersubband stimulated emission in a hypothetical far-infrared quantum-cascade-laser design.[1,2,3,4] In particular we have, for the asymmetric double-quantum-well tunneling structure with schematics shown in Figure 1.1 and resonant-level separation $\Delta \approx 11$ meV, investigated the intersubband decay and resulting population inversion.

In this concluding chapter we first summarize the results of our investigations and then discuss a set of open questions beyond the scope of this dissertation. We stress in particular that while we have demonstrated that a finite intersubband population inversion can be maintained that not does ensure that actual far-infrared (or Tera-Hertz) intersubband lasing will result.

V.A Summary of dissertation results

In the quantum-cascade-laser design[1,2,3,4] a strong nonequilibrium current injection exclusively into the upper subband provides a finite intersubband population inversion *if* the lower-level tunneling escape rate Γ_{c1} *exceeds* the intersubband decay rate Γ_{nr}. An intersubband population inversion density $\Delta n \sim 10^{11}$ cm^{-2} as in the existing mid-infrared quantum cascade laser[1,2,3] will provide a significant net stimulated emission because the intersubband transitions are concentrated at a single frequency ω_Δ given by the subband separation, Δ, and because the optical transitions are characterized by very large dipole matrix elements.

Our choice of specific tunneling structure was motivated by the recent experimental determination[5] of a very small intersubband decay rate — $1/\tau \leq 0.03$ meV at temperatures $T \leq 50$ K — measured at weak optical pumping of the corresponding isolated double-quantum-well structure.[5,6] Such a small intersubband decay rate is possible because the optical-phonon frequency, $\Omega_{LO} \approx 36$ meV, exceeds the subband separation $\Delta \approx 11$ meV. Optical-phonon emission processes are thus inhibited at temperatures below the thermal activation energy,[5] $\Omega_{LO} - \Delta \approx 25$ meV.

We can, as a consequence, assume the total *single*-electron decay bounded, $\Gamma_{se} \leq 0.03$ meV at $T \leq 25$ K, also in the presence of the nonequilibrium current injection. This single-electron decay, i.e., containing interface-defect, impurity, and electron-acoustic/optical-phonon scattering, is in particular much smaller that the lower-level tunneling escape rate, $\Gamma_{c1} \approx 0.5$ meV, that we have estimated for the tunneling structure.

We have found, however, that the exclusive upper-subband current injection results in a very strong nonequilibrium electron-electron scattering which we have evaluated assuming a complete upper-subband occupation below the emitter chemical potential, $\mu_L \equiv E_2 + \mu_2$. We have in particular estimated the nonequilibrium scattering Γ ($\Gamma_{22\to21}$) which involves two upper-subband electrons which both decay (of which only one decays) to subband E_1 and have found that neither scattering rate is significantly affected by screening. Also, the dominant scattering rate Γ is not affected by the Pauli exclusion principle since we have assumed population inversion. Moreover, we have found that measured large[5,6] depolarization shift,[7,8,9,10] $\Delta^* - \Delta \approx 2$ meV, of the equilibrium absorption peak, Δ^*, directly indicates a very strong nonequilibrium scattering (Γ.)

We have consequently provided a detailed study of the nonequilibrium electron-electron intersubband scattering within the Figure 1.1-tunneling structure and have (1) identified a simple scaling of nonequilibrium electron-electron scattering rate Γ with the electron occupation μ_2, (2) explained how the Pauli exclusion within the upper-subband prevents such a scaling for the scattering rate $\Gamma_{22\to 21}$, (3) identified a dramatic voltage-drop dependence of both nonequilibrium electron-electron scattering rates, Γ and $\Gamma_{22\to 21}$, associated with the quantum-confined Stark effect[11] on the wavefunction inversion symmetry,[12] (4) documented that this wavefunction-symmetry variation in particular allows a significant reduction of also the combined electron-electron intersubband decay, $\sim 2\Gamma + \Gamma_{22\to 21}$, (5) predicted a very strong decay rate, $\sim 2\Gamma \approx 1$ meV, for an upper-subband sheet-density, $n_2 \approx 10^{11}$ cm^{-2}, comparable to that in the mid-infrared quantum cascade laser,[1,2,3] and finally (6) demonstrated that a smaller population inversion density ($\sim 0.2 \times 10^{11}$ cm^{-2}) *can* be maintained at a moderate tunneling current density.

V.B Open questions

We have in this dissertation demonstrated that an intersubband population inversion *can* be maintained thanks to the nonequilibrium current injection. The predicted population inversion is smaller than the intersubband inversion in the existing mid-infrared quantum cascade laser[1,2,3] and it reasonable to question if a comparable net stimulated emission can be obtained. Specifically, it is relevant to ask: **(a)** is it possible to achieve a peak material gain comparable to that in the mid-infrared quantum cascade laser? and **(b)** if so, is it possible to achieve a good waveguide confinement of the resulting radiation and hence achieve actual lasing?

A definite answer to either of these questions is beyond the scope of this dissertation. Below we include only a brief discussion and emphasize (in addressing point **(b)**) that although a net stimulated far-infrared emission may appear possible that does *not* ensure the realization of actual lasing.

(a) The peak material gain.

The peak material gain is introduced in Section II.C as the amplification of the (potentially) lasing mode (of frequency ω_Δ) when traveling entirely within a superlattice of back-to back optically active tunneling structures and interjacent injector layers serving as emitter and collector leads.

The optical transitions betweens subbands E_i and E_j is described by the oscillator strength

$$f_{ij} \equiv 2m_e^* \Delta |\langle \Psi_i | x | \Psi_j \rangle|^2, \tag{1}$$

through which we can in particular express the total spontaneous emission rate

$$\Gamma_{ij}^{sp} \propto f_{ij} \Delta^2. \tag{2}$$

The peak material gain depends in turn on both this total spontaneous emission rate, Eq. (2), the line width, Γ_ϕ, of this spontaneous emission, and on the intersubband population-inversion density

$$\gamma_{mat}(\omega_\Delta) \propto (\Delta n/\Gamma_\phi)\left(\frac{\Gamma_{ij}^{sp}}{\omega_\Delta^2}\right). \tag{3}$$

However, both the mid-infrared quantum cascade laser[1,3] and the Figure 1.1 tunneling structure is characterized by very large oscillator strengths, $f_{ij} \sim 1$. Thus it is clear that the discussion of the resulting peak material gain reduces to a comparison of the ratio $\Delta n/\Gamma_\phi$, for the two quantum-well tunneling structures.

On the one hand we have in Section IV.E (at the avoided crossing $V = V_{sym}$) estimated a population inversion density,

$$\Delta n \lesssim 0.17 \times 10^{11}\ \mathrm{cm}^{-2}, \tag{4}$$

significantly smaller than the value, $\gtrsim 10^{11}\ \mathrm{cm}^{-2}$, reported[3] for the mid-infrared quantum cascade laser.

On the other hand, however, the mid-infrared quantum cascade laser is characterized by a wide spontaneous emission peak with a full-width-at-half-maximum value,[3] $2\Gamma_\phi^{qcl} \approx 22$ meV. This wide emission peak results in part from the significant interface-scattering in the very narrow (8 Å) upper-resonant-level quantum well. One can thus hope that the wider quantum wells of the hypothetical Figure 1.1 tunneling structure will result in significantly smaller values for Γ_ϕ.*

* It is in particular encouraging that the measured (equilibrium) *absorption* peak for the corresponding isolated double-quantum-well structure[5,6] appears limited by the temperature[13] T even at $T \sim 10$ K. This measured absorption line width tend to predict a narrow spontaneous emission peak (described by $2\Gamma_\phi \sim 1$ meV) in the Figure 1.1-tunneling structure. On the other hand, the increased scattering under the nonequilibrium conditions (i.e., current injection) may cause a finite increase in the value Γ_ϕ.

(b) The waveguide confinement

In addition to a large peak material gain, the realization of actual intersubband lasing also requires the design[1,2,3] of a good waveguide confinement. Specifically, because of the finite extension of the optically active superlattice such a waveguide is, as discussed in Section II.D, essential to (i) concentrate the lasing mode which can then stimulate further transitions, and (ii) prevent reabsorption in the (heavily) doped outside regions.

In discussing the problems involved in achieving such a waveguide confinement for a far-infrared (potentially lasing) mode we assume that the optically active superlattice (comprising tunneling regions and interjacent leads) is surrounded by a set of waveguide cladding layers with a lower effective index of refraction. We furthermore assume these cladding layers are doped to $N_{3D} \geq 1.5 \times 10^{17}$ cm^{-3} (as in the mid-infrared quantum cascade laser) which should prevent a large plasmon reabsorption of the far-infrared radiation emitted at $\omega_\Delta \approx \Delta \approx 11$ meV. Specifically, the choice of $N_{3D} \geq 1.5 \times 10^{17}$ cm^{-3}, results in plasmon frequencies,

$$\Omega_{pl} = 4\mathrm{Ry}^* \sqrt{N_{3D}\pi(a^*)^3} \geq 16 \text{ meV}. \tag{5}$$

To discuss the resulting waveguide confinement we follow the discussion in Section II.D. In particular we denote by n_{mode} (n_{clad}) the effective index of refraction of the far-infrared mode (the background index of refraction of the cladding layers) and obtain the estimate,

$$\frac{1}{\kappa_{pl}} \sim \frac{1}{2\pi} \frac{\lambda_\Delta}{\sqrt{n_{mode}^2 - n_{clad}^2 + (\Omega_{pl}/\omega_\Delta)^2}}, \tag{6}$$

for the decay length of the mode into the cladding layers. Note that, in contrast to the discussion in Section II.D, we have in Eq. (6) kept the plasmon contribution, $(\Omega_{pl}/\omega_\Delta)^2$, to the cladding-layer effective dielectric constant because ω_Δ is now *smaller* than this plasmon frequency, Ω_{pl}.

It follows from Eq. (6) that the waveguide confinement may thus be *aided* by a large plasmon frequency in the cladding layers. It is in particular possible that the waveguide confinement can be improved by increasing the doping concentration in the cladding layers. However, because such an increase of the doping concentration will also result in an increased impurity-aided single-electron reabsorption[14] it is uncertain if this will provide an actual increase in the net effective gain.

It is in any case clear from Eq. (6) that the long wavelength, $\lambda \sim 100$ μm, of the far-infrared radiation will make a good waveguide confinement very difficult. Specifically, it appears necessary to grow waveguide cladding layers significantly thicker than in the mid-infrared quantum cascade laser[1,2,3] to achieve a similar waveguide confinement of the far-infrared radiation.

Finally we observe, as a consequence, that even a significant material gain does not ensure that actual lasing can be realized in the far-infrared regime. On the other hand, a far-infrared quantum-cascade-laser design might still be able to serve as an amplifier of such radiation generated by other means. It may in particular be possible to amplify the (pulsed) coherent radiation arising from quantum beats or Bloch oscillations[15,16] in the asymmetric double-quantum-well tunneling region with a femto-second *interband* optical excitation. The build-in advantage of amplifying such quantum-beats radiation would be that the radiation pulse is automatically tuned at (or close to) the peak material gain at frequency $\omega_\Delta \sim \Delta$.

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