Contribution of Electron-Electron Interactions to the Total Electron Scattering Rates in Quantum Cascade Laser in Magnetic Field

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ABSTRACT

Quantum Cascade Laser (QCL) represents one of the finest examples of the impact that quantum-mechanical engineering and the tuning of basic structural parameters can have on structure's output characteristics. Intersubband transitions in QCLs are associated with very fast transport of carriers and this has a strong influence on laser performance. Given that these processes are characterized by an extremely short carrier lifetime in the excited state (of the order of 1 ps), threshold currents in this type of lasers exceed those in conventional interband lasers [1]. For this reason, a strong magnetic field is introduced. It contributes to reducing of the system dimensionality by introducing additional quantization of the electron motion in the x-y plane, thus splitting the two-dimensional subbands into a series of discrete Landau levels (LLs), whose energies depend on the field [4]- [6]. Hence, by varying the strength of this field, we are able to detect regions with significantly reduced scattering rates. This applies to all relevant types of scattering - electron/(optical and acoustical) phonon and electron/electron scattering.

In the previous work [7], the optical gain in QCLs in a strong magnetic field has been calculated by considering only the electron relaxation processes due to longitudinal optical (LO) and acoustic (AC) phonon induced transitions between Landau levels. The method is based on determining the electron scattering rates, then finding the electron distribution over the states of the system by solving the full set of rate equations describing the transitions between levels, and eventually calculating the optical gain. Here, we have expanded the model by considering the influence of electron-electron scattering processes in three and four level QCL in a strong magnetic field, and compared the calculated values with previously obtained ones.

NUMERICAL RESULTS

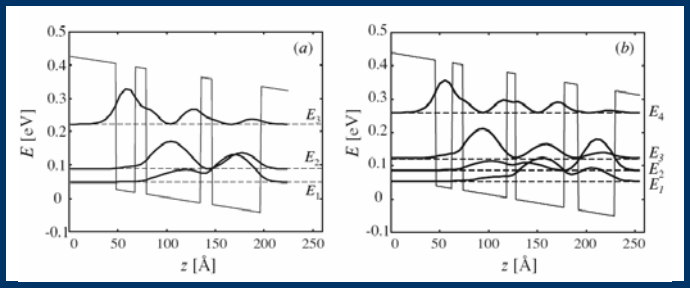

FIGURE 1. *(a) The conduction-band diagram of the active region of a GaAs/$Al_{0.45}Ga_{0.55}$ As QCL described in detail in [3], in an electric field of 48 kV cm^{-1} and zero magnetic field. The layer widths are 46, 19, 11, 54, 11, 48 and 28 Å, going from emitter towards the collector barrier. The corresponding wave functions squared are also shown. (b) Active region of the optimized double-LO phonon GaAs/$Al_{0.45}$ $Ga_{0.55}$ As structure fully described in [4,8]. The layer widths are 46, 17, 11, 45, 8, 50, 14, 38 and 25 Å , going from emitter towards the collector barrier. The subband positions, together with the corresponding wave functions squared, are given at zero magnetic field, and the electric field is 48 kV cm^{-1}.*

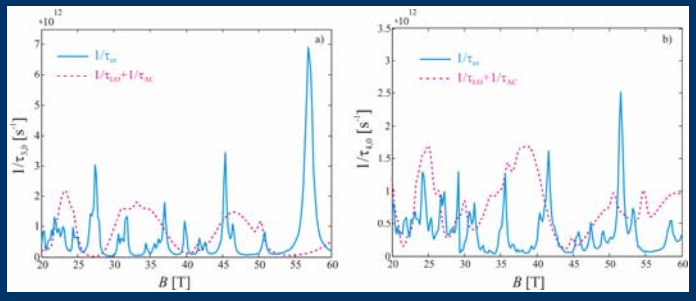

FIGURE 2. *(a) scattering rate diagram of electrons from the upper laser level, for the three-level QCL structure, due to electron-electron (solid line), and electron-phonon (dashed line) scattering (b) scattering rate diagram of electrons from the upper laser level for the four-level QCL structure.*

THEORETICAL CONSIDERATIONS

The relaxation rate due to electron-electron scattering can be represented by:

$$W_{kl,mp} = \frac{4\pi}{\hbar}\left|V_{kl,mp}\right|^2 \delta\left(E_k + E_m - E_l - E_p\right)$$

where the matrix element, which contains the perturbation potential, has the following form:

$$V_{kl,mp} = \int \Psi_k^*(\vec{r})\Psi_m(\vec{r}')\hat{H}_{e-e}\Psi_l(\vec{r})\Psi_p(\vec{r}')$$

Indices *k* and *m* correspond to the initial, and *l* and *p* to the final states. The perturbation potential used for calculating the matrix element is Coulomb's potential:

$$\hat{H}_{e-e} = \frac{e^2}{4\pi\varepsilon\left(\vec{r}-\vec{r}'\right)}$$

In order to obtain the total scattering rate via Fermi's golden rule, $\left|V_{kl,mp}\right|$ must be squared and then integrated over the two final state "indices" β_m and β_p. Finally, the result of these integrations needs to be averaged over the initial state index β_k. This results in a seven-fold integral for the matrix element for two-electron transition between initial (*k*,*m*) and final (*l*,*p*) states, hence the execution of numerical calculations in this model is an extremely demanding task. The maximum possible resolution, that is the number of points in which the integration is to be performed, represents a compromise between the desired accuracy and a reasonable computational time.

The electron relaxation processes due to longitudinal optical (LO) and acoustic (AC) phonon induced transitions between Landau levels have already been analyzed in [7]. It is apparent that electron-electron scattering is strongly influenced by magnetic field variations and that these processes cannot be neglected in the course of calculating optical gain of the structure.

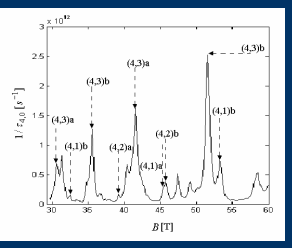

FIGURE 3. *Series of peaks describing two types of situations in the four level system, when (a) one of the LLs from lower subbands matches the upper laser level, and (b) when there are two LLs from the same subband in the vicinity of the upper laser level, equally spaced above and below it. The right indices in the figure refer to lower subbands that the corresponding LLs stem from.*

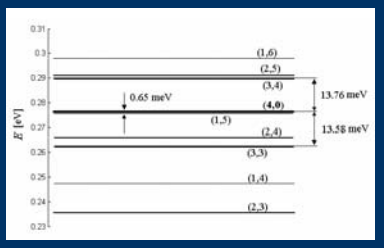

FIGURE 4. *Illustration of the electronic structure of the four level QCL when one of the maxima is obtained, for B=35.6 T, in the vicinity of the highest (4,0) level. In this figure, the second index refers to the LL. Dominant transitions occur into the final states (3,3) and (3,4), with their energy separations from (4,0) indicated in the figure. Although level (1,5) is very close to (4,0), the corresponding matrix element is rather small (≈ 30 times smaller than for the other two transitions).*

REFERENCES

[1] C. Becker, C. Sirtori, O. Drachenko, V. V. Rylkov, D. Smirnov and J. Leotin, *Appl. Phys. Lett.* 81 (2002) 2941

[2] H. Page, C. Becker, A. Robertson, G. Glastre, V. Ortiz and C. Sirtori, *Appl. Phys. Lett.* 78 (2001) 3529

[3] A. Mirčetić, D. Indjin, Z. Ikonić, P. Harrison, V. Milanović and R. W Kelsall, *J. Appl. Phys.* 97 (2005) 084506

[4] G. Scalari, M. Graf, D. Hofstetter, J. Faist, H. Beere and D. Ritchie, "THz quantum cascade detector in a strong perpendicular magnetic field *Semicond. Sci. Technol.* 21 (2006) 1743

[5] L. Y. Yu, J. C. Cao, and C. Zhang, "Optical absorption coefficients in two-dimensional semiconductors under strong magnetic field", *J. Appl. Phys.* 99, 123706 (2006)

[6] A. Leuliet, A. Vasanelli, A. Wade, G. Fedorov, D. Smirnov, G. Bastard, and C. Sirtori, "Electron scattering spectroscopy by a high magnetic field in quantum cascade lasers", Phys. Rev. B 73, 085311 (2006).

[7] J. Radovanović, A. Mirčetić, V. Milanović, Z. Ikonić, D. Indjin, P. Harrison and R. W. Kelsall, *Semicond. Sci. Technol.* 21 (2006) 215

[8] D. Indjin, S. Höfling, A. Mirčetić, V. D. Jovanović, Z. Ikonić, N. Vukmirović, P. Harrison, R. W. Kelsall, V. Milanović, J. P. Reithmaier and A. Forchel, *MIOMD-7 (Lancaster, UK, 12–14 Sept.)* (2005) p. 49 (Abstract Book)

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