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

Jelena Radovanović, Božidar Novaković, Aleksandra Mirčetić, Vitomir Milanović, Zoran Ikonić,
Dragan Indjin

***Abstract*—The aim of this work is to calculate carrier relaxation rates from the upper laser level due to electron-electron interactions in three and four-level quantum cascade lasers (QCLs) in a strong magnetic field. The comparison between calculated results and previously obtained values for acoustical and optical phonon scattering processes indicates that carrier-carrier scattering might have noticeable influence on laser output properties, depending on the structural design. Numerical results are presented for two λ~9µm GaAs–based QCLs in magnetic fields between 20 T and 60 T and the band nonparabolicity is taken into account.**

***Index Terms*—Quantum well lasers, Scattering, Magnetic fields**

I. INTRODUCTION

THE *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.

II. USED STRUCTURES AND RESULTS

A. *Structures*

The structures used in calculations are the active regions of three and four level $GaAs/As_{0.45}Ga_{0.55}$ QCLs previously described in [2] and [3], respectively. The classically designed active region of a QCL structure comprises three coupled quantum wells (*QWs*) biased by an external electric field. This system has three energy subbands $(n = 1, 2, 3)$, and the laser transition takes place between subbands $n = 3$ and $n = 2$, named the upper and the lower laser state, respectively. The supplementary subband $(n = 1)$ is positioned one LO phonon energy below the lower state of the laser transition with the role of assisting its fast depopulation via resonant optical-phonon emission. This is known as a single LO phonon depopulation mechanism.

Another design possibility for the active region, which is expected to provide a more efficient extraction of electrons from the lower laser state, comprises four QWs. This structure accommodates an extra level, which belongs to a 'ladder' of

Jelena Radovanović is with the Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia (phone:381 113370163, fax: 381 11 3248681, e-mail: radovanovic@etf.bg.ac.yu)

Božidar Novaković is with the Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia (e-mail: bozansec@yahoo.com)

Aleksandra Mirčetić is with Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia (e-mail: aleksandram@telekom.yu)

Vitomir Milanović is with the Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11120 Belgrade, Serbia (e-mail: milanovic@etf.bg.ac.yu)

Zoran Ikonić is with the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK (e-mail: Z.Ikonic@leeds.ac.uk)

Dragan Inđin is with the Institute of Microwaves and Photonics, School of Electronic and Electrical Engineering, University of Leeds, Woodhouse Lane, Leeds LS2 9JT, UK (e-mail:D.Indjin@leeds.ac.uk)

three states being mutually separated by exactly one LO phonon energy. In view of that, the active subbands corresponding to the laser transition are now marked as $n = 4$ and $n = 3$. This so-called 'double-LO' structure is predicted to have a decreased lower laser level carrier lifetime and consequently a higher degree of population inversion [3, 8].

B. Results

The execution of numerical calculations within this model is an extremely demanding task due to the existence of a seven-fold integral representing the matrix element for two-electron transition between initial *(k, m)* and final *(l, p)* states. A large number of cycles need to be performed, so certain approximations have to be made. These convenient simplifications provide considerable reductions in the number of possible combinations. 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 results of numerical calculations of the relaxation rates from the lowest LL of the upper laser level, taking into account all three types of scattering, are presented in Figs. 1(a) and 1(b) for the three and four level QCL structures, respectively.

III. CONCLUSION

We have presented a detailed model, together with numerical results, for calculating electron relaxation rates in three (the conventional TQW structure) and four-level (the 2LO phonon structure) QCL, in strong magnetic fields. In particular, the aim of this work is to obtain the electrons relaxation rates from the upper laser level due to electron-electron interactions and compare them with previously found electron-phonon relaxation rates. It is apparent that electron-electron processes cannot be neglected in the course of calculating optical gain of the structure. Furthermore, this type of scattering is strongly influenced by magnetic field variations as well. Hence, in order to attain more accurate results, this contribution to the total relaxation rate needs to be included in the system of rate equations while calculating optical gain of the whole system.

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** 1743-1746, 2006.

[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)

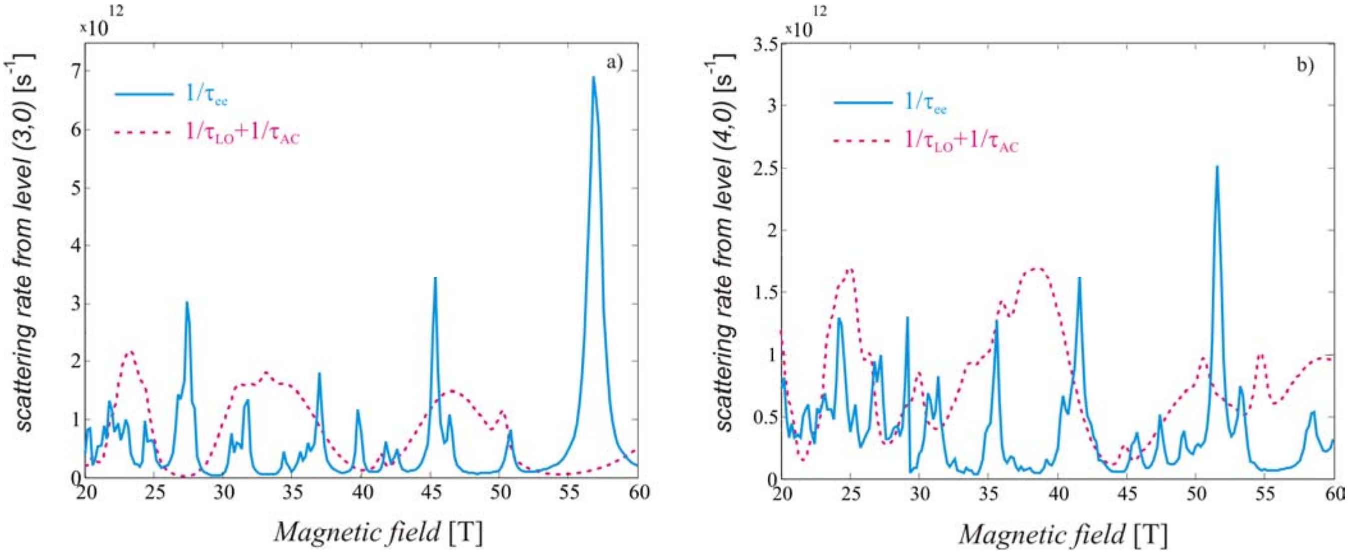

Fig. 1. (a) scattering rate diagram of electrons from the upper laser level, for the three-level QCL structure, due to electron-electron (solid line), and electron-phonon (dashed line) scattering (b) scattering rate diagram of electrons from the upper laser level for the four-level QCL structure.