Band Structure Engineering for Terahertz Quantum Cascade Lasers

J. Ulrich, R. Zobl, W. Schrenk, G. Strasser, K. Unterrainer, E. Gornik

**Institut für Festkörperelektronik,TU Wien,
Floragasse 7, 1040 Wien, Austria**

We have investigated intra- and interwell transition schemes in magnetotransport and intersubband electroluminescence experiments regarding their potential as a central part of a terahertz quantum cascade laser. The conductivity of the interwell structure is smaller, indicating a reduced nonradiative scattering rate compared to the intrawell structure. The interwell transition exhibits a Stark shift, as expected. The intrawell transition shows a smaller shift which agrees with band structure calculations.

1. Introduction

The need of compact sources of coherent radiation in the frequency regime between 1 and 10 THz has stimulated the development of a terahertz (or far-infrared) quantum cascade (QC) laser [1] – [3]. A simple scaling of successful band structure concepts of mid-infrared QC-lasers [4] is impracticable because resonant emission of longitudinal optical (LO) phonons (in GaAs at 8.7 THz, 36 meV) cannot be utilized likewise, and fast non-radiative intersubband relaxation counteracts population inversion [1]. The relaxation rate decreases as initial and final subband of the laser transition are spatially separated by a barrier. Two band structure schemes (emission around 18 meV, 4.4 THz) have been compared, one based on an intrawell transition between the second and the first subband of one quantum well, the other based on an interwell transition between the first subbands of two adjacent quantum wells separated by a barrier [5].

2. Experimental

The samples consist of 50 periods of a 3-well system with GaAs wells and $Al_{0.15}Ga_{0.85}As$ barriers grown on n+-doped GaAs substrates employing molecular beam epitaxy. The central well of each period is lightly n-doped ($1x10^{16}$ cm-3). On top of the layer system is a 100 nm thick n+-doped GaAs contact layer. Calculated conduction band profiles of the two samples are shown in Fig. 1. The structures were designed for emission between the subbands denominated as |i> (initial) and |f> (final). The narrower quantum wells serve as an energy filter to extract electrons from |f> and inject them into the subband |i’> of the adjacent period. We processed emission samples as 4 (intrawell) or 32 (interwell) parallel ridge mesas, each of the dimensions 25 µm x 1000 µm, with 25 µm distance between them. These ridges are connected on both ends with two perpendicular mesas of 175 µm x 80 µm (intrawell) or 1575 µm x 80 µm (interwell), which serve as bond pads. The total surface of the mesas is 0.112 mm^2 (intrawell) or 0.924 mm^2 (interwell). The mesas were shaped by 4.3 µm deep reactive ion etching through the whole layer system into the substrate. Ohmic AuGe contacts were then produced on top of the mesa structure and on the backside of the substrate.

The magnetotransport- and electroluminescence measurements were performed in the same set-up [2]. The spectral response of an InSb cyclotron resonance photodetector was tuned in the magnetic field B of a superconducting magnet from 8.7 meV (B = 1 T) up to 26 meV (B = 3.4 T). The detector and the sample were located in a closed waveguide immersed in liquid He. A second magnet controlled the magnetic field oriented perpendicular to the epitaxial layers at the position of the sample. In all measurements we applied 22 µs long voltage pulses at 23 kHz repetition rate between the top and the back contact.

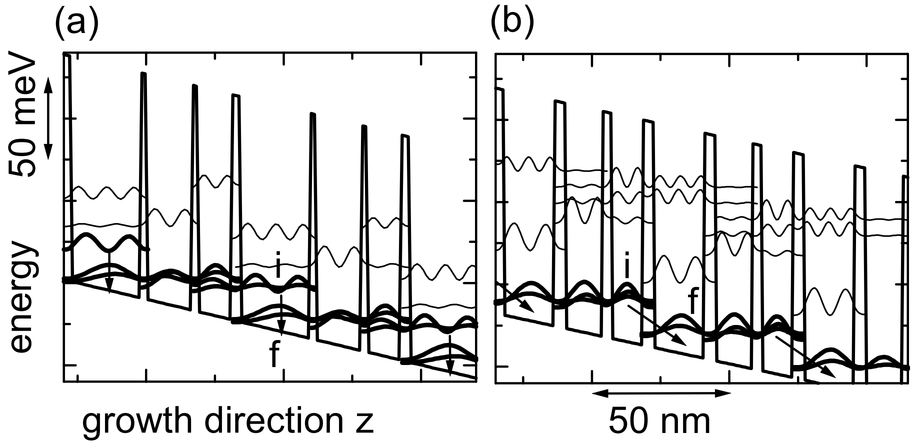

Fig. 1: Band structure calculation for 2½ periods of (a) the intrawell and (b) the interwell structure at an electric bias of 3.6 kV/cm. The moduli squared of the envelope wavefunctions of the involved subbands (thick lines) and of higher subbands (thin lines) are plotted at their energies. The radiative |i>-|f>-transitions are marked with arrows. The well- and barrier (underlined) widths in nm are: (a) 25.0 / <u>2.7</u> / 16.0 / <u>2.5</u> / 12.4 / <u>2.8</u> and (b) 18.5 / <u>4.0</u> / 13.5 / <u>3.3</u> / 11.4 / <u>4.0</u>.

The conductivity of the two samples is remarkably different, for example, the current densities at a bias of 5 kV/cm are 419 A/cm^2 in the intrawell sample and 31 A/cm^2 in the interwell sample. This is a direct consequence of the different spatial overlaps between the |i> and |f> subbands. We conclude that the |i> – |f>-transition rate governs the transport through the whole structure. In a magnetic field the current is quenched in an oscillatory manner as depicted in Fig. 2(a). The quenching originates from a suppression of intersubband scattering caused by Landau quantization of the in-plane electron motion. The maxima in the current resemble magneto-intersubband resonances [6]. The knowledge of the resonance positions allows a determination of the subband energy difference. Identifying the current maxima with a change of Landau index of M = 2, 3, 4, 5 and using the GaAs effective mass $m^* = 0.0667\ m_e$, we derived the transition energies plotted in Fig. 2(c) versus the electric field. The data should be compared with the center frequency of the electroluminescence peak (solid circles). Some original spectra are given in Fig. 2(b). For a pure intrawell transition no first order Stark shift is expected since the centers of charge of |i> and |f> are at the same position. In the high bias region (F > 6 kV/cm) the energy of the transition is fairly field-independent (left panel of Fig. 2), whereas at low biases it changes from 17 meV (at 2 kV/cm) to 20 meV (at 6 kV/cm). The transition energy was calculated (Fig. 2(c), line) solving Poisson's and Schödinger's equations. Apart from an offset of 1.8 meV the experimental data are well described by the calculation. The energy of the interwell transition (right panel of Fig. 2) suffers a clear Stark shift, visible in the magnetotransport as well as in the electroluminescence data. The linewidth is on the average 0.4 meV broader than that of the intrawell transition. This is consistent with the argument of alloy scattering in the barrier. The slope of the measured Stark shift is somewhat smaller than the one predicted by the calculation under the assumption of a homogeneous electric field.

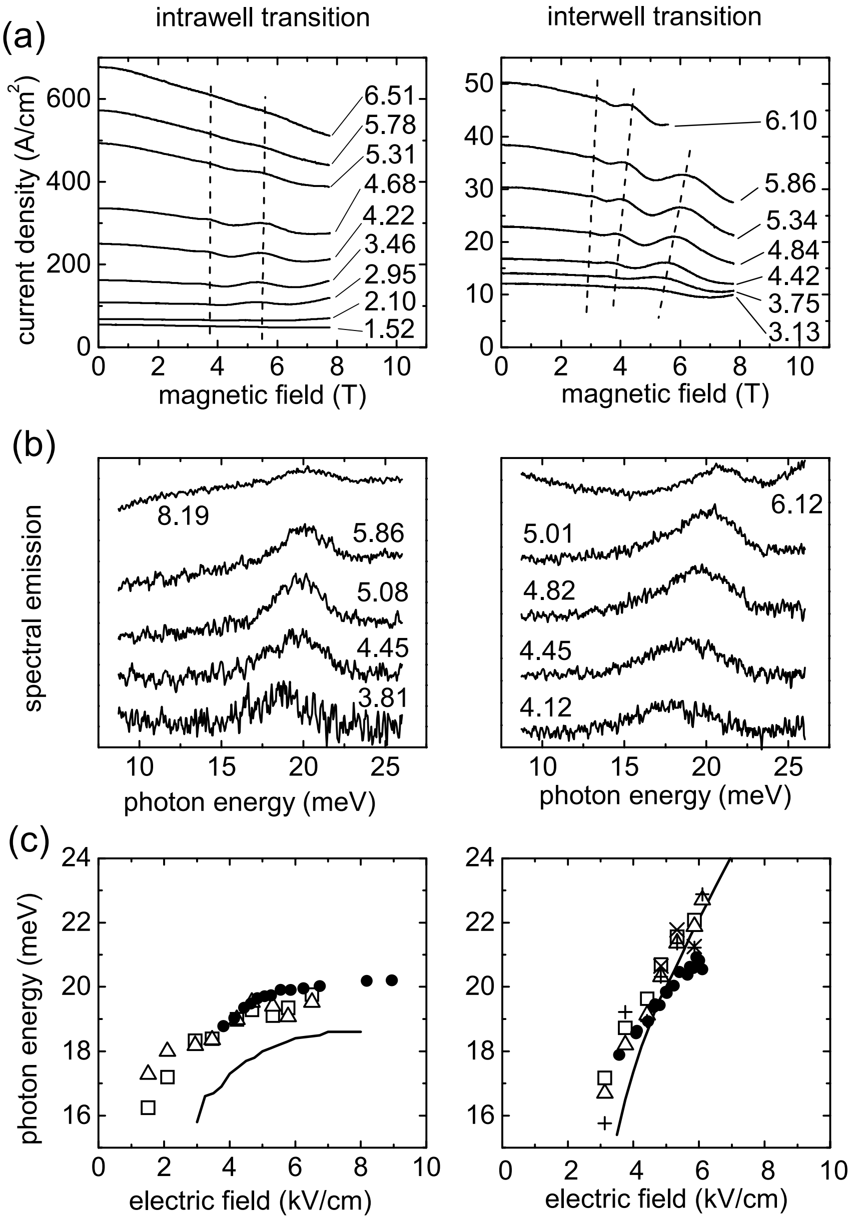

Fig. 2: (a) Current density versus magnetic field for various values of the electric field given in kV/cm. The dashed lines mark the magneto-intersubband resonances. (b) Electroluminescence spectra at electric fields as indicated in kV/cm. The spectra are plotted with arbitrary offsets. (c) Transition energy versus electric field extracted from the positions of the magneto-intersubband resonances for M = 2 (open squares), 3 (open triangles), 4 (+) and 5 (x); photon energy from the electroluminescence spectra (solid circles); and transition energy $E_i - E_f$ from Poisson-Schrödinger caculations (line).

3. Conclusion

Our comparison of an intrawell and an interwell quantum cascade structure yields: The interwell sample exhibits a Stark shift. This transition scheme could therefore form the basis of an electrically tunable source. The energy of the intrawell transition is also blue shifted in an electric field as the mixing of the transition subbands with those of the injectors is reduced. The lower current density of the interwell sample at an emission intensity, comparable to that of the intrawell sample, demonstrate the reduction of non-radiative scattering by spatial separation of the |i> and |f> subbands. A low scattering rate is an essential condition for population inversion and hence for lasing.

Acknowledgements

This work was supported by the Austrian Science Foundation (START Y47, Wittgenstein Award) and by the EU-TMR Program (INTERACT).

Reference

[1] M. Rochat, J. Faist, M. Beck, U. Oesterle, M. Ilegems: “Far-infrared (λ= 88 μm) electroluminescence in a quantum cascade structure” *Appl. Phys. Lett.*, vol. 73, pp. 3724 – 3726, 1998.

[2] J. Ulrich, R. Zobl, N. Finger, K. Unterrainer, G. Strasser, E. Gornik: “Terahertz electroluminescence in a quantum cascade structure”, *Physica,* vol. B 272, pp. 216 – 218, 1999.

[3] B. S. Williams, B. Xu, Q. Hu, M. R. Melloch: “Narrow-linewidth terahertz intersubband emission from three-level systems”, *Appl. Phys. Lett.,* vol. 75, pp. 2927 – 2929, 1999.

[4] J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, A. Y. Cho: “Quantum cascade laser”, *Science,* vol. 264, pp. 553 – 556, 1994.

[5] J. Ulrich, R. Zobl, W. Schrenk, G. Strasser, K. Unterrainer, E. Gornik: “Terahertz quantum cascade structures: Intra- versus interwell transition”, *Appl. Phys. Lett.,* vol. 77, 1928 – 1930, 2000.

[6] J. Ulrich, R. Zobl, K. Unterrainer, G. Strasser, E. Gornik: “Magnetic-field-enhanced quantum-cascade emission”, *Appl. Phys. Lett.* vol. 76, pp. 19 – 21, 2000.