International Journal of Modern Physics B, Vol. 16, Nos. 20, 21 & 22 (2002) 2952–2955

INTERSUBBAND MAGNETOPHONON RESONANCES IN QUANTUM CASCADE STRUCTURES

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We report on magnetotransport measurements of GaAs/GaAlAs quantum cascade structures in magnetic fields up to 62 T parallel to the current. We observe novel quantum oscillations series in tunneling current that are periodic in reciprocal magnetic field and have field positions *independent* of the applied bias. These oscillations are explained as intersubband magnetophonon resonance due to electron relaxation by emission of optical or acoustic phonons.

The magnetophonon effect is a powerful tool to investigate electron-phonon interaction in semiconductor systems, particularly in confined structures.[1] For the in-plane transport in a two dimensional (2D) electron gas of a quantum well (QW), quantization of the carrier motion into discrete Landau levels (LLs) gives rise to quantum oscillations at elevated temperatures due to resonant absorption of LO phonon.[2] The resonance field positions are at $B_N=\frac{1}{N}\frac{m^*}{e}\omega_{LO}$. In the case of perpendicular transport, magnetotunneling measurements in 2D double barrier (DB) quantum well structures have evidenced optical-phonon-assisted tunneling from 2D LLs emitter states into LLs of the DB central well.[3] However, these measurements did not show any evidence of intersubband resonant relaxation via optical phonon inside the central QW of the DB. This relaxation scheme occurs when electrons injected in the Landau ground state of a j-th subband $E_{j,0}$ relax by resonant emission of a LO phonon into a Landau state of an i-th subband $E_{i,N}=E_i+N\hbar\omega_C$. This magnetophonon resonance process is characterized by the equation $\hbar\omega_{LO}=E_j-(E_i+N\hbar\omega_C)$, which defines field positions at $B_N=\frac{1}{N}\frac{m^*}{e}\left(\frac{E_j-E_i}{\hbar}-\omega_{LO}\right)$. In this case, the intersubband distance in the central well must exceed the optical phonon energy $\hbar\omega_{LO}$. We report in this paper the intersubband magnetophonon effect in vertical transport measurements of DB structures based on GaAs/GaAlAs.

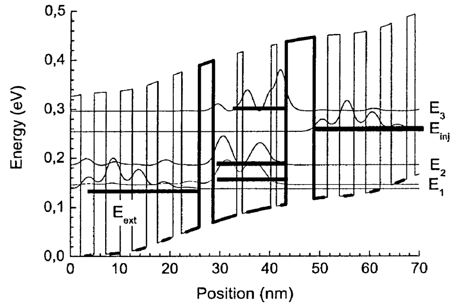

Figure 1: Electronic structure of a GaAs/GaAlAs QCL sequence biased at 117 mV per period. Ground state subband energy levels and wave functions of the DB system are displayed.[6]

For this purpose, we used a specific DB structure, which is implemented in quantum cascade lasers (QCLs) (see Ref. [4]).

The QCLs consist of sequences of DB-like structures, each consisting of a central QW structure between a 2D emitter and collector. When a suitable high bias voltage is applied to the QCL, the upper subband in the central QWs becomes populated by tunneling injection while the ground state is quickly emptied by tunneling collection. In this voltage bias range, the current becomes dependent on electron recombination rates inside the central QWs. This opens up the possibility to detect intersubband magnetophonon resonance as current oscillations under constant voltage bias or conversely voltage oscillations at constant current. Considering the constant current situation, we have a fixed electron supply rate into the central well which is equal to the recombination rate into the QWs ground state: n/τ , n being the upper subband electron population and τ its lifetime. As a result, if the relaxation rate $1/\tau$ increases, the electron population in the QW decreases. This builds up a positive charge in the well which in turn decreases the bias across the emitter barrier and consequently across the entire QCL sample.

Magneto-tunneling measurements were performed in magnetic fields up to 62T generated by a pulsed magnet with total pulse duration of 100ms (see Ref. [5]). GaAs/GaAlAs QCL samples including forty periods[6] were measured at 4.2K with constant DC current applied parallel to the magnetic field. Figure 1 depicts the electronic structure along a sequence Emitter-QWs-Collector of the QCL structure under applied bias. In this system, the central QWs include three coupled wells developing three subbands E_1, E_2 and E_3. Emitters and the collectors are identical multi-quantum-wells structures which are degenerately n-doped in their central portion at the concentration of $6{\cdot}10^{11}$ cm^{-3}. The electronic structure was obtained by a self-consistent calculation including electron charge transfer across the DB sequence. The calculated intersubband separations agree well with our optical measurements data: $E_3-E_2= 108.7$ meV, and $E_3-E_1= 147$ meV.

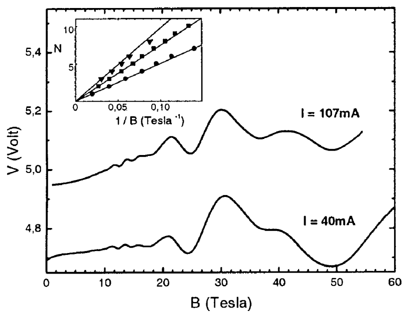

Figure 2: (a) Voltage across the QCL biased at 40 mA and 107 mA. The inset shows three series given by resonance numbers versus the inverse magnetic field curve.

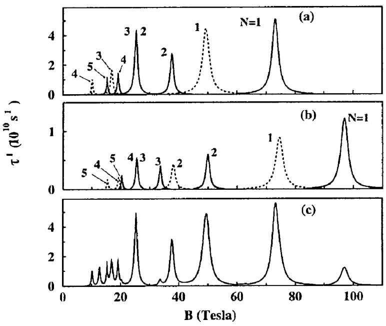

Figure 3: LO phonon (a) and acoustic-phonon (b) emission rate as a function of the applied magnetic field. Transitions into E_1 and E_2 subbands are shown by solid and dotted lines, respectively. The total electron relaxation rate is shown in (c).

In the following, we focus on the magneto-tunneling study in the range of current where the electrons are injected into the E_3 subband. Figure 2 shows two recordings of the voltage across the structure measured at 40mA and 107mA. Resonances are labeled as voltage minima, which means relaxation rate maxima. One series of oscillations dominates with a fundamental field near 50 T. Two other series become clearly visible on the second derivative curve. We observed that magnetic field resonance positions are independent of bias in this current range.

The three series are identified in the inset, which plots integer N versus reciprocal magnetic fields. The fundamental fields are obtained from the slopes at the values $B_1^{(1)}$ =50T, $B_1^{(2)}$ =75.5T, and $B_1^{(3)}$ =95T. From these fields, we derive cyclotron energies $\varepsilon^{(i)}=\hbar e B_1^{(i)}/m^*$ by using effective mass values measured in 2D GaAs electron gas in the same magnetic field range, in order to account for non parabolicity.[7] We obtain (within 3% experimental accuracy): $\varepsilon^{(1)}$ =72meV, $\varepsilon^{(2)}$ =109meV, and $\varepsilon^{(3)}$ =149meV. These energy values must be only related to the central QWs electronic structure since they are insensitive to the Emitter-Collector bias. Remarkably, $\varepsilon^{(1)}+\hbar\omega_{LO}=E_3-E_2$ and $\varepsilon^{(2)}+\hbar\omega_{LO}=E_3-E_1$ which is a clear signature of intersubband magnetophonon resonance while $\varepsilon^{(3)}=E_3-E_1$ is supporting the idea of an elastic scattering process from E_3 into E_1 subbands.

Theoretical results presented below account for all observed series, assuming the two inelastic series are caused by the LO phonon emission, and the elastic one by acoustic phonon emission. Figure 3 displays electron scattering rates from $E_{3,0}$

into $E_{i,N}$ LLs subbands by the emission of LO or acoustic phonons as calculated in Ref. [8]. The LO phonon emission rate plotted in Figure 3(a) as a function of the magnetic field for N=1–5 shows sharp resonances when $E_3 - E_2 - \hbar\omega_{LO}$ or $E_3 - E_1 - \hbar\omega_{LO}$ equal $N\hbar\omega_C$. Similarly, Figure 3(b) gives the total rate of acoustic phonon emission. Finally, in Fig. 3(c) shows the total electron relaxation rate due to emission of acoustic and optical phonons. The model explains the observed resonance field positions fairly well. For example, the optical phonon emission series agree within ~1% with the data for the B_N^1 series (relaxation into E_2 subband), and within ~3% with the data for the B_N^2 series (relaxation into E_1 subband). Notice that, this later inelastic series into the E_1 subband coincide with the elastic series into E_2 subband because $E_2 - E_1 \approx \hbar\omega_{LO}$. This explains why only three and not four series are viewed in our QCL structure.

In summary, intersubband magnetophonon oscillation series were identified in the tunneling current across a GaAs/GaAlAs DB structure based on a QCL.

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