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Terahertz intersubband emission in strong magnetic fields

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Electroluminescence in quantum-cascade structures based on vertical transitions is studied in a strong perpendicular magnetic field in the limit in which the cyclotron energy is larger than the intersubband transition energy. Cyclotron emission and a luminescence intensity enhancement up to a factor of 6 is observed in GaAs/AlGaAs and InGaAs/InAlAs vertical transition-based quantum-cascade structures.

The physics of intersubband transitions in the far-infrared is very different from the mid-infrared, because the scattering mechanisms are not only controlled by optical phonons. At low temperature the main scattering mechanisms are electron–electron scattering[1–3] and interface roughness.[4,5] A strong perpendicular magnetic field will break the in-plane dispersion of the subbands and create a ladder of Landau levels attached to each subband, which strongly modifies these scattering mechanisms by reducing the phase space.[6,7] The electron–electron scattering has a maximum of efficiency for processes in which the energy of the individual electrons is conserved.[8] Therefore antiresonant Landau level emission is an efficient way of quenching the nonradiative scattering. Due to this additional quantization, the system has strong analogies with quantum boxes. Depending on the magnetic field, intersubband Landau resonances arise when the Landau levels of each subband align with a Landau level of a different subband with a level index-change $\delta n = 1,2,3,\ldots$ The condition for such a resonance is then

$$E_{\mathrm{trans}} = \delta n \cdot \hbar \omega_c , \qquad (1)$$

where E_{trans} is the intersubband transition energy and $\omega_c = eB/m^*$ is the cyclotron energy. Coherent tunneling between intersubband Landau levels with different indices is forbidden in ideal cases, but these resonances are possible due to the scattering between the Landau levels. Such resonances have already been used to derive the energy spectrum.[9–11]

In this paper we explore the magnetic limit at which the cyclotron energy $\hbar \omega_c$ is larger than the intersubband transition energy E_{trans}; for our samples, this is the case at about 9.3 T for GaAs material system and 5.9 T for InGaAs material system (for $h\nu = 16$ meV). The increase of the lifetime of the upper state of the transition in a structure based on a diagonal transition,[9] as well as the suppression of a sequential tunneling current in a three-barrier, two-well heterostructure,[12] and the enhancement of the electroluminescence (EL) in a vertical transition[13] have also been observed by applying such a perpendicular magnetic field.

The structures were grown using molecular beam epitaxy and were designed to emit photons at energies of 15 and 16 meV. These vertical transition structures are based on either InGaAs/InAlAs lattice matched to an n^+-InP substrate or GaAs/AlGaAs lattice matched to a n-doped GaAs substrate and consist of 35 periods. The latter structure is in fact a copy of the first design which gave far-infrared EL,[14] but with a higher doping that enables large injection currents (the negative differential resistance appears here at $j = 150$ A/cm^2 at low temperature). The calculated band structures and thicknesses of the different layers are presented in Fig. 1.

For the EL experiments, the samples were processed into 450 μm×450 μm mesas with Ti/Au ohmic contact. The light was coupled out of the structures by a 15 μm grating

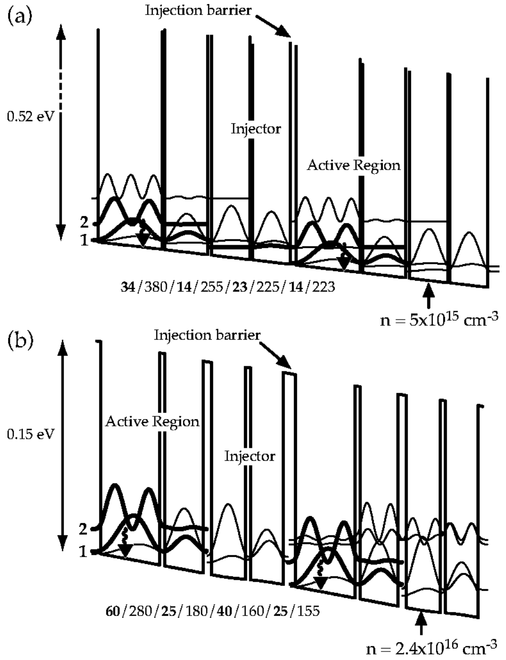

FIG. 1. Energy band diagrams of two periods of the vertical transition-based structures (a) in $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ and (b) in $GaAs/Al_{0.15}Ga_{0.85}As$ material systems under average electric fields of 1.9 and 2.5 kV/cm, respectively. The conduction band offsets are, respectively, 0.52 eV and 0.15 eV for InGaAs and GaAs material systems. Shown are the moduli squared of the relevant wave functions. The wavy lines indicate the transitions responsible for EL emissions between states 2 and 1. The layer sequences of one period are indicated in nanometers (thicknesses of the barriers in boldface) starting with the injection barrier. The third well of each structure is doped with Si.

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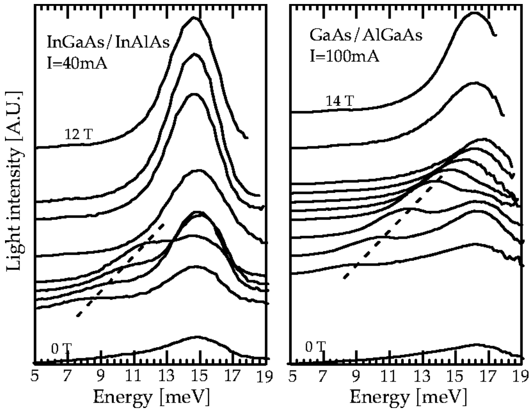

FIG. 2. EL spectra at 3 K on both vertical transition-based structures at applied magnetic fields of, from bottom to top, 0, 3, 3.5, 4, 4.5, 6, 8, 9, and 12 T for InGaAs/InAlAs, and 0, 5, 6, 7, 8, 8.5, 9, 9.5, 10, 12, and 14 T for GaAs/AlGaAs. The vertical displacement of the curves is proportional to the magnetic fields. The dashed lines indicate the peaks due to cyclotron emission.

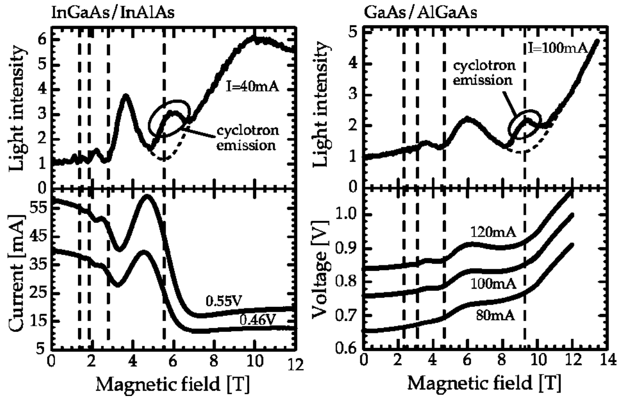

FIG. 3. Upper: light intensity as a function of the magnetic field at a fixed current for both vertical transition-based structures. The intensity is normalized to the zero field value. Lower: current (or voltage) vs magnetic field curves.

provided on the top by evaporation. The EL and magnetotransport measurements were performed with the sample mounted in the center of a superconducting magnet (adjustable between 0 and 14 T). The emitted light was coupled by a copper light-pipe to a cyclotron resonance InSb detector[15,16] tunable by a small superconducting coil (0–2.5 T). The spectra are then recorded by tuning the detector magnetic field while leaving the sample magnetic field constant. The best signal over noise of the InSb detector was obtained by decreasing the temperature of the He bath to 3 K. The intrinsic linewidth of the InSb detector is on the order of 2.8 meV, directly deduced by measuring an intersubband terahertz laser.[17] For the EL measurements, we applied electrical pulses between top and back contact at 6 kHz repetition rate and at a duty cycle of 50%. For the magnetotransport measurements, we applied a continuous voltage on 220 μm $\times$220 μm samples and measured the current while sweeping the magnetic field between zero and 14 T.

The EL spectra at a constant current of the two vertical transition-based structures ($I = 40$ mA for InGaAs sample and $I = 100$ mA for GaAs sample) are displayed in Fig. 2 for different applied magnetic fields. We observed an increase of the luminescence intensity for both materials. The light intensity normalized to the zero field value is displayed for both materials in Fig. 3 as a function of the magnetic field ($L-B$ curves). These measurements show an increase by a factor of almost 6 in InGaAs at 12 T and almost 5 in GaAs at 14 T. An additional peak which tunes linearly with applied magnetic field is also observed in Fig. 2 (dashed curves); it corresponds to the cyclotron emission of the samples. Electron injection into the excited Landau level is suppressed when the cyclotron energy is larger than the intersubband transition energy, quenching the cyclotron emission as observed experimentally.

This enhancement of the light intensity for vertical transition-based structures indicates that the nonradiative lifetime of the upper state of the transition increases with applied magnetic field, if we consider that the radiative lifetime should remain constant. At low temperature, this nonradiative lifetime was measured to be 11 and 14 ps for InGaAs and GaAs, respectively.[18] That means that the lifetime increases up to 66 ps at 12 T for InGaAs and up to 70 ps at 14 T for GaAs.

The width of the intersubband peak seems to be narrowed by about 30% for InGaAs and about 20% for GaAs under application of magnetic field (see Fig. 2). However, that is not the true narrowing of the intersubband emission because the resulting spectrum is broadened by the intrinsic linewidth of the InSb detector. The experimental data are a convolution between the detector's impulse response and the intersubband transition peak. Using a laser as a probe of the InSb intrinsic linewidth, we have convolved this response function with the expected unbroadened Lorentzian shape intersubband spectrum, obtaining an estimate of the narrowing due to the field roughly equal to 60% (with respect to the zero field value). Since, for the tested structure, the linewidth at zero magnetic field measured in a vacuum Fourier-transform infrared spectrometer (FTIR) is 1 meV, we can claim that the real linewidth at high magnetic field is only on the order of 0.4 meV. This zero field measured intersubband linewidth is too large to originate from lifetime broadening ($0.06\ \text{meV} = \hbar/e\tau$) of the upper state whose lifetime is estimated to about 14 ps.[18] Consequently we cannot attribute the observed linewidth narrowing in magnetic field to the increase in intersubband lifetime. However, the measurements are consistent with a picture in which the intersubband linewidth originates from intrasubband scattering events that are efficiently quenched by the magnetic confinement.

In Fig. 3, we see that the light intensity increases in an oscillatory manner. These oscillations are due to the intersubband Landau resonances [see Eq. (1)]. Minima in the $L-B$ curves correspond to maxima in the current (or minima in the voltage) versus magnetic field curves, since an increase of the current corresponds to an increase of the nonradiative scattering. The vertical dashed curves in Fig. 3 indicate the positions of such resonances calculated using $m^* = 0.0427$ for InGaAs and $m^* = 0.067$ for GaAs. There is good agreement with the observed experimental resonances except for the resonance occurring at high field corresponding to $\delta n = 1$ ($\sim$5.5 T for InGaAs and $\sim$9 T for GaAs).

To understand this effect, we have displayed the respective positions of the intersubband and cyclotron emissions as a function of the magnetic field in Fig. 4. The cyclotron emissions of the two different materials are in good agree-

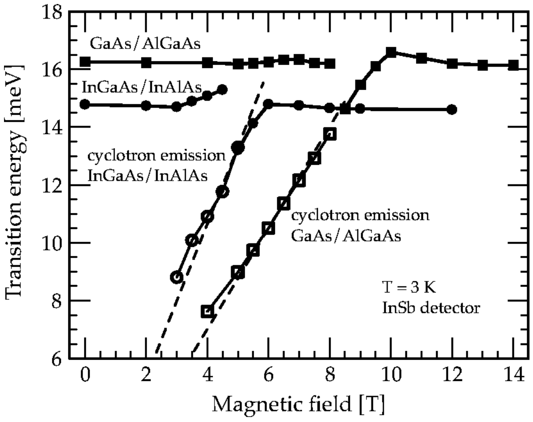

FIG. 4. Intersubband (full) and cyclotron (open) transition energies of the EL spectra in function of the magnetic field for both GaAs/AlGaAs (squares) and InGaAs/InAlAs (circles) materials. The dashed curves indicate the theoretical values of the cyclotron emission using $m^* = 0.067$ for GaAs and $m^* = 0.0427$ for InGaAs.

ment with the theoretical values calculated with an effective mass of $m^* = 0.067$ for GaAs and $m^* = 0.0427$ for InGaAs (dashed curves in Fig. 4). At the energies where the intersubband and cyclotron transitions energies are approximately the same, we observed an effect of repulsion between them. In a perpendicular magnetic field, Landau and intersubband confinements are only coupled in the presence of elastic scattering events. This coupling will also lead to the repulsion between the cyclotron and intersubband emission, with an energy scale given by the strength of the scattering. It is therefore not a surprise that the energy level repulsion observed in Fig. 4 is on the order of the linewidth of the intersubband peak (of 1 or 2 meV measured in the FTIR). At the magnetic fields corresponding to this repulsion effect, the cyclotron emission overlaps with the intersubband emission which is at its minimum. The dashed curves in Fig. 3 show the expected behavior of the intersubband emission intensity, suppressing the cyclotron emission. Thus, based on the repulsion observed in Fig. 4 and the additional unexpected resonance in Fig. 3, we can conclude that this resonance must be due to cyclotron emission.

We have shown that the application of a strong perpendicular magnetic field, in the limit in which the cylotron energy is larger than the intersubband transition energy, enhances radically the terahertz intersubband emission in vertical transition-based quantum-cascade structures based on both GaAs/AlGaAs and InGaAs/InAlAs material systems. We estimated that the linewidth of the emission peak narrowed by roughly 60%, giving a real linewidth at high magnetic field of only 0.4 meV. The energy positions of the cyclotron emission of both samples observed in the spectra are in good agreement with the theoretical values.

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