Intersubband Relaxation Rates of a Two-Dimensional Electron Gas under High Magnetic Fields

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The electron-bound hole luminescence of a GaAs-based heterojunction has been investigated as a function of magnetic fields at low temperatures. The study of the intensities originating from different Landau levels allows one to obtain precious information about the relaxation rates within these levels and provides values far above those predicted by standard theories. A new mechanism involving impurity-assisted phonon emission is proposed which gives good agreement with the experimental results. [S0031-9007(97)05136-3]

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The intersubband relaxation (ISR) of carriers in a two-dimensional electron gas (2DEG) has been the object of intensive studies because it governs the efficiency of light emitting devices based on those systems [1]. These studies have been essentially performed on undoped quantum wells without magnetic field using time resolved techniques [2–5] and demonstrated scattering times between a few ps up to 750 ps depending on the energy splitting of the electric sublevels. When this energy is higher than the longitudinal-optic (LO) phonon energy, short times are observed and well explained by standard analysis of the LO phonon emission rate [6,7]. On the other hand, when this condition is not fulfilled, though the times get longer, they still remain much shorter than expected from simple acoustical phonon emission rates [8]. However under magnetic fields there are indeed very few experimental reports [9–11] and it appears also that times shorter than 1 ns are obtained for ISR and this deserves more systematic investigations.

We have performed polarized optical experiments under high magnetic field and very low temperature on n-type modulation doped GaAs/GaAlAs heterojunctions with a buffer layer of about 30 nm and a GaAs layer width of 500 nm. A single δ-doped layer of acceptors [C (sample A) or Be (sample B) with a concentration of about 10^{10} cm^{-2}] is located in GaAs 35 nm away from the interface and the electron-bound hole luminescence is excited by the 514.5 nm Ar^+ laser line with incident powers less than 2×10^{-2} W cm^{-2}. The emitted light is collected by a fiber system and recorded with a DILOR *XY* spectrometer equipped with an optical multichannel analyzer detection. These samples have well known specific properties [11] and, in particular, the emission is strongly spin polarized at low temperatures [12] where only the lower hole energy impurity level is occupied with a spin $\frac{3}{2}$. Consequently this luminescence probes only the electronic properties of spin up 2DEG in each Landau level (LL) and can be modeled quite easily [13] which will allow us to obtain absolute values of the ISR rates. The observed system is in fact in dynamic equilibrium and the resulting 2DEG concentration n_S can be monitored by the incident laser power. This ISR can therefore be studied continuously as a function of the magnetic field and n_S. The resulting data are analyzed with a semiempirical model showing the importance of fluctuating potentials inside the heterojunction.

A typical evolution of luminescence spectra with magnetic field B is displayed in Fig. 1 for constant incident laser power P_L and an electron density of $n_S = 2.2 \times 10^{11}$ cm^{-2}. At low energies, the LL structures originating from the lower electric subband evolve progressively transferring the oscillator strength to the lower LL because of the increase of its density of states B/ϕ_0 (ϕ_0 being the flux quantum). Note that the LL energies undergo abrupt changes near integer values of the filling factor $\nu = n_S \phi_0 / B$ reflecting a reorganization of the electric field inside the heterojunction. One still observes at higher energy a weak structure which corresponds to the $N = 0$ LL of the second electric subband with an intensity $I_{20\uparrow}$ which clearly oscillates with B. To quantify this variation we have deconvoluted the low energy part of the spectrum in order to extract the intensity $I_{10\uparrow}$ of the $N = 0$ LL and plotted the ratio $I_{20\uparrow}/I_{10\uparrow}$ as a function of B [Fig. 2(a)]. This quantity is directly proportional to the ratio $N_{20\uparrow}/N_{10\uparrow}$ of the corresponding level populations and to $|M_{20}|^2/|M_{10}|^2$ the ratio of the square of the optical matrix elements between the wave function of each of these levels and that of the 1s wave function of the acceptor. These matrix elements are easily computed [13] as a function of B taking for the electric part of the

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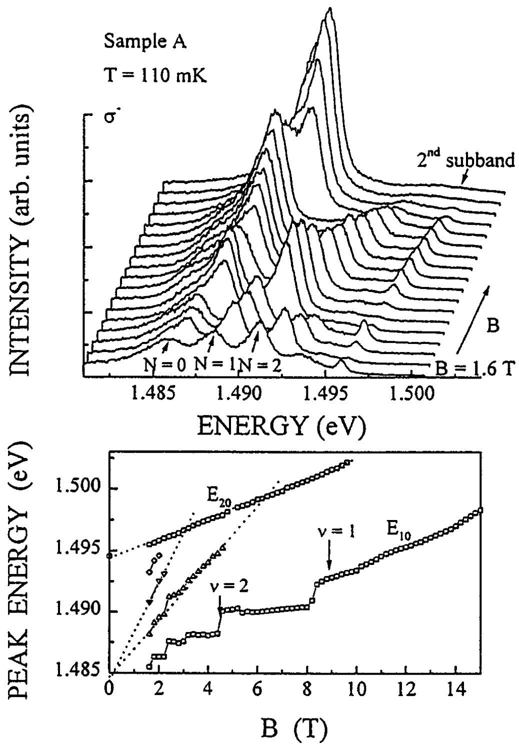

FIG. 1. Upper part: Electron-bound hole luminescence spectra of sample A for increasing values of the magnetic field by steps of 0.2 T ($P_L = 1.3 \times 10^{-2}\ \mathrm{W\,cm^{-2}}$ corresponding to $n_S = 2.2 \times 10^{11}\ \mathrm{cm^{-2}}$). The lower part shows the corresponding variation of the Landau level energies. The dotted lines are linear interpolations of the $N = 0$ and 1 Landau level energies showing the existence of subband level crossings at about 3.1 and 6.3 T.

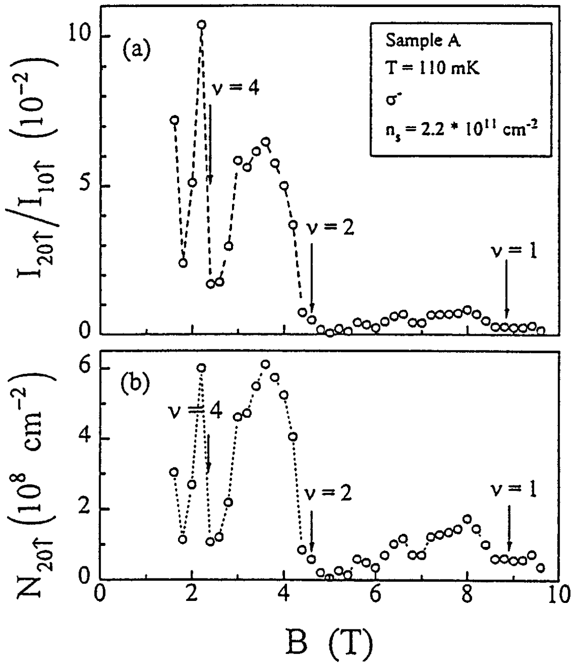

FIG. 2. Ratio of the luminescence intensities originating from the $N = 0$ Landau levels of the second and first electric subbands (a) and corresponding electron population of the second electric subband (b) as a function of B.

2DEG wave function the Fang-Howard model [14] which depends on a single parameter b fitted self-consistently with the known parameters of the structure. In particular the model allows us to calculate radiative recombination times τ_{R1} (200–300 ns) and τ_{R2} (20–30 ns) from the $n = 0$ LL of the two electric subbands in good agreement with experiment [9]. As long as $\nu > 1$, $N_{10\uparrow} = B/\phi_0$ and $N_{10\uparrow} = n_S$ when $\nu < 1$. Therefore the variation of $I_{20\uparrow}/I_{10\uparrow}$ can be transformed in the variation of the *absolute value* of $N_{20\uparrow}$ with B as depicted in Fig. 2(b). Note that $N_{20\uparrow}$ has a mean value about 3 orders of magnitude smaller than n_S, goes through minima close to even values of ν and through a broad maximum for $1 < \nu < 2$. The rate equations describing the dynamics of the whole system are quite complicated and will be reported later [15]. They have to take into account the spin conserving relaxation rates between the different LL of index N related to the subband i, E_{iN}, and also the spin flip relaxation rates within each LL. For $\nu > 2$, the relaxation mainly occurs towards the empty states of the different LL as long as these levels do not cross the second electric subband (see Fig. 1). The corresponding relaxation rates vary from 10^8 to $10^{10}\ \mathrm{s^{-1}}$ being enhanced close to the subband level crossing which is explained by the emission of acoustic phonons with the deformation potential mechanism [16]. However, for $\nu < 2$ and at magnetic fields above the level crossing, this mechanism gives rates of the order of $10^6\ \mathrm{s^{-1}}$, i.e., at least 4 orders of magnitude smaller than those expected to reproduce the variation of $N_{20\uparrow}$. In that condition ($\nu < 2$) the rate equations simplify. Figure 3(a) schematically presents the main relaxation channels which have to be considered [15] and which lead to the following relation describing $N_{20\uparrow}$ in stationary conditions:

$$N_{20\uparrow} = \frac{n_S}{2\tau_{R1}} \times \frac{(2-\nu)/\tau_{20-10} + 1/\tau_{20-11} + 2/\tau_{S2}}{(2-\nu)/\tau_{20-10} + 1/\tau_{20-11} + 1/\tau_{S2}} \times \frac{1}{\alpha/\tau_{20-10} + 1/\tau_{20-11} + 1/\tau_{R2}}. \quad (1)$$

$N_{20\uparrow}$ depends on τ_{R1}, τ_{R2}, and on times τ_{20-10} and τ_{20-11} corresponding to spin conserving processes between E_{20} and E_{11} and between E_{20} and E_{10}, respectively. τ_{S2} is related to the spin flipped process within E_{20}. τ_{S2} has been calculated with the model of Bastard [17] which provides rates in the range of few $10^9\ \mathrm{s^{-1}}$ in excellent agreement with reported data [9]. In Eq. (1), $\alpha = 1 - \nu_{10\uparrow}$ is a measure of the number of places made available for relaxation due to the radiative recombination from E_{10} with a relative occupation number $\nu_{10\uparrow}$. α is clearly small for $\nu > 1$ and its value fitted at $\nu = 2$ is varying proportionally to the measured radiative intensity. For $\nu < 1$, $\alpha = 1 - \nu$. In Eq. (1), τ_{20-11} has been evaluated with the standard electron-acoustic phonon

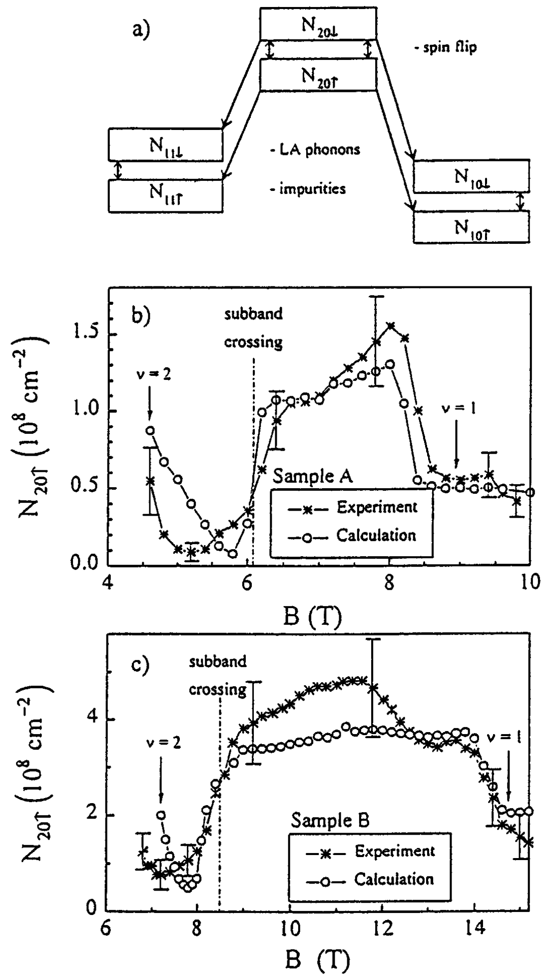

FIG. 3. (a) Scheme of relaxation channels between different states considered in the rate equations. (b),(c) Comparison between the calculated and experimental values of $N_{20\uparrow}$, the electron concentration of the second electric subband for (b) sample A and (c) sample B.

model [16] and this contribution gets very strong before E_{11} crosses E_{20} and disappears afterwards. The reason why τ_{20-10} is not reproduced by standard models is that the acoustic phonon energy released by the recombination ($\approx$10 meV) corresponds to a momentum q which cannot be transferred by a pure noninteracting 2DEG under magnetic field. One has to invoke fluctuations of the potential with an appropriate length scale which could assist the relaxation with phonons. These fluctuations could have different origins such as electron-electron interactions or electron impurity interactions. This latter part has to be considered seriously because for a given concentration n_S of electrons one has the same amount of ionized centers beyond the buffer layer. Because of the structure of samples this effect is largely dominant as compared to that due to the remaining ionized acceptors. On pure theoretical grounds the problem is not easy to solve since one has to deal with a system which is degenerate in the ground state. We have adopted an empirical approach to model the relaxation assisted by impurity potential fluctuations between the levels E_{20} and E_{10} split by ΔE. Each impurity μ is located at a distance $z_\mu(<0)$ from the interface and exchange an energy ε_t with the electron to reach an intermediate state t before relaxing via the emission of a longitudinal-acoustic (LA) phonon of energy $\hbar v_{\mathrm{LA}} q$ propagating at a speed v_{LA}. We will assume in the following that these impurities are located in a single layer distant from the interface by the buffer thickness. In the second order perturbation theory the corresponding rate $W_{20\to 10}$ can be written as

$$W_{20\to 10} = \frac{1}{\tau_{20-10}} = \frac{2\pi}{\hbar}\int \frac{d^2k}{(2\pi)^2}\int \frac{d^3q}{(2\pi)^3} \times \sum_\mu |M^{(2)}|^2 \delta(\Delta E - \hbar v_{\mathrm{LA}} q \pm \varepsilon_t), \qquad (2)$$

in which **k**, **r** and **q**, **R** are wave vectors and vectors of the fluctuating potential in 2D space and of the phonons in 3D space, respectively. The most efficient component of the second order matrix element $M^{(2)}$ is the one describing first the interaction of the initial state i with the fluctuating potential followed by the emission of an acoustic phonon to the final state f. This element can be written as

$$M^{(2)} = A_\mu(k)\sqrt{B(q)} \sum_t \frac{\langle i|e^{-ikz}e^{i\mathbf{k}\cdot\mathbf{r}}|t\rangle\langle t|e^{i\mathbf{q}\cdot\mathbf{R}}|f\rangle}{\varepsilon_t}, \qquad (3)$$

where $A_\mu(k)$ and $B(q)$ are the Fourier components of the screened fluctuating potential (SFP) and of the electron-phonon deformation potential, respectively. The SFP is described within the random phase approximation and $A_\mu(k) = 2\pi e^2/\varepsilon_0[k + \tilde{F}(k)]^{-1}e^{kz_\mu}$, where $\tilde{F}(k)$ has an analytic expression depending on the static dielectric function ε_0 and the electron effective mass of GaAs [18]. In the spirit of the self-consistent Born approximation [17,18], an empirical approach consists in assuming a mean value Γ for ε_t which has to be fitted. With this approximation one obtains

$$W_{20\to 10} = \frac{3}{2}(2\pi)^4 \frac{a_{nk}^2 N_\mu}{\hbar\rho v_{\mathrm{LA}}^2}\frac{1}{\Gamma^2}\left(\frac{e^2}{\varepsilon_0}\right)^2\left(\frac{\omega}{v_{\mathrm{LA}}}\right)^5 \int_0^\infty dy\, \frac{y e^{2bz_\mu y}}{[y + \tilde{F}(y)]^2}\frac{(1+3y^2)^2}{(1+y)^{10}}\exp\left(-\frac{b^2\ell_B^2}{2}y\right) \times \int_0^1 du \exp\left[-\left(\frac{\omega}{v_{\mathrm{LA}}}\right)^2\frac{\ell_B^2}{2}u\right]\frac{\sqrt{1-u}}{\{1+[\omega/(bv_{\mathrm{LA}})]^2(1-u)\}^4}. \qquad (4)$$

Besides Γ there is no adjustable parameter in this expression since a_{nk}, the conduction band deformation potential, and ρ, the density of GaAs, are tabulated, ℓ_B, the magnetic field length, is known, N_μ, the number of ionized donors impurities, equals n_S and ω, the phonon frequency, corresponds essentially to the splitting $\Delta E = \hbar\omega$. The solution of Eq. (4) is very sensitive to this value and increases strongly with magnetic field. The results obtained by a numerical integration using the *measured* splitting give rates in the range 10^{10}–10^{11} s^{-1} and allow us to calculate, with Eq. (1), $N_{20\uparrow}$. The comparison of the calculations with the experimental results is shown in Figs. 3(b) and 3(c) for samples A and B, respectively. The value chosen for Γ is the half-width of the luminescence line measured for each sample ($\Gamma = 0.35$ meV for sample A and 0.5 meV for sample B). It is very interesting to note, considering the approximations, that the main features are reproduced quantitatively. This is also true when n_S is changed [15]. We think that the agreement between the model and the experimental results cannot be completely fortuitous. In both cases the minimum of $N_{20\uparrow}$ for $\nu \leq 2$ is shifted to high fields and is very likely due to the fact that the relaxation towards E_{11} should also be treated with a similar approach. Note that the large increase or decrease of $N_{20\uparrow}$ occurs when the splitting ΔE changes abruptly (see Fig. 1). Indeed the observed variation turns out to be a delicate balance between a smooth increasing variation of τ_{S2} [15] and an irregular variation of τ_{20-10}. Finally, one can compare the present results providing τ_{20-10} times of the order of 20 to 50 ps to those obtained, at zero field, by Murdin *et al.* [8] ranging from 40 to 100 ps in samples with $\Delta E \approx 18$ meV: The expected trend is verified but a detailed comparison is difficult because the relation between relaxation rates and times implies the knowledge of the occupancy factors of the states which are strongly sample dependent. This stresses the importance of modeling the electron-phonon relaxation rates in order to compare the actual measurements in different conditions.

In conclusion the study of the intensities of the electron-bound hole luminescence in GaAs/GaAlAs heterostructures as a function of B allows us to obtain directly information about the intersubband relaxation rates in these structures. The large values obtained cannot be explained by a simple acoustical phonon emission process. It has been shown that within a semiempirical model which assumes that such an emission is assisted by the impurity potential fluctuations a good quantitative agreement is found with the experimental results. It would be interesting that such a model could be justified on more fundamental theoretical grounds.

The Grenoble High Magnetic Field Laboratory is laboratoire associé à l'Université Joseph Fourier et L'Institut National Polytechnique de Grenoble.

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