Magnetooptic oscillations in the intensity of recombination radiation in connection with intersubband relaxation of 2D electrons

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Magnetooptic oscillations of a new type have been observed in the intensity of the recombination radiation of 2D electrons from the first excited quantum-well subband at a GaAs–AlGaAs single heterojunction. These oscillations are explained in terms of an elastic relaxation of electrons upon a crossing of corresponding Landau levels of different subbands.

1. The quantization of the cyclotron motion of electrons and the resulting discrete nature of the spectrum of two-dimensional (2D) electron systems in a magnetic field lead to oscillations in corresponding thermodynamic and kinetic characteristics. There have been several recent reports[1,2] of an optical analog of Shubnikov–de Haas oscillations, observed on the magnetic-field dependence of the intensity of the recombination radiation of 2D electrons. Attempts were made in Refs. 1 and 2 to describe these oscillations in terms of Coulomb correlations in the system consisting of the 2D electron gas plus the photoexcited holes. The sharp peaks observed in Ref. 2 on the magnetic-field dependence of the intensity of the recombination radiation of the first excited quantum-well subband coincide precisely with the positions of integer filling factors of the 2D electron gas in the ground subband. These peaks were attributed to a screening of the Coulomb potential of photoexcited holes. Specifically, if the conductivity σ_{xx} in the ground subband is not zero, the electrons of the ground subband will be the most effective in screening the attractive potential of the holes (because the excited subband is filled only slightly). Correspondingly, these electrons will be more effective in the recombination. If, on the other hand, σ_{xx} in the ground subband vanished (the case of integer filling factors), the contribution of the electrons of the excited subband to the screening and thus to the recombination will increase significantly.

These magnetooptic oscillations might also be caused by the complex kinetics of the carrier relaxation and recombination during steady-state illumination. Specifically, under conditions of continuous photoexcitation, the system is in a nonequilibrium (but steady) state, and the line intensities observed are determined not only by the thermodynamic-equilibrium particle distribution but also by the kinetics of the relaxation of the nonequilibrium component of the electron gas. Consequently, the magnetic-field dependence of the intensities of the lines corresponding to emission from states with a nonequilibrium population contain valuable information about the nature of the relaxation process in the 2D gas. In particular, this is true in the case in which quantizing magnetic fields are applied.

2. In this letter we are reporting a study of the magnetooptic oscillations and the concentration dependence of the intensity (I_1) of the emission of 2D electrons from the first excited quantum-well subband, with a nonequilibrium population, at a single GaAs–AlGaAs heterojunction. The thickness of the silicon-doped AlGaAs layer was 525 Å, the spacer thickness was 225 Å, and the thickness of the GaAs layer was 1000 Å. The mobility of the 2D electrons measured in darkness at 4.2 K and at a density $n_s = 5.5 \times 10^{11}$ cm^{-2} was 1.6×10^5 cm^2/(V·s). To distinguish the recombination component corresponding to the small number of nonequilibrium electrons from the upper subband (these electrons fill this subband to a slight extent during constant illumination), we used a method based on the radiative recombination of 2D electrons with photoexcited holes bound at acceptors in the δ-doped layer.[3] This layer lay at a distance of 300 Å from the interface. The 2D density of acceptors in the δ layer was 2×10^{10} cm^{-2}. Since the acceptor layer is distant from the electron channel, the overlap of the wave functions of the states of the upper subband with the wave function of a hole at an acceptor is exponentially greater than that for states from the ground subband. It thus becomes possible to experimentally detect the comparatively slight nonequilibrium filling of the upper subband and its changes ($\sim 10^9$ cm^{-2}). In order to monitor the intensity of the recombination line corresponding to recombination from the upper subband, we chose appropriate rates for scanning the field and the monochromator, so that the position of the monochromator slit tracked the spectral position of this line. The optical measurements were accompanied by simultaneous measurements of the diagonal component of the resistivity, $\rho_{xx}(H)$. In addition, the continuous illumination made it possible to control the electron density n_s in the 2D channel and the intersubband splitting ϵ_{10} (Ref. 4). It thus became possible to vary n_s over a broad interval and to find the magnetic-field dependence $I_1(H)$ for both the equilibrium population ($\epsilon_F > \epsilon_{10}$) and a nonequilibrium population ($\epsilon_F < \epsilon_{10}$) of the upper subband. The second of these cases is of interest from the standpoint of the kinetic aspects of recombination.

3. In a magnetic field the spectrum of 2D electrons is a set of lines corresponding to series of Landau levels constructed from quantum-well states in the well. Figure 1 shows a typical magnetoluminescence spectrum in the structures which were used. Working directly from the spectra—from the positions of the maxima of the lines at various values of H—we can construct a fan of Landau levels. Working from the relative intensities of the various lines from the lower subband, we can draw conclusions about the filling of this subband. The clearly defined line in the violet part of the spectrum in Fig. 1 corresponds to the zeroth Landau level of the upper subband. As the magnetic field is strengthened, this line shifts up the energy scale in proportion to $\hbar\omega_c/2$, and its intensity also changes significantly. The $I_1(H)$ dependence found for the case $\epsilon_F = \epsilon_{10}$ is shown in Fig. 2a for two temperatures. Also shown here is the measured $\rho_{xx}(H)$ dependence (curve 3). On the $I_1(H)$ curve we can clearly see oscillations. In low fields, they consist of an alternation of sharp maxima and minima. In high fields, they consist of individual maxima against the background of broad

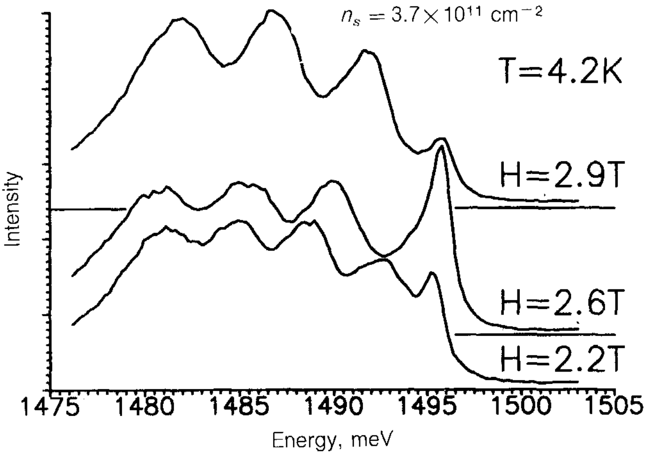

FIG. 1. Recombination spectrum of a 2D electron gas in a transverse magnetic field H.

regions of low intensity. Figure 2b shows the results of an analysis of the experimental $I_1(H)$ and $\rho_{xx}(H)$ data for the cases $\epsilon_F = \epsilon_{10}$ (the triangles) and $\epsilon_F < \epsilon_{10}$ (the circles). The reciprocal of the field is plotted along the x axis here, while the quantum number of the oscillations is plotted along the y axis. Lines 1 and 2 are drawn through the points corresponding to the positions of the $\rho_{xx}(H)$ minima. The slope of these lines is determined by the Fermi energy of the 2D electrons. Lines 3 and 4 are drawn through the points corresponding to the maxima of the optical oscillations. We see that in the case $\epsilon_F = \epsilon_{10}$ the slopes of the transport and optical lines are the same, while in the case $\epsilon_F < \epsilon_{10}$ the optical line has a greater slope. From this slope we can calculate the energy parameter which determines this slope. This energy turns out to be equal to ϵ_{10}. We are therefore obliged to assume that these optical oscillations are associated with a crossing of the Landau levels of the ground subband and the zeroth Landau level of the excited subband. This conclusion is illustrated by Fig. 3, in which the fan of Landau levels is shown below a plot of the optical oscillations for the case $\epsilon_F = \epsilon_{10}$. This fan was found through an analysis of a series of recombination spectra in various magnetic fields. We see an unambiguous correspondence between the positions of the "cuttoff" of the optical signal and of the level crossing. The mechanism responsible for this cutoff may be the elastic relaxation of carriers from the excited subband with its nonequilibrium population to the ground subband. In this case, a perturbation which mixes the wave functions of the different subbands is represented by the atoms of the residual impurities near the 2D layer. Support for this interpretation comes from the results of Ref. 5 on the optical detection of a cyclotron resonance. Gubarev *et al.*[5] observed that the cutoff of the recombination signal $I_1(H)$ coincided with the abrupt appearance of an optical cyclotron-resonance signal from the excited subband. The observation of such a signal required a crossing of the levels of the ground subband and the excited subband.

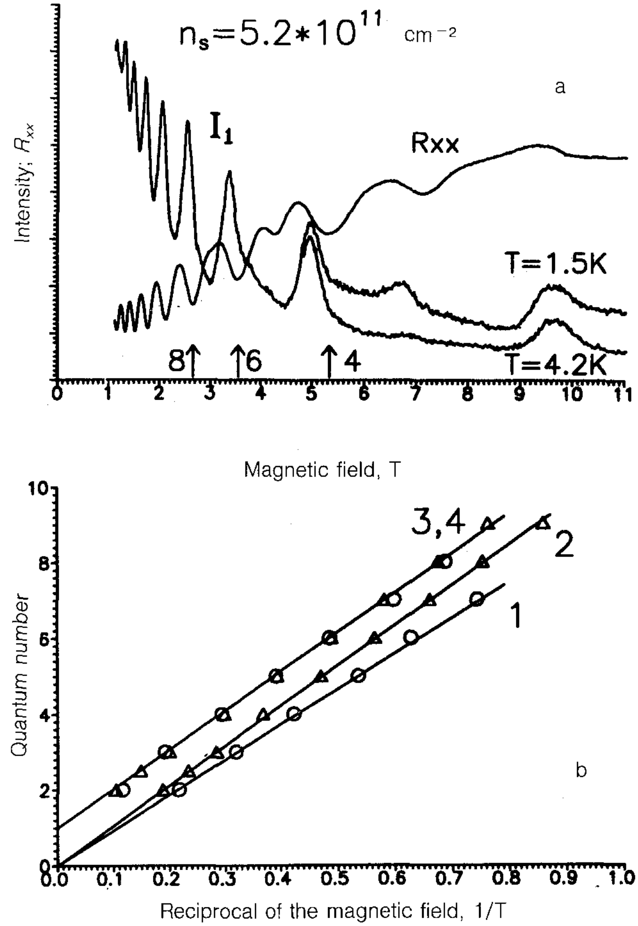

FIG. 2. a: Intensity of the recombination radiation of the first excited quantum-well subband, I_1, and diagonal component of the resistivity of the 2D electron gas, R_{xx}, versus the magnetic field ($\epsilon_F = \epsilon_{10}$; R_{xx} is shown for $T = 1.5$ K). b: Quantum number of the transport oscillations (lines 1 and 2) and of the optical oscillations (lines 3 and 4) versus the reciprocal of the magnetic field. Triangles—$\epsilon_F = \epsilon_{10}$; circles—$\epsilon_F < \epsilon_{10}$.

The shape of the oscillations in $I_1(H)$ is determined by the magnetic-field dependence of the unfilled positions in the ground subband and the dependence of the relaxation matrix element on the energy "gap" between the corresponding levels. Although we are not able to unambiguously identify the relaxation mechanism in the intervals between the cutoffs, it is possible that the increase observed in $I_1(H)$ is due to a slowing of the electron relaxation accompanied by the emission of an acoustic phonon as this "gap" shrinks.

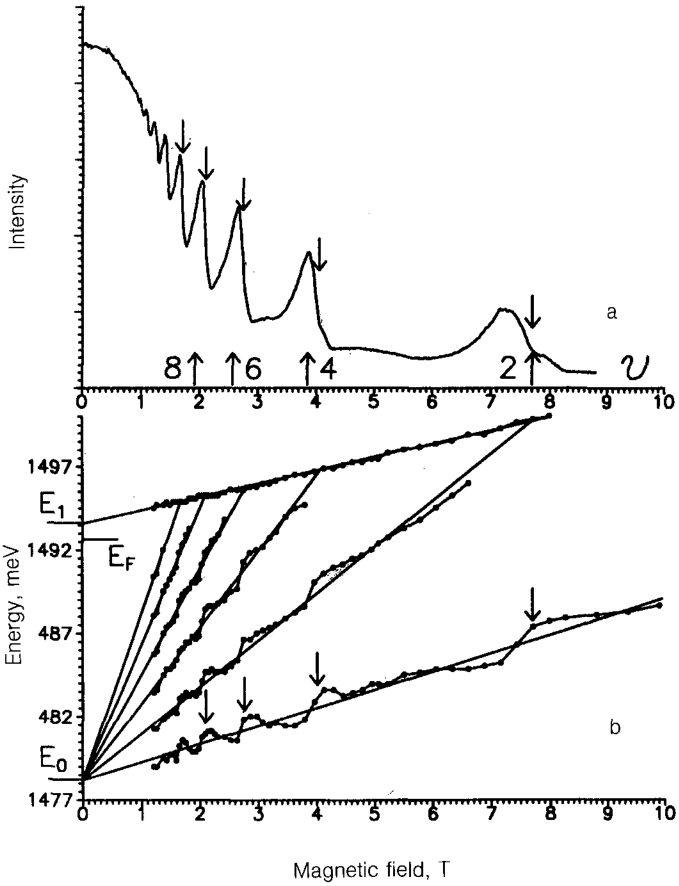

FIG. 3. a: Intensity of the recombination radiation of the first excited quantum-well subband, I_1, versus the magnetic field for the case $\epsilon_F < \epsilon_{10}$. b: Spectral positions of the luminescence lines versus the magnetic field. The arrows pointing downward show the crossings of the zeroth Landau level of the excited subband with the Landau levels of the ground subband. The arrows pointing upward show the even filling factors ν.

Note also that the spectral positions of the luminescence lines corresponding to the various Landau levels behave in a nonmontonic fashion (Fig. 3b). They oscillate with respect to the straight lines, which are plots of $\epsilon_N = (N + 1/2)\hbar\omega_c$. We attribute this effect, which is seen only when there is a substantial filling of the excited subband, to a change in the shape of the potential well and thus a change in the position of its bottom, as a result of the redistribution of electrons between subbands.

We attribute the additional maximum which appears on the $I_1(H)$ curve as the temperature is lowered to 1.5 K, near a filling factor $\nu = 3$ (Fig. 2a), to a crossing of a level of the excited subband with the upper spin sublevel of the first Landau level of the ground subband. The large energy splitting of the spin sublevels arises because of a significant increase in the effective g-factor of the 2D electrons, itself a consequence of an increase in the exchange interaction near odd values of the filling factor.[6]

In summary, it has been concluded from a study of the magnetic-field dependence of the intensity of the recombination radiation of 2D electrons, and from a comparison of these results with the magnetotransport oscillations, that the optical oscillations originate from an elastic relaxation of carriers from a quantum-well subband with a nonequilibrium population upon a crossing of corresponding Landau levels of the ground and excited subbands. We wish to stress that the optical oscillations observed in the present study differ from those observed in Refs. 1 and 2 in that they are not directly related to Shubnikov–de Haas transport oscillations.

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