Magnetooscillations in the luminescence decay time of a 2D electron gas at a single GaAs–AlGaAs heterojunction with a monolayer of acceptors

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A study has been made of the kinetics of the radiative recombination of 2D electrons at a single GaAs/AlGaAs heterojunction. Magnetooscillations are observed in the decay time of the luminescence of 2D electrons from an excited quantum-well subband. These oscillations are in phase with the magnetooscillations observed previously (V. E. Kirpichev *et al.*, This Issue) in the recombination intensity itself. This result is attributed to a periodic change in the probability for intersubband relaxation.

1. Oscillations in the intensity of the magnetoluminescence of 2D electrons are usually[1] an analog of Shubnikov–de Haas oscillations and result from an abrupt change in the chemical potential of the electrons in a magnetic field. In this case the corresponding structural features (minima[2] or maxima[3]) on the plot of the luminescence intensity versus the magnetic field are observed in phase with the magnetotransport features, specifically, at integer fillings of Landau levels. In this case the oscillatory dependence of the intensity of the recombination radiation of electrons from an excited quantum-well subband is explained on the basis that at an integer filling the electrons of the ground subband do not take part in the screening of the attractive potential of a free hole, and there is a correlation between holes and electrons from the excited subband. Magnetoluminescence oscillations of a new type were observed in Ref. 4. They differ from the magnetotransport oscillations. They were explained in terms of an elastic relaxation of 2D electrons from an excited subband into the ground subband upon a crossing of corresponding Landau levels. A study of the kinetics of the recombination of electrons from the excited subband under these conditions will make it possible to choose directly between these two mechanisms.

2. The test sample contained a single GaAs–$Al_xGa_{1-x}As$ heterojunction ($x = 0.3$), at which a monolayer of acceptors—Be atoms in a concentration of 2×10^{10} cm^{-2}—was produced in the GaAs buffer layer at a distance $z_0 = 300$ Å from the heterojunction.[5] The sample was excited by laser pulses 1 ps long with a wavelength of 605 nm and a repetition frequency of 800 kHz (a Spectra Physics system). In these experiments, the average power density at the sample was 25 mW/cm^2; this figure corresponds to 0.3 nJ over 1 ps in a spot 1 mm^2 in size. The level of the optical

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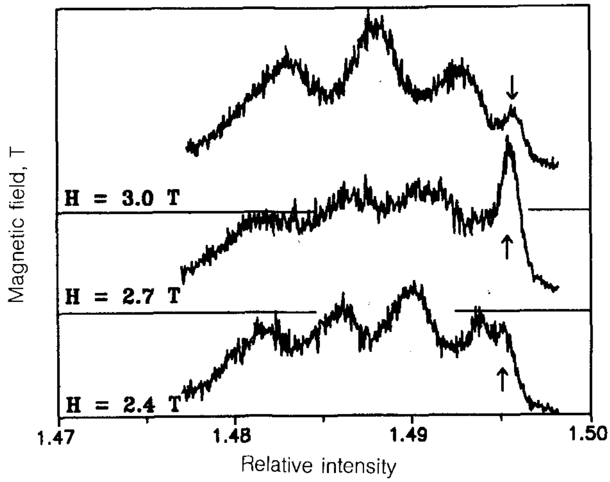

FIG. 1. Time-integrated luminescence spectra measured at $H = 2.4$, 2.7, and 3.0 T. The arrows show the lines representing recombination of 2D electrons from the excited subband.

pumping was kept this low in order to maintain a constant density of 2D electrons after the laser pulse, for a time characteristic of the recombination processes under study.[6] The experiments were carried out in an optical cryostat with a superconducting solenoid at a temperature of 1.6 K. The luminescence signal was detected by a time-correlated photon counting system. This approach made it possible to record both spectra and luminescence decay curves at a fixed spectral position with a time resolution of 0.2 ns.

3. Figure 1 shows time-integrated luminescence spectra measured at a fixed density of the 2D electrons, specifically $n_s = 4\times10^{11}$ cm^{-2}, in perpendicular magnetic fields $H = 2.4$, 2.7, and 3.0 T. In the luminescence spectrum we see the recombination radiation of 2D electrons from the excited quantum-well subband (the corresponding lines are marked by arrows) and from the ground quantum-well subband. In a perpendicular magnetic field, the luminescence lines split into Landau levels, in accordance with the filling factor of the levels, $\nu = n_s/(eH/h)$. With increasing magnetic field, the Landau levels shift toward higher energies. This shift increases with increasing number of level index N in the given subband $\hbar\omega_c\,(N + 1/2)$, where $\hbar\omega_c$ is the cyclotron energy. The spectra shown here, which were measured during pulsed pumping agree qualitatively with the spectra recorded during continuous pumping, under otherwise similar conditions.[4] It can be seen from Fig. 1 that the intensity of the line corresponding to recombination of 2D electrons from the excited subband changes substantially upon a slight change in the magnetic field. Curve 1 in Fig. 2 shows the behavior of the intensity versus the field. This behavior is oscillatory in nature. As was shown in Ref. 4, a sharp decay of the intensity occurs when the lower Landau level of the excited subband crosses the lowest unfilled Landau level of the ground subband. At this time the level energies become paired; this circumstance is responsible for the resonant increase in the probability for intersubband relaxation, as a result of elastic scattering by the atoms of the residual impurities. Consequently, a mechanism for a radiationless escape of 2D electrons from the excited subband comes into play; it leads to a decrease

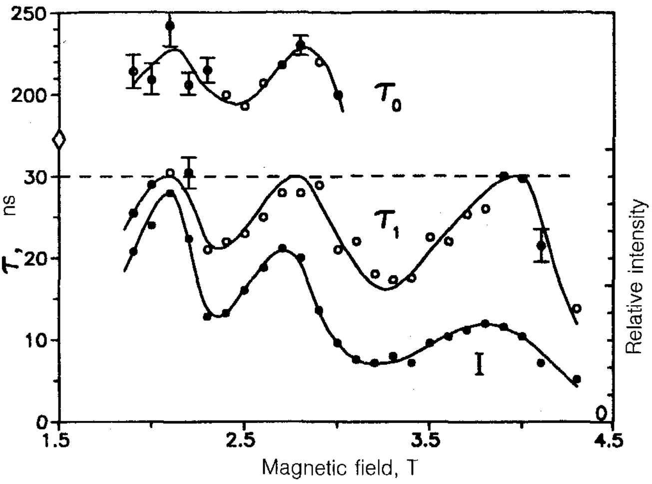

FIG. 2. Magnetic-field dependence of the intensity of the line representing recombination of 2D electrons from the excited subband (curve 1; scale at right), of the time over which the 2D electrons leave the excited subband (curve τ_l), and of the time scale of the recombination of 2D electrons from the ground subband with holes localized in the monolayer of acceptors (the curve τ_0).

in the intensity of the radiationless recombination.

As was pointed out in Ref. 6, this luminescence decay is fairly complex in nature which depends on the degree of filling of the excited subband. When there are few 2D electrons in the excited subband (the upper and lower curves in Fig. 1), the kinetics of the recombination of the 2D electrons from the ground subband with holes localized in the acceptor monolayer is described well by a simple exponential function. With increasing degree of filling of the excited subband, we observe a deviation from an exponential behavior on the initial part (~ 100 ns) of the decay curve. The reason for this deviation is that in this time interval the holes recombine with 2D electrons from both the ground and excited quantum-well subbands. Since the densities of photoexcited holes (n_h) and of 2D electrons from the ground (n_{s0}) and excited (n_{s1}) quantum-well subbands are related by $n_{s1} \ll n_h \ll n_{s0}$, the initial part of the kinetic curve describing the escape of 2D electrons from the excited subband can be assumed to be approximately exponential. Curve τ_1 in Fig. 2 shows the magnetic-field dependence of the time over which the 2D electrons leave the excited subband, $\tau_1(H)$. Values of $\tau_1(H)$ were found by an approximation based on a minimization of the χ^2 value of the experimental decay curves. As we see from this figure, $\tau_1(H)$ oscillates in phase with the intensity (curve 1). The values at the oscillation minima decrease with increasing magnetic field, while the values at the maxima remain constant, equal to ≈ 30 ns (dashed line). It follows from an analysis of the spectra that, when the intensity of the line representing the recombination of 2D electrons from the excited subband is at a maximum, the density of holes in the monolayer is four times the density of 2D electrons in the excited subband. In all other cases, the inequality $n_{1s} \ll n_h$ is stronger. If this inequality is violated, there may be a deviation from an exponential law for the corresponding decay curve. However, it is simple to show that such a deviation could result in only a smoothing of the size of the observed oscillations.

There are two ways for a 2D electron to leave the first excited subband: radiative recombination and relaxation to the ground subband. We can therefore write 1/

$\tau_1 = 1/\tau_{\rm rel} + 1/\tau_{\rm rec}$, where $\tau_{\rm rel}$ and $\tau_{\rm rec}$ are the time scales for relaxation and recombination, respectively. As was shown in Ref. 4, slight changes in the shape of the quantum well with increasing magnetic field do not have any strong effect on the wave function of a 2D electron from an excited subband. Since $\tau_{\rm rec}$ is determined by the overlap integral representing the overlap of the wave functions of the 2D electrons from the excited subband and the photoexcited holes, localized in the monolayer of acceptors, this time can be assumed to remain constant, close to the value of τ_1 at the oscillation maxima. The observed shape of the $\tau_1(H)$ curve is thus determined by the oscillations of $\tau_{\rm rel}$. When the energy of the lowest-lying unfilled Landau level of the ground subband becomes comparable to that of the lower Landau level of the excited subband, i.e., at the point at which the corresponding branches of the Landau fan cross, the time $\tau_{\rm rel}$ decreases sharply. This decrease is the result of a resonant increase in the probability for the transition of a 2D electron from the excited subband into the ground subband, because of an elastic scattering by atoms of residual impurities. The reasons for the subsequent increase in $\tau_{\rm rel}$ are not completely clear, but one might suggest that, since the intersubband relaxation involves the emission of a corresponding phonon, changes in the emission conditions due to a change in the energy gap between levels can lead to a decrease in the relaxation probability.

The τ_0 curve in Fig. 1 is the magnetic-field dependence of the time scale for the recombination of 2D electrons from the ground subband with photoexcited holes localized in the acceptor monolayer. We see from this figure that $\tau_0(H)$ oscillates in phase with the amplitude of the line representing the recombination of 2D electrons from the excited subband. The magnetooscillations in τ_0 result from a change in the shape of the potential well near the interface. This shape is sensitive to charge variations in the depletion layer. With increasing electron density in the excited subband (and with increasing intensity of the corresponding recombination), the negative charge in the depletion layer becomes greater, and the width of the well and the size of the electron wave function become correspondingly smaller.

We note in conclusion that the magnetooscillations which we have observed in the decay time of the intensity of the recombination radiation of 2D electrons from the excited subband can be explained in terms of an elastic intersubband relaxation of electrons in a 2D channel upon the crossing of corresponding Landau levels.[4] These oscillations are at odds with arguments based on a screening of the attractive potential of the holes.[3]

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