Kinetics of the radiative recombination of 2D electrons with photoexcited holes at a single GaAs/AlGaAs heterojunction with a monolayer of acceptors

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The kinetics of the radiative recombination of 2D electrons with photoexcited holes, localized in a monolayer of acceptors at a given distance from the interface, has been studied at a single GaAs/AlGaAs heterojunction. The time scales for the recombination of the 2D electrons from the ground and excited quantum-well subbands have been determined for various distances between the 2D channel and the monolayer of acceptors.

1. Experiments on radiative recombination of two-dimensional (2D) electrons with photoexcited holes provide an opportunity to directly study the energy spectrum of 2D electrons in a perpendicular magnetic field under conditions corresponding to the quantum Hall effect.[1] This method has recently also been used to study the fractional quantum Hall effect[2–5] and the Wigner crystallization of 2D electrons.[6,7] These two effects are observed only when the electron system is at a very low temperature. The time scale of the radiative recombination of the 2D electrons is thus a crucial matter in these experiments, because it largely determines the effective electron temperature. In the present letter we are reporting a study of the kinetics of the radiative recombination of 2D electrons at a single GaAs/AlGaAs heterojunction with a monolayer (a δ layer) of acceptors at a given distance from the heterojunction. We used the method of time-correlated photon counting.

2. We studied single GaAs/$Al_xGa_{1-x}As$($x = 0.3$) heterojunctions in which a

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monolayer of acceptors (Be) with a concentration of 2×10^{10} cm^{-2} was produced in the GaAs buffer layer at a given distance (z_0) from the interface.[8] The test samples had values (z_0) = 250, 300, and 350 Å. As the excitation source we used a Spectra Physics picosecond laser system with an output pulse length of 1 ps. The pulses were tunable in wavelength (λ) and repetition frequency (f). All the measurements were carried out at $\lambda = 605$ nm and $f = 800$ kHz. The average power density at the sample was 2.5×10^{-2} W/cm^2, while the peak power density was 30 kW/cm^2. This figure corresponds to 0.3 nJ over 10^{-12} s in a spot 1 mm^2 in area. The density of the 2D electrons in the structures could be reduced by increasing the photoexcitation intensity.[9] In the present experiments, however, the level of the optical pumping was kept low enough ($<2.5\times10^{-2}$ W/cm^2) that the time scale of the increase in the density of 2D electrons after the laser pulse was many orders of magnitude longer than the recombination-radiation time. Under these experimental conditions, the density of 2D electrons thus was not varied. It was close to the maximum value, realized in darkness. The density of photoexcited holes was two orders of magnitude lower than the electron density in all cases. The measurements were carried out in an optical cryostat with a superconducting solenoid at 1.6 K. After the luminescence signal passed through an MDR-23 monochromator, it was detected by a system which performed a time-correlated photon count. This system was capable of recording both the lumines-

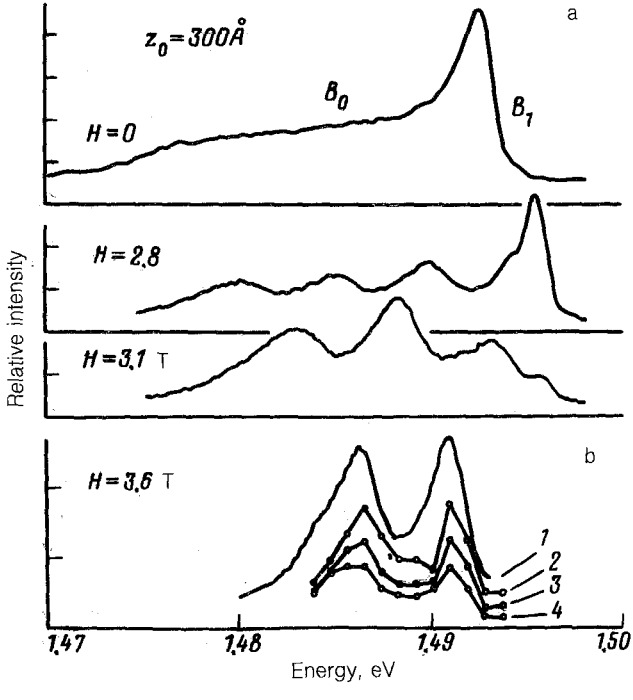

FIG. 1. a: Time-integrated luminescence spectra measured at $n_s = 4\times10^{11}$ cm^{-2} in a structure with $z_0 = 300$ Å at $H = 0$, 2.8, and 3.1 T. b: Time evolution of the luminescence spectra. 1—Time-integrated spectrum; 2–4—spectra measured at delays of 50, 100, and 300 ns, respectively.

cence spectrum at a given delay time and the kinetics of the luminescence decay at a fixed spectral position, with a time resolution of 0.2 ns.

3. Figure 1a shows time-integrated luminescence spectra measured at a fixed density of the 2D electrons, namely, $n_s = 4 \cdot 10^{11}$ cm^2, at $H = 0$ and also in a perpendicular magnetic field $H = 2.8$ or 3.1 T. Depending on the electron density and the magnetic field, we see the recombination radiation of 2D electrons from the ground (B_0) or excited (B_1) quantum-well subbands in the luminescence spectrum. In a perpendicular magnetic field the luminescence lines split into Landau levels in accordance with the level filling factor $\nu = n_s/(eH/h)$. A perpendicular magnetic field was necessary for this study of the kinetics of the radiative recombination, so that the signal associated with the 2D electrons could be distinguished. The reason is that a bulk donor–acceptor recombination from the buffer GaAs layer may be observed in

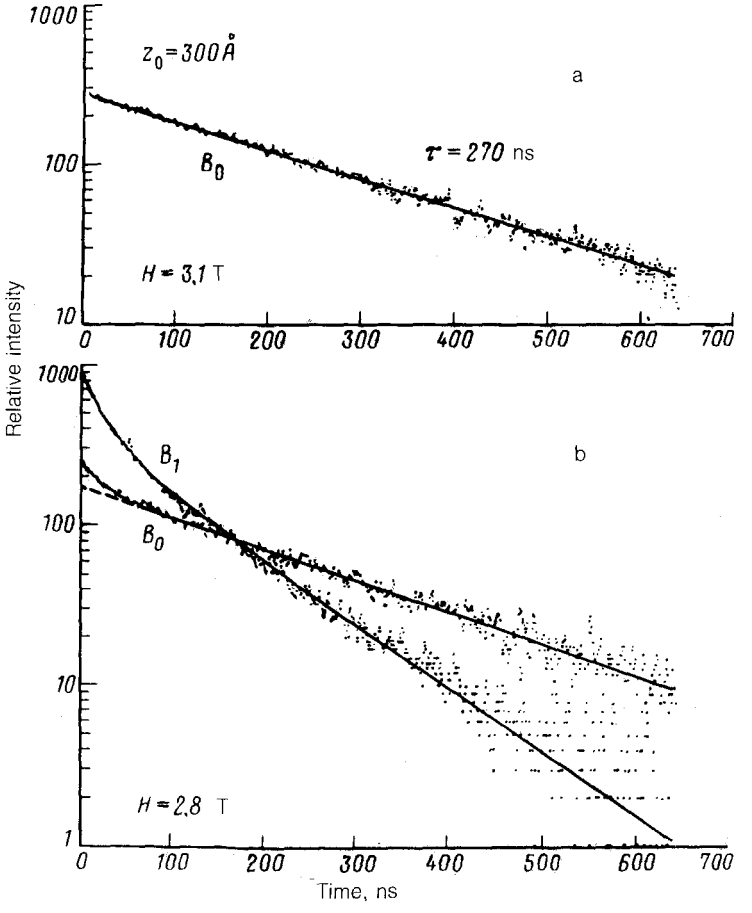

FIG. 2. Kinetics of the decay of the luminescence of 2D electrons. a—The excited quantum-well subband is empty; b—this subband is partially occupied. The plots of B_0 and B_1 correspond to the recombination of 2D electrons from the ground and excited subbands, respectively.

this spectral region.[10] As can be seen From Fig. 1b, the luminescence spectrum, which reflects several filled Landau levels of the ground quantum-well subband, is essentially unaffected by an increase in the delay to 300 ns. Its shape is the same as that of the time-integrated spectrum. It follows that the radiative-recombination time is independent of the energy of the 2D electrons in a first approximation, since the wave functions of the electrons of the ground subband are identical and independent of the kinetic energy of these electrons.

In general, the kinetics of the radiative recombination may be quite complex, impossible to describe by a single exponential function. The reason is that the wave functions of the 2D electrons from the different quantum-well subbands are different, as are the densities of the photoexcited holes (n_h) and of the electrons from the ground (n_{s0}) and excited (n_{s1}) subbands. The situation is simplest when the excited subband is not filled. As we see in Fig. 2a, the kinetics observed for the luminescence decay in this case can be described by a simple exponential law with a time scale $\tau = 270$ ns. When the excited quantum-well subband is slightly populated (under the

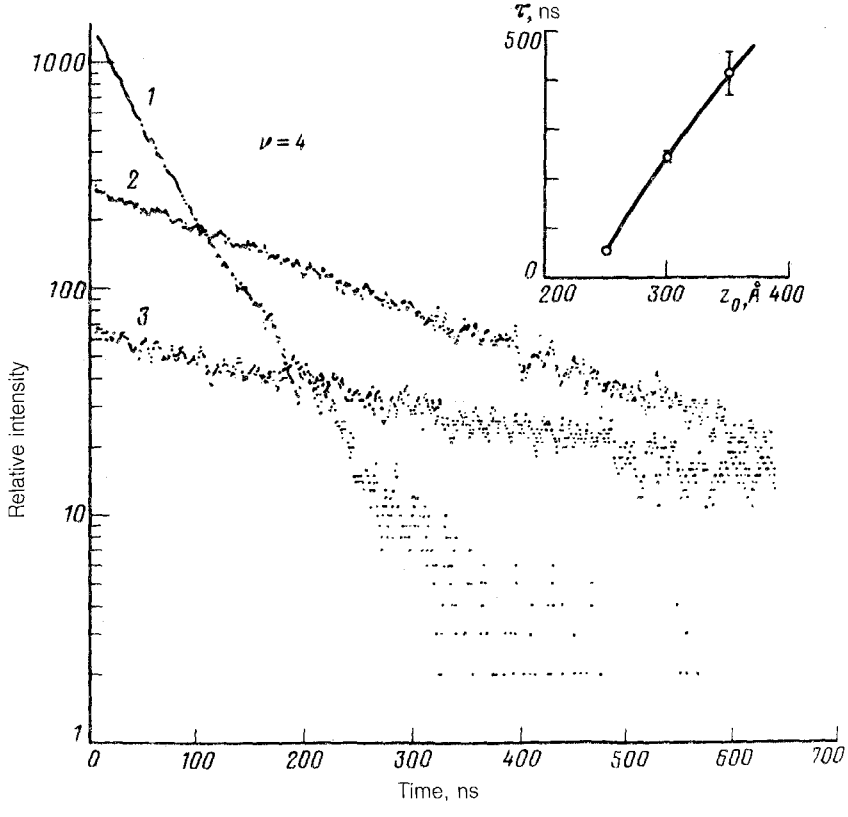

FIG. 3. Luminescence decay of 2D electrons measured at $\nu = 4$ in various structures, in which the δ layer of acceptors lay at distances (1) $z_0 = 250$ Å, (2) 300 Å, and (3) 350 Å from the interface. The inset shows the recombination time as a function of the distance z.

conditions $n_{s1} \ll n_h \ll n_{s0}$; Fig. 2b), the kinetics of the luminescence decay cannot be described by a single exponential function. We accordingly approximated it by a sum of two exponential functions. The first, and faster, of these functions describes the escape of holes from the δ layer and the escape of electrons from the first excited subband. This recombination is considerably faster because the wave function of the 2D electrons from the excited subband is larger in size than the wave function of the ground subband. For this reason, the overlap of the wave function of these electrons with the wave function of the holes bound at acceptors of the δ layer is considerably greater. The second, and slower, exponential function describes an escape of holes in the δ layer as a result of recombination with ground-subband electrons. This process is predominant after the excited subband is emptied (the dashed line in Fig. 2b).

With increasing distance between the δ layer of acceptors and the interface, the integrated luminescence signal decreases.[8] This decrease is accompanied by an increase in the recombination time. Figure 3 shows the behavior of the luminescence decay according to measurements for the 2D electrons of the ground subband ($\nu = 4$) in various structures with $z_0 = 250$, 300, and 350 Å. It can be seen from the inset in Fig. 3 that as z_0 is increased from 250 to 350 Å, the recombination time increases from 50 to 400 ns. We can work from the $\tau(z_0)$ dependence, which is determined by the change in the overlap of the wave functions of the 2D electrons and the holes bound at acceptors of the δ layer, to reconstruct the spatial profile of the electron wave function.

4. An important result of this study is that the time scale of the radiative recombination of 2D electrons with holes bound at acceptors of the δ layer at a single GaAs/AlGaAs heterojunction is on the order of 10^{-6} s. This result distinguishes this case in a fundamental way from the recombination of 2D electrons with free holes,[11] for which we would have $\tau = (1\text{–}5) \times 10^{-9}$ s. It is for this reason that the heating of the electron system is insignificant at a single GaAs/AlGaAs heterojunction with a δ layer of acceptors under the conditions of an optical experiment.[12]

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