Spin relaxation of photoexcited electrons and holes in a single GaAs/AlGaAs heterojunction

A. I. Filin, A. F. Dite, I. V. Kukushkin, and O. V. Volkov
Institute of Solid State Physics, Russian Academy of Sciences, 142432, Chernogolovka, Moscow obl., Russia

K. von Klitzing
Max-Planck-Institut für Festkörperforschung, Stuttgart, FRG

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The spin relaxation of photoexcited electrons and holes in a single GaAs/AlGaAs heterojunction has been determined in a direct experimental study of the kinetics of the recombination radiation in which the circular polarization was analyzed. The hole spin relaxation time in different magnetic fields has been determined. The upper limit of the time it takes to establish spin equilibrium in the electron subsystem has been determined.

1. The spin relaxation of photoexcited carriers can proceed at a much slower rate than the recombination processes because spin flip requires magnetic interaction, which is a weak process. This circumstance was exploited in the experiments on the optical orientation of photoexcited charge carriers, carried out using a 3D system—a AlGaAs compound.[1] The nonequilibrium magnetization in the electron system in this case was obtained by means of photoexcitation by circularly polarized light, and the recombination photoresponse was also strongly circularly polarized. Two-dimensional systems support the suggestion that because of the discrete structure of the energy spectrum, the spin relaxation in a prependicular magnetic field is abnormally slow.[2] However, the time-resolved experiments on the optical orientation, which were carried out in 2D quantum wells, surprisingly have shown that the spin relaxation times are unusually slow.[3] To solve this puzzle, simple experimental studies of the kinetics of the recombination radiation in a perpendicular magnetic field, with analysis of the circular polarization, must be carried out. In this letter we present the results of such an experimental study, in which we used samples containing a single GaAs/AlGaAs heterojunction and a δ layer in the acceptors, in which the photoexcited holes are bound.

2. We studied a sample which contain a single GaAs–$Al_xGa_{1-x}As$ heterojunction ($x=0.3$). In this heterojunction an acceptor monolayer—a concentration 2×10^{10} cm^{-2} of Be atoms—was formed in the GaAs buffer layer at a distance of 300 Å from the heterojunction interface.[4] The pump light source was a *Spectra Physics* picosecond laser with the following output parameters: pulse length $\tau = 1$ ps, radiation wavelength $\lambda = 605$ nm, and repetition frequency $f = 800$ kHz. The average power density at the sample in this case was 25 mW/cm^2, which corresponded to an energy of 0.3 nJ per picosecond at the spot 1 mm^2 in size. The 2D electron concentration was controlled by varying the intensity of optical pumping.[5] A rather low pumping level was chosen so that the variation in the concentration of 2D electrons could be ignored during a time characteristic of the processes which we were studying.[6] The sample was immersed into an optical liquid-helium cryostat which was held at a temperature of 1.6 K. The luminescence was measured at the monochromator exit, using a system designed for time-correlated counting of γ rays. This method allowed us to record both the luminescence kinetics in a certain spectral position and the spectra which were time-delayed in a certain way.

3. The Zeeman splitting in a magnetic field leads to the appearance of two electronic spin sublevels and four hole spin sublevels. The level splitting and the allowed transitions are shown schematically in the inset in Fig. 1a. In our experiment we studied the two most intense, circularly polarized luminescence components—the σ^- component (the result of the recombination of electrons from the sublevel $s = +1/2$ with the holes from the sublevel $J_z = -3/2$) and the σ^+ component ($s = -1/2$, $J_z = +3/2$).

Figure 1 shows the time-integrated spectra in the σ^- and σ^+ polarizations in fields of 4.2 and 5.5 T. An important point here is that the degree of polarization of the recombination line of the 2D electrons of the first excited subband, B_1, is stronger than that of the recombination lines of the 2D electrons of the Landau levels of the ground subband, B_0. In the ground subband the Landau levels are completely filled; i.e., the population of the two spin sublevels is the same and the degree of polarization of the B_0 line is determined exclusively by the state of the hole spin subsystem, while the electron spin orientation affects the polarization of the B_1 line.

The kinetics of the recombination of 2D electrons from the lowest-lying Landau level (the B_0 line) in the σ^- and σ^+ polarizations is shown in the inset in Fig. 2. The rapid decay of the signal in the initial part of the lower curve (σ^+) is attributable to

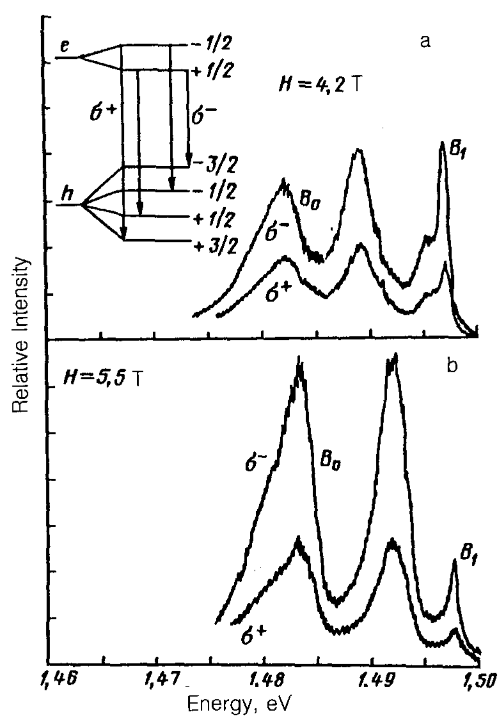

FIG. 1. a,b: Time-integrated luminescence spectra in σ^- and σ^+ polarizations in fields of 4.2 T and 5.5 T. Inset—Schematic diagram of the electron and hole level splitting in a magnetic field.

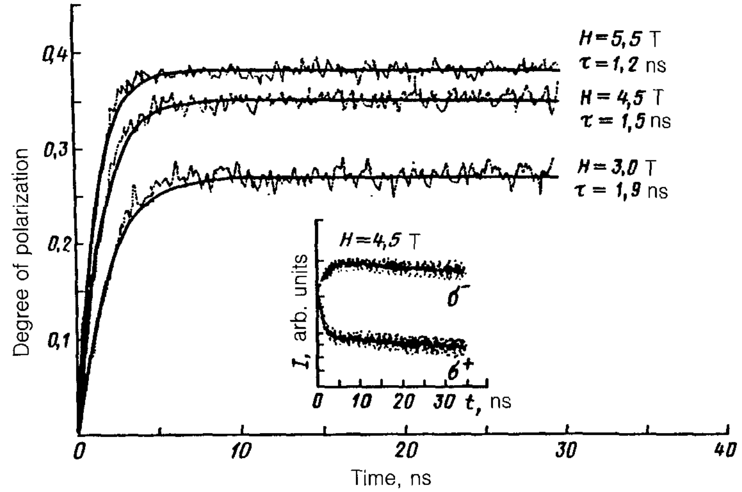

FIG. 2. Degree of hole polarization, γ_h, versus time in fields of 3.0 T, 4.5 T, and 5.5 T. Inset—Kinetics of the recombination of 2D electrons from the lower Landau level of the ground subband with photoexcited holes of the lower (σ^-) and upper (σ^+) hole spin sublevels.

the presence of two channels by which the holes escape from the upper (in terms of energy) hole spin sublevel ($J_z = +3/2$): the recombinations and relaxations to the lower spin sublevel. In turn, the initial part of the upper curve (σ^-) rapidly rises, which reflects the increase in the population of the lower spin sublevel as a result of the departure of the holes from the upper spin sublevel. After the spin equilibrium in the hole subsystem has been established, the relative population of the upper and lower spin sublevels will no longer change—the kinetic curves run parallel to each other.

Figure 2 is a plot of the degree of polarization, $\gamma = (\sigma^- - \sigma^+)/(\sigma^- + \sigma^+)$, in various magnetic fields, as a function of time. The solid curves represent the result of an approximation of the experimental data, using a function of the type $\gamma_h(t) = \gamma_0(1 - \exp(-t/\tau_h))$, where γ_0 is the degree of polarization which is observed in the corresponding field in the steady state. This polarization can be determined from the time-integrated spectra from the ratio of the line intensities of the σ^- and σ^+ polarizations.

4. The spectra which were analyzed by us contain a background from the donor–acceptor volume recombination, which rapidly decays with time and with the increase in the wavelength. At times on the order of several nanoseconds, this background is negligible in the part of the spectrum corresponding to the lower Landau level. This circumstance has made it possible for us to directly measure the kinetics corresponding to the filling of the hole spin sublevels. In the short-wave part of the spectrum, however, the donor–acceptor background must be taken into account at times on the order of 1 ns. This circumstance makes it more difficult to directly observe the kinetics of interest to us in the part of the spectrum corresponding to the B_1 line. We have

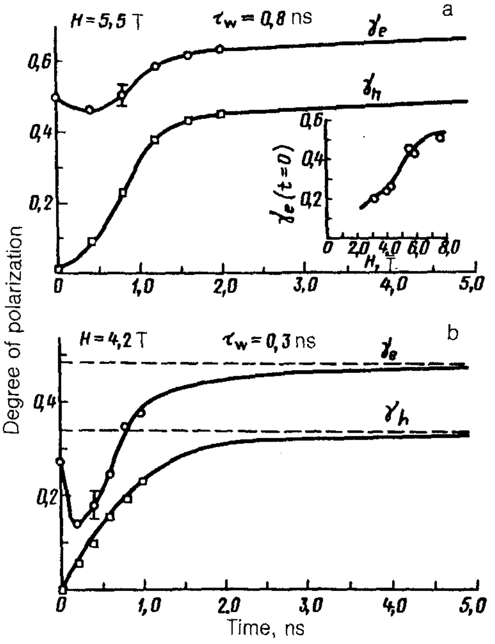

FIG. 3. Degree of polarization versus time for the recombination lines of 2D electrons from the lower Landau level of the ground subband and the excited subband (the open squares and open holes, respectively). a: $H = 5.5$ T; time-resolved window $\tau_w = 0.8$ ns; b: $H = 4.2$ T; time resolved window $\tau_w = 0.3$ ns. Inset—Degree of electron polarization versus the magnetic field.

recorded several time-delayed luminescence spectra, from which we determined the time evolution of the intensity of the line of interest here, after subtracting the background. The degree of polarization of the B_1 line in fields of 4.2 T and 5.5 T (near the filling factor) is plotted in Fig. 3 as a function of time. The open circles and open squares represent points obtained from an analysis of the B_1 and B_0 lines, respectively (the lower Landau level was analyzed in the ground subband). The widths of the time-resolved window, at which the initial spectra were recorded, are 0.8 ns (Fig. 3a) and 0.3 ns (Fig. 3b). As the zero-valued time lag we chose the time at which the trailing edge of the time-resolved widow coincides with the maximum value of the measurement system's response. The solid curves are given for convenience, and the dashed curve corresponds to the degree of polarization of the relevant lines. This polarization was determined from the time-integrated spectrum.

The lower curves (γ_h) in Figs. 3a and 3b are the previously discussed time evolution of the hole degree of polarization. The upper curve in each figure (γ_e) represents the total contribution to the degree of polarization of the recombination radiation from the electrons and holes. Characteristic feature of all the curves for the degree of electron polarization versus time, which we obtained, is the fact that the electronic subsystem is strongly polarized even when the time lag is zero. It can thus be concluded that at times shorter than those resolved by our detector ($\sim$300 ps) the population of the upper spin sublevel of the excited subband decreases considerably relative to the population of the lower sublevel. We then see a decrease in the effect of the electronic component on the degree of polarization of light, which is attributable to the establishment of the electron spin equilibrium. From the time the γ_e and γ_h curves begin to run parallel to each other, it can be assumed that the electronic component has stopped changing. It can be seen from Fig. 3 that the electronic subsystem acquires spin equilibrium in a time on the order of 0.5 ns.

In the excited subband the g-factor of the electron is larger than in the ground subband because of the weaker nonparabolocity effects.[7] In other words, the spin splitting in an excited subband is stronger. The energy gap between the upper spin sublevels of the excited subband and the ground subband is therefore larger than that between the lower spin sublevels. The probability for the transition from the upper spin sublevel of the excited subband to the upper spin sublevel of the main subband is therefore higher than the probability for such an intersubband transition from the lower spin sublevel to the lower spin sublevel, since the probability of relaxation from the excited subband to the ground subband increases with increasing energy gap between the initial state and the final state of the electron.[8]

For a filling factor of $\gtrsim 3$, at which the functional dependences shown in Fig. 3 are lifted, another mechanism may account for a more rapid emptying of the upper spin sublevel of the excited subband compared with that of the lower sublevel: Since there are much fewer free sites in the ground subband for electrons with spin up, situated at the lower spin sublevel of the excited subband, than for electrons with spin down, the probability for an intersubband relaxation without a spin flip is much higher than for electrons from the upper spin sublevel.

The degree of polarization of the electron subsystem versus the magnetic field is shown in the inset in Fig. 3. The experimental points correspond to the value of γ_e for a zero delay, where the hole component can be disregarded. The solid line is drawn for convenience. We see that the curve begins at the origin and reaches saturation in large fields.

5. The system which we are studying therefore has the following hierarchy of times: The shortest time is that of the intersubband electron relaxation without a spin flip—<0.3 ns; then follows the time it takes the electron spin equilibrium to be established—~ 5 ns; the hole spin relaxation time is 1–2 ns; much longer times are those of the recombination of 2D electrons from the excited quantum-size subband (~ 30 ns) and from the ground subband (~ 300 ns).[6,8]

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[1] F. Meier and B. P. Zakharchenya (Eds.), Opt. Orient., Modern Problems in Cond. Matt. Sciences, Vol. 8, North-Holland, Amsterdam, 1984.

[2] M. Potemski, J. C. Maan *et al.*, Phys. Rev. Lett. **63**, 2409 (1989).

[3] T. C. Damen, K. Leo, J. Shah, and J. E. Cunningham, Appl. Phys. Lett. **58**, 1902 (1991).

[4] I. V. Kukushkin, K. von Klitzing, K. Ploog, and V. B. Timofeev, Phys. Rev. B**40**, 7788 (1989).

[5] I.V. Kukushkin, K. von Klitzing, K. Ploog *et al.*, Phys. Rev. B**40**, 4179 (1988).

[6] A. F. Dite, K. von Klitzing, I. V. Kukushkin *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **54**, 393 (1991) [JETP Lett. **54**, 389 (1991)].

[7] M. Dobers, Proceedings of EP2DS8, Grenoble, France, 1989.

[8] A. F. Dite, K. von Klitzing, I. V. Kukushkin *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **54**, 635 (1991) [JETP Lett. **54**, 642 (1991)].

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