Wave function of 2D electrons in a parallel magnetic field

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(Submitted 24 March 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **61**, No. 8, 684–688 (25 April 1995)

The electron density in the tail of the wave function of 2D electrons has been observed to depend in a nonmonotonic way on the strength of a parallel magnetic field. This behavior is explained in terms of a competition between two processes. In the limit of weak magnetic fields, the amplitude of the wave function is observed to increase with increasing field. This increase occurs because the maximum of the electron density is driven away from the interface by the Lorentz force. In strong fields, in contrast, the predominant effect is a localization of the electron wave function within a magnetic length of the interface. The experimental data agree well with theoretical results derived in the parabolic approximation. © *1995 American Institute of Physics.*

1. Most properties of a 2D electron gas are sensitive to the normal component of the magnetic field but not to its parallel component.[1] For example, an effect of a parallel magnetic field on the mass of 2D electrons can be seen only in the limit of very strong magnetic fields or very low electron densities, at which the cyclotron energy is greater than the energy of the 2D quantization.[2] However, a parallel magnetic field can strongly influence the wave function of 2D electrons and the shape of a potential well near an interface. Such an effect has been observed indirectly in experiments on resonant photoconductivity, which have revealed a change in an intersubband resonance.[3]

Direct studies of the wave function of 2D electrons are based on a study of the radiative recombination of 2D electrons with holes bound at acceptors of a δ-layer localized at a certain fixed distance from the interface.[4] In a perpendicular magnetic field the luminescence spectra measured for such systems reflect the density of states of 2D electrons, since the wave function of the electrons does not depend on their energy. The recombination kinetics is sensitive to the amplitude of the wave function at a distance from the interface corresponding to the distance to the monolayer of acceptors. The recombination time increases markedly with increasing distance between the interface and the monolayer. When a parallel component of the magnetic field is introduced, the situation becomes more complicated.[5] The wave function of the 2D electrons acquires an energy dependence, and the luminescence spectrum ceases to reflect the functional behavior of the density of states. Another interesting effect of a parallel magnetic field on the wave function is that a competition arises between the Lorentz force, which strengthens with increasing magnetic field and which drives some of the electrons away from the interface, and the localization of the electron wave function near the interface, within a

magnetic length $l_B \propto B^{1/2}$. There are accordingly grounds for expecting both an increase and a decrease in the recombination time of 2D electrons as the result of the application of a parallel magnetic field.

In this letter we are reporting a study of the behavior of the amplitude of the wave function of 2D electrons at a distance from an interface corresponding to the position of the δ-layer of acceptors. Specifically, we studied the recombination kinetics of 2D electrons at various densities in a parallel magnetic field.

2. We studied the recombination spectra of 2D electrons from a single GaAs–$Al_xGa_{1-x}As$ ($x=0.3$) heterojunction with photoexcited holes bound at acceptors of the δ-layer. In the test sample, the δ-layer, with Be atoms in a concentration of 2×10^{10} cm^{-2} was separated from the interface by a distance of 30 nm. We used a method of compositive optical excitation: by pulsed and cw lasers simultaneously. The source of the pulsed excitation was a picosecond laser system with a wavelength of 605 nm, a pulse length of 1 ps, and a repetition frequency of 800 kHz. The average output power of the pulsed light at the sample was ~ 50 mW/cm^2. The sample was simultaneously excited by the beam from a cw Ar laser with a wavelength of 488 nm. This approach made it possible to control the density of 2D electrons[6] over the range $(1.5–4.0)\times10^{11}$ cm^{-2} by varying the intensity of the cw pump. The sample was inside a helium cryostat at a temperature of 4.2 K with a solenoid in a magnetic field parallel to the interface. An optical-fiber device transferred the light from the sample to the entrance slit of a monochromator. The light was detected by a time-correlated photon-counting system, which was capable of recording both the spectra, with a certain time delay, and curves of the luminescence decay in a certain spectral position with a resolution of 0.5 ns. The recombination times were determined by approximating the luminescence decay curves through a minimization of χ^2.

3. Figure 1 shows time-integrated spectra of the recombination of 2D electrons with photoexcited holes, localized at acceptors of the δ-layer, in a parallel magnetic field up to 10 T at two electron densities: a) 1.8×10^{11} and b) 3.5×10^{11} cm^{-2}. In the strong-field limit we observe an exponential growth of the intensity at the low-energy edge of the spectrum as the electron energy increases.[5] We should mention that the shape of the time-delayed spectra in these experiments did not depend on the time, since the intensity of the light from the pulsed laser was quite low, and the pulsed excitation did not affect the electron density in the 2D channel.[7] The inset in Fig. 2a shows kinetic curves recorded at spectral positions corresponding to intensity peaks (the spectral position was chosen for convenience, since the shape of the spectrum is independent of the time, as we just mentioned), for a density $n_S=3.5\times10^{11}$ cm^{-2} in fields of 0, 5, and 10 T. The recombination times calculated from the kinetic curves are shown by the points in Fig. 2, a–c, as a function of the strength of the parallel magnetic field for various densities. We attribute the acceleration of the recombination in weak fields to a displacement of some of the electrons away from the interface by the Lorentz force. In strong fields, the dominant factor is the localization of electrons within a magnetic length, so the recombination slows down. The competition between these two effects gives rise to a maximum on a plot of the recombination time versus the field. With increasing density, the Fermi velocity of the 2D electrons increases, and the position of the minimum shifts up the field

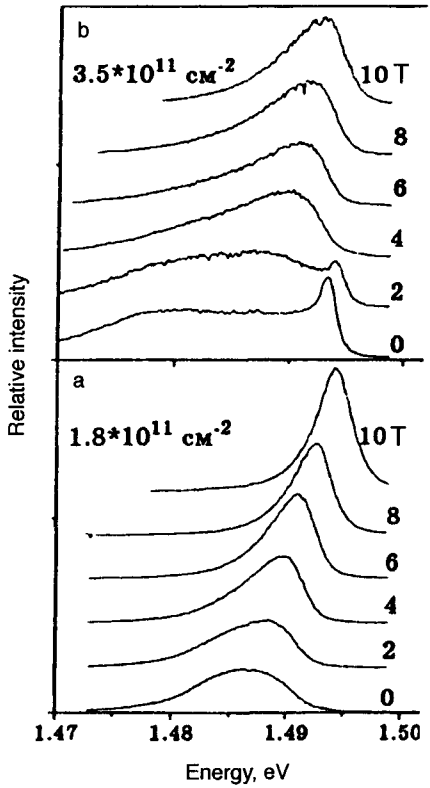

FIG. 1. Time-integrated spectra of the recombination of 2D electrons with photoexcited holes localized at acceptors in the δ-layer, in a parallel magnetic field. a—Electron density of 1.8×10^{11} cm^{-2}; b—3.5×10^{11} cm^{-2}.

scale. The points in Fig. 3 show the density dependence of the strength of the magnetic field at which the minimum recombination time is observed.

4. To compare the experimental data with theory, we use an exact solution of the problem of a 2D electron in a parallel magnetic field, derived for the case of a parabolic potential well.[8,9] In the parabolic approximation, the z component of the wave function of 2D electrons in a parallel field is

$$\Psi_z^e=\left(\frac{m^*\omega}{2\hbar}\right)^{1/4}\exp\left[-\frac{m^*\omega}{2\hbar}(z-z_0)^2\right],\quad \omega=\omega_0[1+(H/H_0)^2]^{1/2},$$

$$z_0=\frac{P_x}{m^*\omega_0}\frac{H/H_0}{1+(H/H_0)^2},$$

where m^* is the effective mass, $\hbar\omega_0=\hbar eH_0/m^*c$ is the intersubband splitting, z_0 is the displacement of the equilibrium position of a simple harmonic oscillator from the origin of coordinates, H is the magnetic field, and P_x is the x component of the momentum.

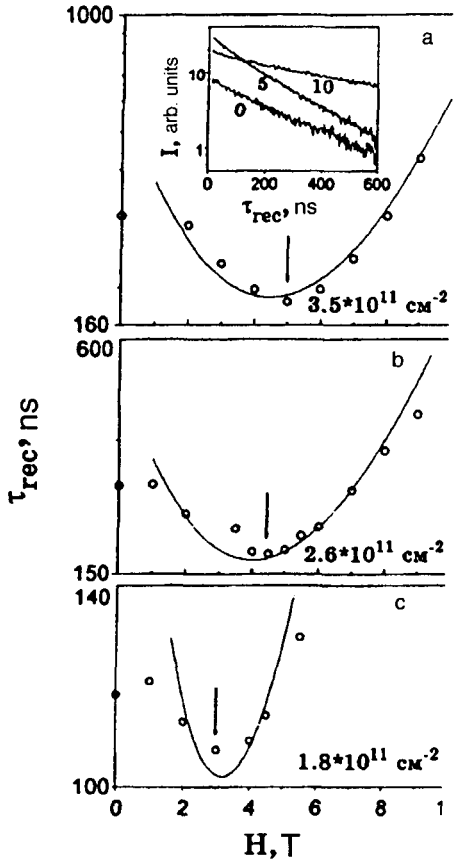

FIG. 2. Recombination time of the 2D electrons versus the strength of the parallel magnetic field. a—The electron density is 3.5×10^{11} cm^{-2}; b—2.6×10^{11} cm^{-2}; c—1.8×10^{11} cm^{-2}. Solid curves) Theoretical; arrows) positions of the minima on the energy dependence. The inset shows recombination curves recorded at spectral positions corresponding to intensity peaks. The numbers are the strength of the parallel magnetic field in teslas.

The time scale ($\tau_{\rm rec}$) for the recombination of 2D electrons with holes localized at acceptors of the δ-layer is determined by the overlap integral for the overlap of the z component of the wave function of the 2D electrons with the wave function of the holes, $\Psi_z^h=\delta(Z-Z_\delta)$:

$$1/\tau_{\rm rec}\propto\int\Psi_z^e\Psi_z^h dz=\Psi_z^e(z=z_\delta,P_x=P_\perp^F),\quad (P_\perp^F)^2=2m^*E_0^F[1+(H/H_0)^2].$$

In the integration in the calculations, only the electrons having a Fermi momentum in the direction perpendicular to the magnetic field are considered. The quantities $\hbar\omega_0$ and E_0^F (the latter is the Fermi energy in a zero magnetic field), which depend on the density, were found from the experiments of Ref. 10.

Results of calculations for densities of 1.8×10^{11}, 2.6×10^{11}, and 3.5×10^{11} cm^{-2} are shown by solid curves in Fig. 2. As an adjustable parameter here we use the coefficient of

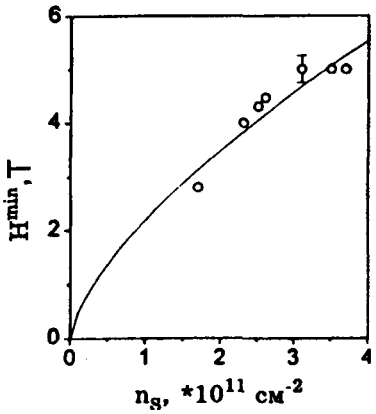

FIG. 3. Strength of the parallel magnetic field at which the minimum recombination time is observed as a function of the density. Points—Experimental; solid curve—theoretical, for a parabolic potential well.

the proportionality between the reciprocal of the recombination time and the overlap integral. It can be seen from Fig. 2 that the curves have a minimum, whose position corresponds quite accurately to the position of the minimum on the experimental curves.

The reciprocal of the overlap integral is minimized as a function of the field. After some straightforward calculations, the density dependence of the field of values corresponding to the minima of τ_{rec} becomes

$$H^{min}(n_S) = 2.2[\mathrm{T}\times \mathrm{cm}^{4/3}]\times n_S^{2/3}.$$

A corresponding curve is shown by the solid line in Fig. 3. This curve was derived without adjustable parameters, but it still agrees quite well with experiment.

5. In summary, we have experimentally studied the amplitude of the wave function of 2D electrons at a distance from an interface corresponding to the distance to the monolayer of acceptors. In weak fields, the amplitude of the wave function increases with increasing field, because the maximum of the electron density is driven away from the interface by Lorentz force. A further increase in the field reduces the amplitude of the tail of the wave function, since the predominant effect in strong fields is a localization of the electron wave function within a magnetic length of the interface. With increasing density, the Fermi velocity of the 2D electrons increases, and the maximum value of the amplitude as a function of the field shifts to a stronger field. The experimental results agree well with a theoretical solution derived in the approximation of a parabolic potential well.

We wish to thank K. Ploog for furnishing the test samples. We also thank the Volkswagen Foundation for support.

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Translated by D. Parsons