Radiative recombination of two-dimensional electrons in acceptor δ-doped GaAs-$Al_xGa_{1-x}As$ single heterojunctions

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(Received 26 April 1989)

We have investigated a new type of heterojunction, which we propose as being especially advantageous for studying the radiative recombination of two-dimensional (2D) electrons. The structure is an *n*-type GaAs-$Al_xGa_{1-x}As$ single heterojunction with a δ layer of acceptors positioned at a well-defined distance from the interface in a wide GaAs buffer layer. The radiative recombination of the 2D electrons with holes bound to these acceptors was investigated and the dependencies of the intensity, broadening, and spectral position of the luminescence line on the distance between the interface and the δ layer were measured. We found that the broadening of the luminescence line due to the holes is very small and this allows direct investigations of the density of states of the 2D electrons.

INTRODUCTION

The radiative recombination of two-dimensional (2D) electrons is usually investigated in quantum wells with different widths.[1,2] These systems have one, but very essential, disadvantage, namely the existence of the reverse heterojunction not far from the 2D channel. Due to the surface roughness of this reverse heterojunction,[3] the mobility of 2D electrons in quantum wells is usually much smaller than that in single heterojunctions (SH). As a consequence, some very interesting effects (such as the fractional quantum Hall effect[4,5] or Wigner crystallization[6,7]) cannot be observed in these systems or, at least, they are strongly suppressed by disorder. In the present paper we propose a new type of heterostructure, which can be used for optical investigations of the 2D electrons, and is different from a quantum well. The structure is an *n*-type single heterojunction with a δ layer of acceptors created at a well-defined distance from the interface in a wide GaAs buffer layer. In these structures one can investigate the radiative recombination of 2D electrons with holes bound to the acceptors from the δ layer. Contrary to the case of quantum wells, in these SH with δ doping it is possible to obtain a very high mobility of 2D electrons by increasing the distance between the monolayer of acceptors and the interface or by a reduction of the concentration of acceptors in the δ layer.

The spectroscopic method, based on measurements of the radiative recombination of 2D electrons with the photoexcited holes is known to be very useful for the investigation of the energy spectrum of 2D electrons.[8–13] It permits the measurements of the splittings in the energy spectrum below the Fermi energy, including the cyclotron,[9] spin,[14] and intervalley splittings.[15] This method was successful in silicon metal-oxide-semiconductor field-effect transistors (Si-MOSFET's) for the investigation of the oscillations of the Landau-level width due to screening effects[10,16] and for measuring the Coulomb gaps under conditions of the fractional quantum Hall effect.[17,18] The limitations on the accuracy and sensitivity of the method in the case of Si-MOSFET's were defined by the broadening of the luminescence line due to the distribution function of the holes participating in the recombination process.[10] It was established that 2D electrons recombine with the holes bound to acceptor atoms[9] and the mentioned broadening was rather large in this case, because of the random distribution of acceptors in the bulk. One of the advantages in the case of GaAs-$Al_xGa_{1-x}As$ single heterojunctions, as compared to Si-MOSFET's, is the possibility to grow, by molecular-beam epitaxy (MBE), very-high-quality structures with well-defined parameters. For example, MBE permits the preparation of structures with a monolayer of acceptor atoms positioned at a well-defined distance from the interface (z_0). In this case one can evaluate the amplitude of the wave function of 2D electrons by changing the value of z_0 and find the distance at which the acceptor atoms most effectively contribute to the radiative recombination intensity. One important problem in the case of Si-MOSFET's was concerned with the position of the luminescence line in the spectrum. It was found that the position of the Fermi energy of the recombination line in the spectrum was lower than the band gap of Si by a value smaller than the binding energy of the acceptor.[9] The same experimental result was found also for GaAs-$Al_xGa_{1-x}As$ single heterojunctions,[12,13] but in this case there is a possibility to investigate the problem using the δ-doping technique, where a single sheet of positively (or negatively) charged impurities is positioned in the GaAs at a given distance from the interface.

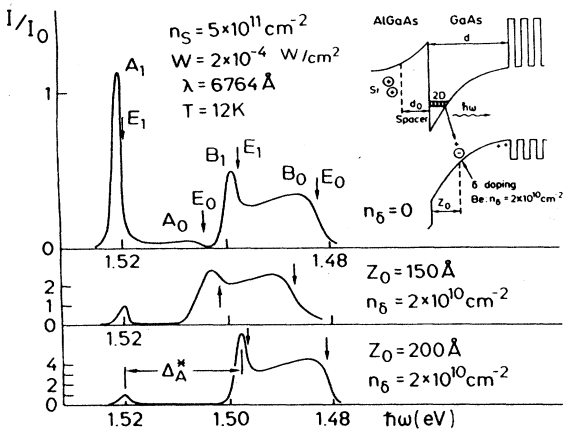

FIG. 1. Spectra of the radiative recombination of 2D electrons with photoexcited holes, measured in acceptor δ-doped SH (a) and (b) and in reference SH without δ doping (c) at $T=12$ K. I_0 is a fixed value of the luminescence intensity. In the inset the scheme of the structure is presented.

EXPERIMENT

We investigated GaAs-$Al_xGa_{1-x}As$ single heterojunctions ($x=0.28-0.32$) in which a δ layer of acceptors (Be) had been positioned in the GaAs buffer layer at the well-defined distance (z_0) from the interface (see the inset of Fig. 1).[19] Due to the low growth temperature of 580° C to avoid diffusion, the acceptors are located within a few monolayers. The value of z_0 varied in our samples from 5 nm to 30 nm and the concentration of δ doping (n_δ) was about 2×10^{10} cm^{-2}. We compared the results obtained in δ-doped samples with the reference samples without a δ layer of acceptors. Except for the δ doping, all samples were grown under similar conditions, and the background p-type (carbon) doping level was estimated as 10^{14} cm^{-3}. In most of the SH the width of GaAs buffer layer (d) was 50 nm. We also investigated heterostructures with $d=2000$ nm but did not find any difference between the results obtained for $d=50$ nm and $d=2000$ nm (for details see below). The typical mobility of 2d electrons at 3×10^{11} cm^{-2} and $T=4.2$ K was $(3-5)\times10^5$ cm^2/V s for $z_0>20$ nm and it was much smaller for $z_0<15$ nm. We have previously shown[20] that at low temperatures under continuous illumination with the laser light, the concentration of 2D electrons could be strongly reduced, and the higher the intensity and photon energy of the light the smaller the concentration of 2D electrons. In all our samples we were able to change the concentration of 2D electrons from 1.5×10^{11} to 6×10^{11} cm^{-2} by continuous illumination with the appropriate intensity and wavelength.[20] Other details of the experiment can be found in Refs. 12 and 20.

RESULTS AND DISCUSSION

In Figs. 1(b) and 1(c) we show the luminescence spectra, measured for the identical SH but with different distances between the interface and the δ layer of acceptors. For comparison, on the same figure, the spectrum measured for a reference SH without δ doping [Fig. 1(a)] is presented. It is seen from this figure that the lines A_1, B_1, and B_0 are observed in the luminescence spectra at $T=12$ K and $n_S=4\times10^{11}$ cm^{-2}, which are due to the recombination of 2D electrons with free holes (A lines) and holes bound to the acceptors (B lines) (the index corresponds to the number of the 2D subband).[12] The presence of the A_1 line in the luminescence spectrum under the indicated conditions enables one to measure the relative intensity of the radiative recombination of 2D electrons with holes bound to acceptors in the δ layer. Therefore, in each sample with different z_0, we normalized the intensities of the B_0 and B_1 line to the intensity of the A_1 line, obtained under the same experimental conditions. It is seen from Fig. 1 that the introduction of the additional δ layer of acceptors close to the interface increases the intensity of the B lines, and this enhancement depends on the distance between the interface and δ layer of acceptors. As well as the intensity, the broadening of the B line and its position in the luminescence spectrum also strongly depend on z_0. The variation of the energy position of the B lines is related to the change of the binding energy of the acceptors in the δ layer as a function of its distance from the interface. This phenomenon will be discussed in detail later. In Fig. 2 we show the dependencies of the intensity, the broadening, and the energy position of the B lines on the distance z_0 between the interface and the δ layer of acceptors. It is seen from Fig. 2(a) that the intensity of the B_0 line is maximal at $z_0=20$ nm. The reduction of the intensity of the B_0 line for $z_0<20$ nm is due to the ionization of the

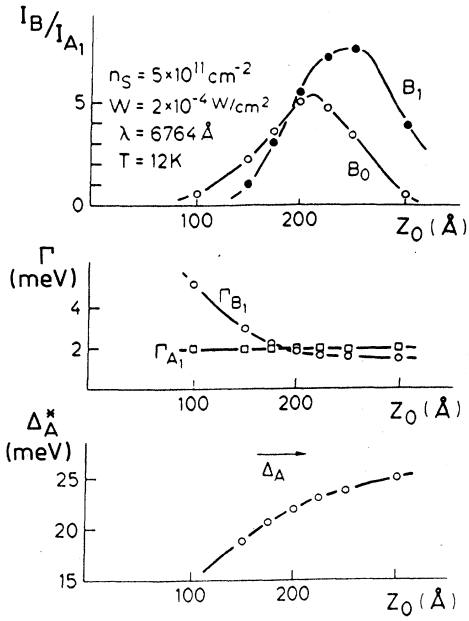

FIG. 2. The dependencies of the intensities of B_0 and B_1 lines, the broadening of the B_1 line, and the effective binding energy of the acceptors on the distance between the interface and the δ layer of acceptors.

acceptors by the strong electric field, which exists near the interface. This conclusion is confirmed by the fact that for $z_0 < 15$ nm the intensity of the Raman scattering signal obtained from neutral acceptors in δ layer is much smaller as compared to the case of $z_0 = 20$ nm. The reduction of the intensity of the B_0 line for $z_0 > 20$ nm is due to a decrease of the overlap of the wave functions of the 3D electrons and the holes bound to acceptors in the δ layer. A similar dependence of the intensity on z_0 was measured for the B_1 line, but the maximum intensity in this case was at $z_0 = 25$ nm, because of the wider wave function of 2D electrons in the first excited subband. From the dependence of the intensities of the B_0 and B_1 lines on z_0 we can estimate the amplitude of the wave function of the 2D electrons for the ground and excited subbands at different z_0 values. One possibility is to analyze the tail of the wave function, which can be described as

$$\psi_{0,1} \sim \exp[-z(2mE_{0,1})^{1/2}/\hbar] , \quad (1)$$

where E_0 and E_1 are the effective heights of the barriers for the ground and the excited subbands, respectively, and m is the mass of the 2D electrons in z direction. Therefore, from the intensities of the lines B_0 and B_1, measured for $z_0 = 25$ nm ($I_{25\text{ nm}}$) and for $z_0 = 30$ nm ($I_{30\text{ nm}}$), one can estimate E_0 and E_1:

$$I_{25\text{ nm}}/I_{30\text{ nm}} \sim \psi^2(z=25\text{ nm})/\psi^2(z=30\text{ nm}) = \exp[2\,\Delta z(2mE_{0,1})^{1/2}/\hbar] , \quad (2)$$

where $\Delta z = 5$ nm. We obtained experimentally $I_{25\text{ nm}}/I_{30\text{ nm}} = 5.1$ for the B_0 line and 2.2 for the B_1 line. From Eq. (2) one can obtain $E_0 = 15.0$ meV and $E_1 = 3.6$ meV. Note that for the intersubband splitting we obtained from the luminescence spectra (see Fig. 1) $E_{01} = 15$ meV, which is reasonably consistent with the difference between E_0 and E_1, found from the dependencies of the intensity of B lines on the distance z_0. We also estimated parameters of the wave functions, written in the form[21]

$$\psi_0 \sim z[\exp(-bz/2)] , \quad (3)$$

$$\psi_1 \sim z(z-a)\exp(-cz/2) , \quad (4)$$

and obtained $b^{-1} = 2.5$ nm and $c^{-1} = 3.3$ nm. For the average distance of 2D electrons from the interface z^{av} we obtained for different subbands: $z_0^{\text{av}} = 3/b \approx 7.5$ nm and $z_1^{\text{av}} \approx 5/c \approx 16.5$ nm, which are in agreement with theoretical calculations by Stern and Das Sarma.[22]

The data of Fig. 2(b) indicate that the broadening of the B_1 line, Γ_{B_1}, depends on z_0. The width of the A_1 line, on the contrary, does not depend on z_0 and remains rather small in all structures. The increase of the broadening of the B_1 line with decreasing distance z_0 is naturally associated with the electric field which strongly increases with the decrease of z_0.

In Fig. 2(c) we show how the binding energy of the acceptors Δ_A^* depends on the distance between the interface and position of the acceptor. The value of Δ_A^* is given by the energy separation between the lines A_1 and B_1 in the luminescence spectra, as shown in Fig. 1. The same dependence can be obtained if the difference between the position of the band gap of GaAs and the Fermi energy of the B line in the spectrum is plotted [due to the fact that the A_1 line is located close to the band gap of GaAs (Ref. 12) in the luminescence spectra]. It is seen from Fig. 2(c) that the binding energy of the acceptors decreases when they are located closer to the interface. A similar result was obtained from a Raman scattering experiment on these acceptor δ-doped samples.[23] The observed reduction of the binding energy of the acceptors for small z_0 corresponds with the theoretical calculations of Levine[24] and Bastard.[25] This phenomenon is due to a deformation of the wave function of the ground state of the neutral impurity (which is symmetrical in the bulk) near the interface by the strong electric field. In the limit of very high electric fields the wave function is not an s-like but a p-like wave function, and due to this fact the binding energy of the impurity at the interface can be 4 times smaller than that in the bulk.[24] Our experiments further revealed that the dependence of Δ_A^* on z_0 is also sensitive to the concentration of 2D electrons. For a comparison of the acceptor binding energy Δ_A^*, of the present study, with theoretical calculations of Refs. 24 and 25, we have to take into account additional subtle effects due to the valence-band bending which may also change as a function of distance from the heterointerface.

We also investigated acceptor δ-doped GaAs-$Al_xGa_{1-x}As$ SH with 2000-nm-wide GaAs buffer layer. In these structures we never found the recombination of 2D electrons with free holes (A_i lines), but the B lines were clearly observed. This was established by investigating the luminescence in magnetic fields.[12] Therefore, the radiative recombination of 2D electrons with free holes, observed in the structures with 50-nm-wide GaAs buffer layer,[12] was due to the spatial confinement of the free holes by a barrier located at the distance of 50 nm from the interface. In the structures with a wider buffer layer the free holes move rapidly far away from the interface,

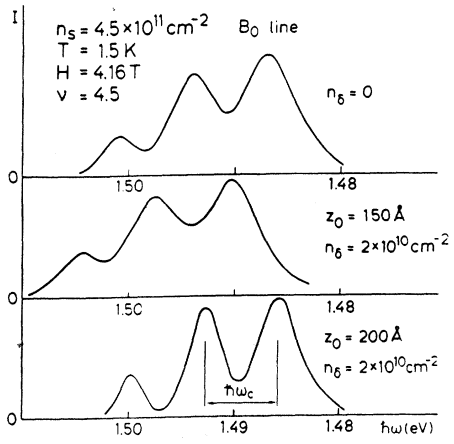

FIG. 3. Spectra of the radiative recombination of 2D electrons with holes bound to acceptors, measured in acceptor δ-doped SH (a) and (b) and in reference SH without δ doping (c) in the perpendicular magnetic field $H = 4.16$ T.

due to a repulsive electric field, and the corresponding recombination is not observed.

In Fig. 3 we show the spectra of radiative recombination of 2D electrons with holes, bound to acceptors, measured in a perpendicular magnetic field for the same structures as in Fig. 1. The broadening of the Landau levels in the luminescence spectrum depends on z_0, similar to the case of $H=0$ T [see Fig. 2(b)]. In the case of the reference structure without δ doping [the spectrum is shown in Fig. 3(a)] the intensity of the B line is much smaller and this recombination is due to residual acceptors (carbon) in the GaAs buffer layer.[12] From the spectral position of the B line and the broadening of the Landau levels we can estimate the average distance of these randomly distributed acceptors from the interface, at which they are most effectively recombining with 2D electrons, and obtain a value of 18 nm and a concentration of 3×10^8 cm^{-2} residual acceptors. For the interpretation of the luminescence spectrum in terms of the density of states of the 2D electrons, it is essential to know the hole states in a perpendicular magnetic field. For this purpose we measured the polarization of the luminescence lines in a magnetic field. To study the A_0 line we select a SH with a very pure 50-nm-wide GaAs buffer layer, so that the intensities of the B_0 line and of the bulk recombination were very small. It is seen from Fig. 4 that the A_0 line shows a small degree of circular polarization (γ) for $H<10$ T. This result is associated with a mixture of the heavy- and light-holes states. Note that the degree of circular polarization is not the same for different Landau levels but is enhanced for the level close to the Fermi energy at $\nu=1,3,5,\ldots$ (see Figs. 4 and 5). This result is due to the spin polarization of the 2D electrons in the highest Landau level at these values of ν.

Contrary to the A_0 line, the B_0 line is strongly circular polarized (σ^- polarization). The degree of circular polarization of the B_0 line in our experiment reaches 0.7. We estimated the degree of depolarization of the window of our cryostat to be 0.25, and therefore we assume that the real degree of circular polarization of the B_0 line is close to 1. In the inset of Fig. 4 the splittings of the energy levels in a perpendicular magnetic field are shown for a 2D electron and for a hole bound to an acceptor. It is seen that at low temperatures only one spin component of the 2D electrons participates in the recombination with a hole from the ground state due to the selection rules. This result is similar to the case of Si-MOSFET's (Ref. 9), but due to the opposite sign of the g factor of 2D electrons, in GaAs-$Al_xGa_{1-x}As$ SH one can investigate the lowest energy state of 2D electrons. The dependence of the degree of circular polarization of the B_0 line on the magnetic field is shown in Fig. 5 for different temperatures. This dependence corresponds to the expected one:

$$\gamma=[1-\exp(-\Delta E_S/k_BT)]/[1+\exp(-\Delta E_S/k_BT)], \tag{5}$$

where $\Delta E_S=2\mu_B g_h H$ is the splitting between the hole states $J_z=-\frac{3}{2}$ and $J_Z=+\frac{1}{2}$ (μ_B is the Bohr magneton and g_h is the g factor of the hole bound to an acceptor). We determined the value of g_h by fitting the experimental dependence to Eq. (5) and obtained $g_h=1.1$. Note that in the structures with $z_0>20$ nm we found that the broadening of the Landau levels in the luminescence spectra due to the distribution function of the holes does not exceed 0.5 meV, and this permits the direct measurement of the density of states of 2D electrons in a perpendicular magnetic field.

CONCLUSION

We have investigated a new type of GaAs-$Al_xGa_{1-x}As$ heterostructure, which we propose as being especially advantageous for studying the radiative recombination of 2D electrons with photoexcited holes bound

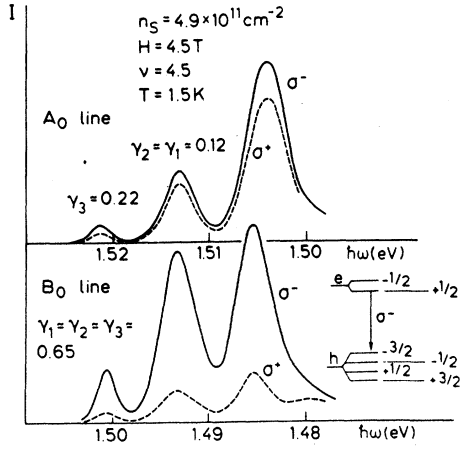

FIG. 4. Spectra of the radiative recombination of 2D electrons with free holes (A_0 line) and with holes bound to acceptors (B_0 line, $z_0=20$ nm, $n_\delta=2\times10^{10}$ cm^{-2}) measured in differnt circular polarizations in the perpendicular magnetic field $H=4.5$ T and $T=1.5$ K. In the inset the splittings of the energy levels of a 2D electron and a hole bound to an acceptor are shown.

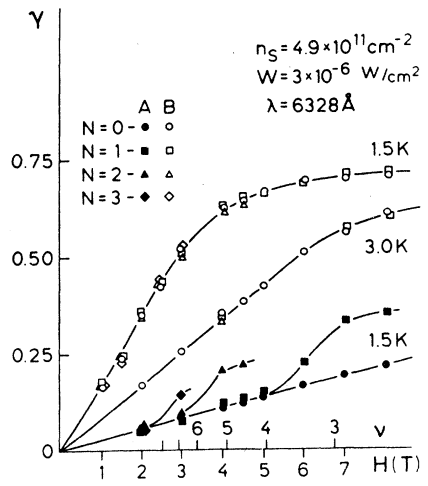

FIG. 5. The dependence of the degree of circular polarization on the magnetic field, measured for A_0 and B_0 lines at $T=1.5$ and 3.0 K. Different symbols correspond to the different Landau levels of these lines, split in a perpendicular magnetic field. The polarization γ is given by $\gamma=(I_- - I_+)/(I_- + I_+)$.

to acceptors. The luminescence obtained from these structures is of high intensity and the broadening of the luminescence line due to the distribution function of the holes is very small if the acceptors are confined to a δ layer and positioned at a given distance from the heterointerface. These narrow luminescence lines allow us to directly investigate the energy spectrum of 2D electrons in GaAs-$Al_xGa_{1-x}As$ heterojunctions in a perpendicular magnetic field. In addition, the high-electron mobilities achievable in these single heterojunctions make it feasible to study the Coulomb gaps in the energy spectrum of the incompressible Fermi liquid under the conditions of the fractional quantum Hall effect.

ACKNOWLEDGMENTS

We would like to thank A. L. Efros and V. D. Kulakovskii for useful discussions, V. E. Kirpichev for the help in the experiment, and A. Plaut for a critical reading of the text. One of us (I.V.K.) would also like to thank Alexander von Humboldt-Stiftung for financial support.

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