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Optical spectroscopy of two-dimensional electrons in GaAs-$Al_xGa_{1-x}As$ single heterojunctions

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The radiative recombination of two-dimensional electrons with nonequilibrium photoexcited holes in the magnetic field has been investigated in GaAs-$Al_xGa_{1-x}As$ single heterojunctions for the first time. Two different channels of radiative recombination are observed—a recombination with free holes and with the holes bound to acceptor atoms. In a magnetic field perpendicular to the two-dimensional (2D) layer, both luminescence lines are split into Landau levels, and these splittings depend only on the normal component of the magnetic field. It is shown that when the concentration of two-dimensional electrons is increased, the first excited two-dimensional subband is populated and an additional intense line appears in both components of the spectrum. The high intensity of this line originates from a considerable overlap of corresponding wave functions of 2D electrons and of the holes and enables one to investigate independently the properties of 2D electrons from the first excited subband.

After the discovery of the integral[1] and fractional[2] quantum Hall effects the interest in investigating the properties of two-dimensional (2D) electrons in a perpendicular magnetic field has considerably increased. In order to obtain a microscopic theory of these phenomena, it is important to know the energy spectrum of the electronic system. All methods based on measurements of magnetoconductivity,[3] magnetosusceptibility,[4] magnetocapacitance,[5] and spin and cyclotronic resonances are sensitive only to the properties of the electrons close to the Fermi energy. One of the most powerful methods for direct investigation of the whole energy spectrum of 2D electrons including measurements of the density of states below the Fermi energy and the splittings between occupied levels is based on the investigation of the radiative recombination of 2D electrons with photoexcited holes.[6] This method has been successful in investigations of properties of 2D electrons in Si-metal-oxide-semiconductor field-effect transistors.[7-9] It permits observation of the oscillations of the width of Landau levels due to screening effects,[7] the oscillations of the spin and valley splittings,[10] and the measurement of the Coulomb gaps in the energy spectrum of the incompressible Fermi liquid under the conditions of the fractional quantum Hall effect.[11]

The principal advantage of the 2D-electron system in GaAs-$Al_xGa_{1-x}As$ heterojunctions in comparison with Si-MOSFET's is the possibility of growing very high-quality structures with well-defined properties by molecular-beam epitaxy (MBE). Besides this it is very important that GaAs is a direct-gap semiconductor with much higher radiative recombination rate than in Si. Finally, the sensitivity of photodetectors in the region of 800 nm is considerably higher than in the region of 1200 nm. All these facts strongly increase the signal intensity in GaAs compared to the case of Si-MOSFET's.[6]

Up to now magneto-optical investigations of 2D electrons in GaAs-$Al_xGa_{1-x}As$ structures were carried out only in multiple quantum wells.[12,13] In this case, the 2D electron systems have several disadvantages. First, because of the small recombination time in the quantum wells, the carriers usually have a high temperature and from this fact a considerable broadening arises in the spectrum.[12] Second, in photoexcited quantum wells usually several 2D subbands are populated and in this case the recombination of the electrons from the highest subband is dominant in the spectrum.[13] Third, the mobility of 2D electrons in quantum wells is usually considerably poorer than in the single heterojunction GaAs-$Al_xGa_{1-x}As$.

The main aim of the present work was to observe and investigate the radiative recombination of 2D electrons with photoexcited holes in GaAs-$Al_xGa_{1-x}As$ single heterojunctions.

The luminescence spectrum of a standard GaAs-$Al_xGa_{1-x}As$ single heterojunction with a 1-μm GaAs buffer layer shows very intense bulk recombination lines from GaAs which overlap with the weak emission line of 2D electrons (see also Ref. 14). This situation is analogous to the case of Si-MOSFET's, but in GaAs due to the large amount of residual impurities there are several bulk lines which cover almost all the interesting energy region. Hence, it is necessary to decrease this bulk signal by reducing the thickness of the GaAs buffer layer. It was experimentally established that the optimal width of GaAs is 50 nm. At this thickness, no reduction in the quality of the 2D channel was observed, but the fraction of the bulk luminescence intensity becomes very small (see Fig. 1).

The samples used for the present study were grown by MBE in a series of experiments to demonstrate high-throughput, high-yield fabrication of modulation-doped GaAs-$Al_xGa_{1-x}As$ heterojunctions by this technique.[15] The layer sequence starting from the (001) semi-insulating undoped GaAs substrate comprises a 10-period GaAs-AlAs short period (2.5 nm) superlattice buffer to prevent propagation of dislocations from the substrate, followed by a 50-nm-thick undoped ($p = 2\times10^{14}$ cm^{-3}) GaAs layer, an undoped $Al_{0.35}Ga_{0.65}As$ spacer of thickness

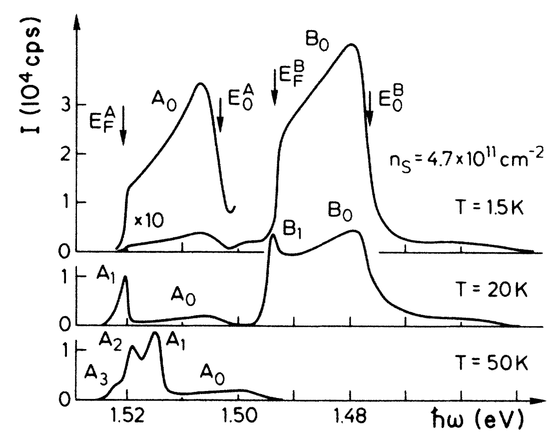

FIG. 1. Spectra of radiative recombination of 2D electrons with photoexcited holes measured from the GaAs-$Al_xGa_{1-x}As$ single heterojunction sample 1 ($n_S=4.7\times10^{11}$ cm^{-2}) at different temperatures: 1.5, 20, 50 K. The lines A_i and B_i correspond to the recombination of 2D electrons with free holes and holes bound to acceptor atoms, respectively. The excitation density is 10^{-5} W/cm^2. The arrows indicate the positions of the subband bottom and the Fermi energy, which were determined from the Landau fan diagrams.

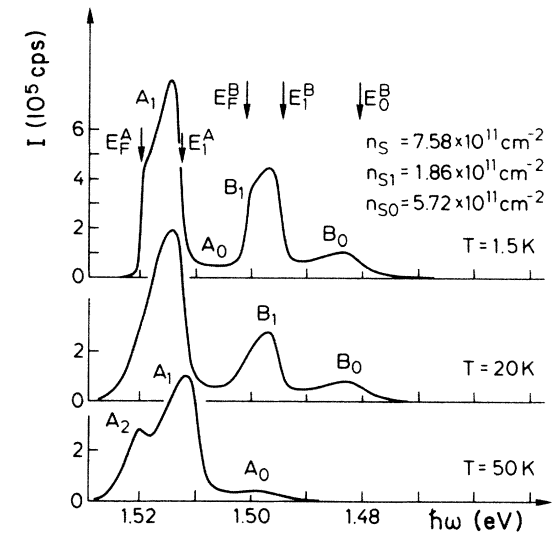

FIG. 2. Spectra of radiative recombination measured from the sample 2 ($n_S=7.58\times10^{11}$ cm^{-2}) at different temperatures. The 2D electron concentrations in different subbands were obtained from Shubnikov–de Haas oscillations.

d_1, a Si-doped n-type $Al_{0.35}Ga_{0.65}As$ layer of thickness d_2, and finally, an undoped GaAs cap layer of 8 nm thickness. All the parameters of the investigated samples are presented in Table I.

The nonequilibrium carriers were created by the use of a krypton laser with the wavelength of 647.1 nm. It is essential that the bulk luminescence does not dominate in the spectrum when the power density is less than 10^{-4} W/cm^2. At higher excitations, additional lines at 1.497 and 1.465 eV appear in the spectrum, and it follows from the investigations in a magnetic field that these lines correspond to the three-dimensional plasma. All spectra were recorded in Faraday configuration with a spectral resolution of 0.1 meV. A split-coil magnet with a maximum field of 7 T was used. The heterostructures could easily be rotated relative to the magnetic-field direction. Simultaneously with the optical studies, magnetotransport measurements were carried out.

In Fig. 1, we show the emission spectra obtained from sample 1 with a low doping concentration. Before illumination the concentration of 2D electrons in this sample was $n_S=6\times10^{10}$ cm^{-3} with a mobility of $\mu=1.2\times10^5$ cm^2/V s at 4 K. Under the laser illumination with a power density of about 10^{-5} W/cm^2, n_S was increased up to 4.7×10^{11} cm^{-2}. It is important to note that n_S usually increased up to 6 or 12×10^{11} cm^{-2} under the conditions of laser illumination for most of the studied samples, which had a very small concentration of 2D electrons (smaller than 10^{11} cm^{-2}) before illumination. In this case, the first excited 2D subband was partly occupied (see, for example, the results obtained for samples 2 and 3). There are two lines (A_0 and B_0) in the luminescence spectra of sample 1 measured at $T=1.5$ K (only the lowest 2D subband is occupied in this case). The energy spacing between these lines approximately corresponds to the acceptor ionization energy. These lines are due to recombination of 2D electrons with free holes (line A) and with the holes bound to acceptor atoms (line B). This follows from the temperature dependence of the emission spectra (Figs. 1 and 2) and also from the splittings of the lines A and B observed in the magnetic field (Fig. 3).

We first consider the changes of the luminescence spectra as a function of temperature. It follows from Fig. 1

TABLE I. Parameters of modulation-doped GaAs-$Al_xGa_{1-x}As$ single heterojunctions (d_1=thickness of $Al_{0.35}Ga_{0.65}As$ spacer, d_2=thickness of doped $Al_{0.35}Ga_{0.65}As$ region, d_3=thickness of GaAs cap layer). In sample 1, the Si concentration in the doped $Al_{0.35}Ga_{0.65}As$ region was reduced from 1×10^{18} cm^{-3} to 5×10^{17} cm^{-3}.

				Dark (4.2 K)		Illuminated (4.2 K)	
Sample	d_1 (nm)	d_2 (nm)	d_3 (nm)	n_s (cm^{-2})	μ ($cm^2V^{-1}s^{-1}$)	n_s (cm^{-2})	μ ($cm^2V^{-1}s^{-1}$)
1	18	76	8	6.0×10^{10}	1.2×10^5	4.7×10^{11}	3.0×10^5
2	18	76	8	1.2×10^{11}	1.5×10^5	7.6×10^{11}	3.7×10^5
3	3	61	8	2.0×10^{11}	3.0×10^5	10.2×10^{11}	6.5×10^5

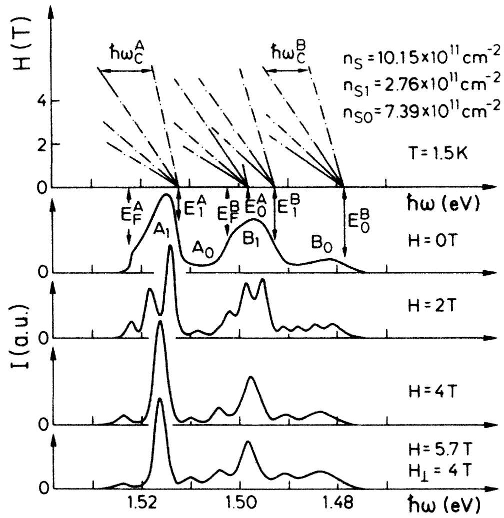

FIG. 3. Spectra of radiative recombination measured from the sample 3 in different perpendicular magnetic fields and in the magnetic field of 5.7 T tilted at 45° to 2D layer. The Landau fan diagrams obtained for different lines A_i and B_i are shown at the top of the figure.

that the increase of the temperature gives rise to the occupation of the first excited 2D subband (and also of the second excited subband at higher temperatures). This occupation of the excited subbands is accompanied by the appearance of the new lines A_i and B_i in the spectrum (the index $i = 0,1,2,\ldots$ corresponds to the number of subband). The recombination of the 2D electrons from the higher subbands is much more effective due to the stronger overlap of the wave function of these electrons with the wave function of the holes. It is seen from Figs. 1-3 that the ratio of the intensities of the lines originating from the first and the ground subband is much larger for the line A than for the line B. This can be explained by the assumption that the bound holes are located closer to the interface than the free holes. Because of this fact the intensity of the line A_0 is always very small.

When the temperature is increased up to 50 K, the lines associated with the recombination of 2D electrons and bound holes (lines B_i) disappear from the spectrum (see Figs. 1 and 2). This disappearance is due to the thermoionization of acceptor atoms. The temperature of ionization is in agreement with the temperature at which the acceptor recombination disappears in bulk GaAs. Note that there is an analogous behavior that we observed in GaAs-$Al_xGa_{1-x}As$ heterojunctions with p channel. In this case also two recombination lines of 2D holes were observed: one with free electrons and the other with the electrons bound to donor atoms. The energy spacing between lines A and B in this case approximately coincides with the donor ionization energy and the line B disappears at 10 K.

It is important that the splitting between the lines A and B is not exactly equal to the ionization energy of the imputity atom, but a little smaller. For example, the acceptor binding energy of carbon in GaAs is 27 meV and the splitting between lines A and B for the samples 2 and 3 is only 19 meV. This difference of 8 meV can be explained by the assumption that after the recombination of a 2D electron with a hole bound to an acceptor a charged impurity center is created and hence, in the final state there is a Coulomb energy of $e^2/(\epsilon d)$, where ϵ is the dielectric constant and d the distance between the 2D electron and the acceptor.[8] This phenomenon is equivalent to the shift of the emission line in the case of donor-acceptor recombination. From the value of 8 meV, we estimate that the acceptors, which are effective in the recombination are located at a distance of about 16 nm from the 2D channel.

In Figs. 2 and 3, we show the luminescence spectra obtained from the samples 2 and 3 in which the concentration of 2D electrons under illumination was 7.6×10^{11} cm^{-2} and 10.1×10^{11} cm^{-2}, respectively. It is seen from the spectra that in these samples the first excited 2D subband is populated already at $T = 1.5$ K. When the temperature is increased, the next subband is populated (the line A_2 appears) and the lines B_i disappear from the spectra due to the thermoionization of acceptors.

Finally, we discuss the behavior of the radiative recombination of the 2D electrons in a magnetic field. It is seen from Fig. 3 that at $H = 2$ T the splitting of the lines A_i and B_i into Landau levels is clearly observed. These splittings are proportional to the magnetic field (exactly speaking to its normal component). The dependence of the spectral position of the different lines on the magnetic field is shown in the upper part of Fig. 3. From these Landau fan diagrams the positions of the bottom of the 2D subbands ($i = 1,2$) and the Fermi energy for both lines A and B can be easily determined.[8] These positions are indicated by arrows in Figs. 1-3. Note that the position of the Fermi energy for the recombination of 2D electrons with free holes is located at higher energy than the band gap of GaAs.

The important result is that the Landau splittings for the lines A_i and B_i are different. It follows from the splittings of the lines A_i in the magnetic field that the effective cyclotron mass is equal to $0.060m_0$, but for the lines B_i we obtain a value of $0.067m_0$, which corresponds exactly to the cyclotron mass of 2D electrons in GaAs-$Al_xGa_{1-x}As$ heterojunctions. This difference in the masses is due to the fact that for the recombination with the free holes the splittings of the Landau levels arise not only for electrons, but also for the holes. In accordance with the selection rules,[12] the recombination is possible only for electrons and holes which have the same Landau-level number. The cyclotronic splittings of the electrons and holes are therefore added and the effective cyclotronic mass is determined by the expression $(m_c^*)^{-1} = (m_c^e)^{-1} + (m_c^h)^{-1}$. A comparison of the values m_c^* obtained from the splittings of the lines A and B allows the determination of the value of m_c^h which proves to be equal to $0.57m_0$. This value is in excellent agreement with the mass of heavy holes in GaAs. The difference in the splitting of the lines A and B in a magnetic field can be also considered as additional experimental evidence that the lines A_i correspond to the recombination of 2D electrons with free holes and the lines B_i with holes bound to acceptors.

It is very important to verify experimentally that the lines A_i and B_i arise indeed from the recombination of 2D electrons. There is a direct experimental evidence for testing two dimensionality—the tilting of the magnetic field. In Fig. 3(d), we show the spectrum which was measured in the total magnetic field of 5.7 T, tilted at 45° to the 2D layer, so that the normal component of magnetic field was equal to 4 T. It follows from the comparison of the Figs. 3(c) and 3(d), that the splitting of the lines A and B is sensitive only to the normal component of the magnetic field.

Figure 4 illustrates the relation between Shubnikov–de Haas oscillations measured simultaneously by magnetotransport and by magneto-optics. For the recording of the magneto-optical oscillations the slit of the spectrometer was located at the position of the Fermi energy in the spectrum (indicated by arrows in Figs. 1–3) and then the dependence of the luminescence intensity on the magnetic field was measured. It is seen from Fig. 4 that transport and optical oscillations are identical. However, in the case when the upper subband is populated, the magneto-optical oscillations are much more sensitive to the properties of 2D electrons from the upper subband. This result gives the opportunity to investigate independently the properties of these electrons.

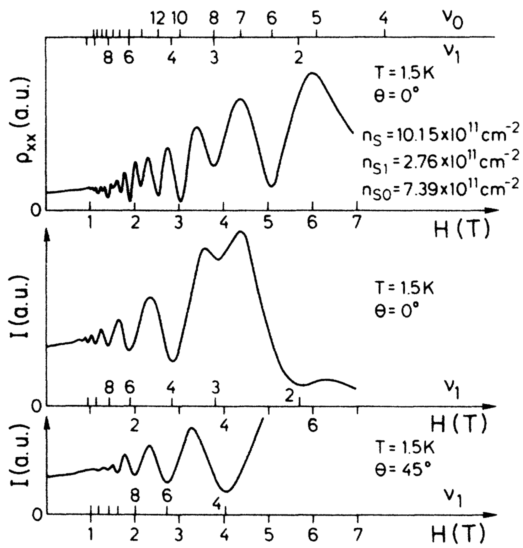

FIG. 4. The Shubnikov–de Haas oscillations measured by magnetotransport and by magneto-optics for the sample 3 at $T = 1.5$ K. The lowest curve was recorded in the magnetic field tilted on 45° to the 2D layer.

In conclusion, we investigated the radiative recombination of 2D electrons with photoexcited holes in GaAs-$Al_xGa_{1-x}As$ single heterojunctions. We found that magneto-optical method can be applied for the investigation of the energy spectrum of 2D electrons in a perpendicular magnetic field. As in the case of Si-MOSFET's we have observed the oscillations of Landau-level width with variation of the filling factor, giant enhancement of the g factor of 2D electrons for odd values of filling factors (the results will be published) and hope to investigate the Coulomb gaps in the energy spectrum of the incompressible Fermi liquid under the conditions of fractional quantum Hall effect.

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