Optical spectroscopy of two-dimensional electrons in a single GaAs-AlGaAs heterojunction

I. V. Kukushkin, K. von Klitzing, and K. Ploog
Max Planck Institute of Solid State Physics, Stuttgart, FRG

(Submitted 24 March 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 10, 511–515 (25 May 1988)

The radiative recombination of 2*D* electrons with nonequilibrium photoexcited holes in single GaAs-AlGaAs heterojunctions has been studied. Two different channels for recombination of 2*D* electrons—with free holes and with holes bound to acceptors—have been detected experimentally. The splitting of emission lines into Landau levels, which depends exclusively on the normal component of the field, has been observed in a magnetic field.

1. After the discovery of integer quantum Hall effect[1] and fractional quantum Hall effect[2] the interest in the study of the properties of 2*D* electrons in a perpendicular magnetic field has increased markedly. A microscopic description of these phenomena requires the knowledge of the energy spectrum of the electronic system. All methods based on the measurement of the magnetoconductivity,[3] magnetic susceptibility,[4] magnetic capacitance,[5] and electron specific heat[6] are sensitive only to the properties of electrons near the Fermi surface. One of the most effective methods of directly determining the energy spectrum of 2*D* electrons is based on the study of the recombination radiation of 2*D* electrons with photoexcited holes.[7] The use of this method in metal-insulator-semiconductor (MIS) silicon structures[7–10] has made it possible to detect an oscillation in the width of the Landau levels due to the filling factor[8] and oscillation of the spin and intervalley splitting[9] and to measure the Coulomb gaps in the energy spectrum of an incompressible Fermi liquid under conditions of the fractional quantum Hall effect.[10]

The principal advantage of the 2*D* electron system in single GaAs-AlGaAs heterojunctions over the Si-MIS structures is its ability to grow high-grade samples with the required properties by the method of molecular-beam epitaxy. The magneto-optical studies of 2*D* electrons in GaAs-AlGaAs heterojunctions have heretofore been conducted only in systems with quantum wells.[11–14] The 2*D* electron system in this case has several disadvantages. First, the temperature of the carriers is relatively high because of the short recombination time in the narrow quantum wells.[14] Secondly, several 2*D* subbands are usually filled in wide quantum wells. In this case, the recombination radiation of electrons from the upper subbands dominates the spectrum.[13] Thirdly, the mobility of 2*D* electrons in quantum wells usually is much lower than in single heterojunctions.

2. The luminescence spectrum of a single standard heterojunction with a 1-μm-thick GaAs buffer layer reveals the presence of several highly intense bulk lines which overlap a less intense 2*D*-electron-recombination line (see Ref. 15). This situation is analogous to the example with Si-MIS structures, although GaAs has, because of the presence of many residual impurities of various kind, simultaneously several bulk lines

spanning a broad energy interval. To study the recombination radiation of 2*D* electrons, we must therefore reduce the bulk recombination signal by reducing the width of the GaAs buffer layer. It has been established experimentally that the optimal width of the GaAs layer is 500 Å. At this width the fraction of the bulk recombination decreases markedly, while the 2*D* electron mobility remains constant.

The samples used in the experiments were grown on a semi-insulating GaAs substrate which was physically separated from the active region by a 30-period superlattice (with a 25-Å period). The presence of a superlattice prevented the propagation of dislocations from the substrate to the active region of GsAs and prevented the photoexcited carriers from entering the substrate. All structures contained a 180-Å spacer. The other parameters of the structures were published elsewhere.[16]

3. Figure 1 shows an emission spectrum obtained from sample 1, in which the AlGaAs layer was doped slightly with silicon. Before exposing the sample to light, the concentration of 2*D* electrons was $n_s = 6\times10^{10}$ cm^{-2} and the mobility was $\mu = 1.2\times10^5$ cm^2/(V·s). Photoexcitation with a krypton laser at a power level $W = 10^{-5}$ W/cm^2 increased the value of n_s to 4.7×10^{11} cm^{-2} [$\mu = 3\times10^5$ cm^2/(V·s)]. At $T = 1.5$ K the luminescence spectrum of sample 1 exhibited two emission lines (*A* and *B*) corresponding to the recombination of 2*D* electrons with free holes (line *A*) and with holes coupled to acceptors (line *B*). This assertion follows, first, from the fact that the splitting between lines *A* and *B* corresponds to the ionization energy of the acceptor; secondly, it follows from the temperature dependence of the emission spectra; and thirdly, it follows from the splitting of lines *A* and *B* in a magnetic field.

Let us first see how the temperature affects the luminescence spectrum. It follows from Fig. 1 that an increase in the temperature leads to a filling of the excited 2*D* subbands, which is accompanied by the appearance of additional lines A_i and B_i in the spectrum (the subscript $i = 0, 1, 2, \ldots$ corresponds to the number of the 2*D* subband). The recombination of electrons from the excited 2*D* subbands is much more efficient

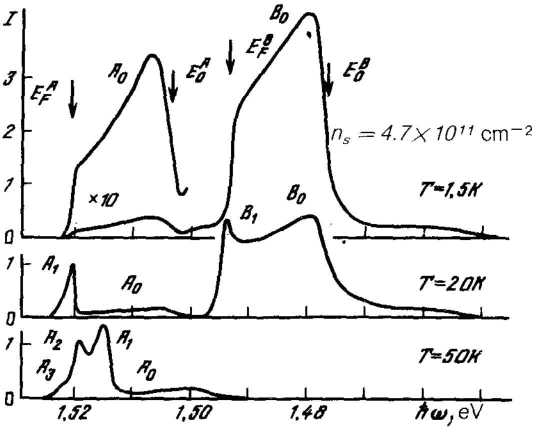

FIG. 1. Spectra of recombination radiation of 2*D* electrons with photoexcited holes, measured for sample 1 at various temperatures. The power density is $W = 10^{-5}$ W/cm^2. The arrows show the positions of the Fermi energy and the bottom of the 2*D* subband, determined from the fan of the Landau levels.

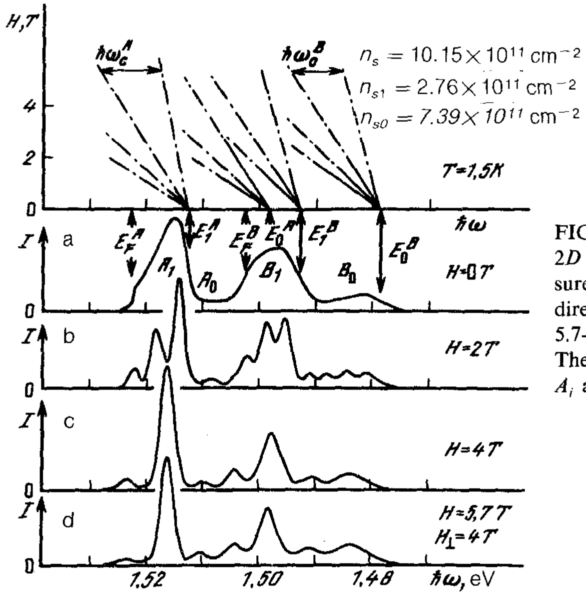

FIG. 2. Spectra of recombination radiation of $2D$ electrons with photoexcited holes, measured for sample 2 in various magnetic fields directed perpendicular to the $2D$ layer and in a 5.7-T magnetic field tilted at an angle of 45°. The fans of the Landau levels found for lines A_i and B_i are shown at the top.

because of the much greater overlap of the wave functions of these electrons and the photoexcited holes. An increase in the temperature to 50 K causes the emission lines, attributable to the recombination of $2D$ electrons with the bound holes (the lines B_i), to disappear in the spectrum (Fig. 1) due to the thermal ionization of the acceptors.

In sample 2 with a higher concentration of the silicon dopant, in which the electron density is 10^{12} cm^{-2} [$\mu = 6.5\times10^5$ cm^2/(V·s) in the photoexcited state, even at $T = 1.5$ K the first excited $2D$ subband is populated by electrons (Fig. 2). As can be seen in Fig. 2, the lines A_i and B_i split into Landau levels in a magnetic field $H = 2T$ perpendicular to the $2D$ layer; the line splitting is proportional to H. The spectral line position versus the magnetic field is plotted in the upper part of Fig. 2. This plot can be used to determine the position of the Fermi energy and the bottom of the size-quantized subbands (as indicated by the arrows in Figs. 1 and 2).[8] An important point is that A and B line splitting is distinguishable in a magnetic field. It follows from A_i line splitting that the effective cyclotron mass is $0.060m_0$ (m_0 is the free electron mass) and for the B_i lines we have the value $0.067m_0$, which is the same as the cyclotron mass of $2D$ electrons in the GaAs-AlGaAs heterojunctions. The difference in the A and B line splittings arises because the cyclotron quantization occurs not only in the case of $2D$ electrons but also in the case of free holes. According to the selection rules, optical transitions can occur only if the electrons and holes have the same number of the Landau level. In the case of the A_i lines, therefore, the cyclotron splittings of electrons and holes are added and the effective cyclotron mass decreases. A comparison of the A and B line splitting can be used to determine the cyclotron mass of the holes, which turned out to be $0.57m_0$. This value corresponds to the mass of the heavy holes in GaAs. The difference in the A and B line splittings in a magnetic field also suggests that the A_i lines correspond to the recombination of $2D$ electrons with free holes and

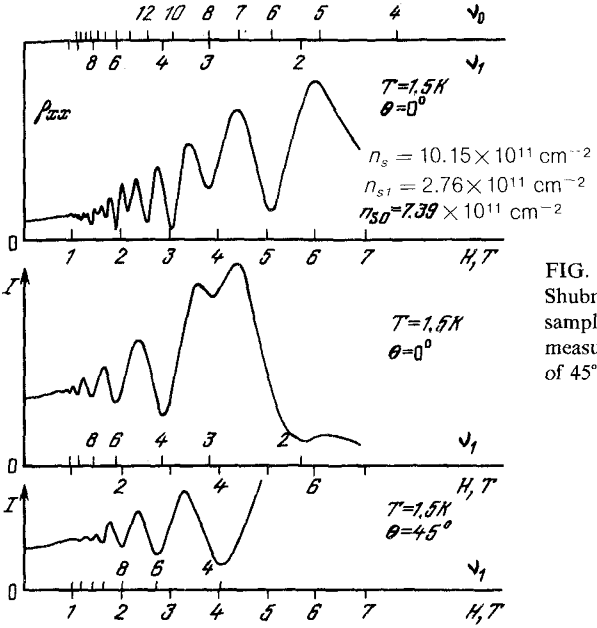

FIG. 3. Magnetotransport and magnetooptical Shubnikov-de Haas oscillations measured for sample 2 at $T = 1.5$ K. The lower curve was measured in a magnetic field tilted at an angle of 45° to the $2D$ plane.

B_i lines correspond to the recombination of $2D$ electrons with the holes which are coupled to acceptors.

We used the magnetic field rotation method to verify experimentally whether the A and B lines actually appear as a result of recombination of $2D$ electrons. Figure 2d shows a spectrum obtained in a field $H = 5.7$ T which is tilted 45° with respect to the $2D$ layer, so that the normal component of H is 4 T. A comparison of spectra c and d in Fig. 2 shows that the A and B line splitting depends exclusively on the normal component of the magnetic field.

The Shubnikov-de Haas oscillations measured by the magnetic-transport and magneto-optical methods are shown in Fig. 3. In recording the magneto-optic oscillations we fixed the spectral position of the spectrometer slit, which coincided with the position of the Fermi energy in the luminescence spectrum (indicated by the arrows in Figs. 1 and 2). When only the lowest $2D$ subband was filled, the magneto-optic and magnetic-transport oscillations were nearly the same. When an excited $2D$ subband was filled, the magneto-optic oscillations were found to be much more sensitive to the electron recombination from the upper subband, making it possible to study the properties of these electrons independently. The lower part of Fig. 3 shows the magneto-optic oscillations measured in a tilted magnetic field. These oscillations imply that the electrons which participate in the recombination have a two-dimensional nature.

The shape of the $2D$ electron emission lines measured in the Si-MIS structures differs markedly from the shape of these lines measured in single GaAs-AlGaAs heterojunctions. Figure 4 shows these emission lines measured when the Fermi energy of $2D$ electrons is ≈ 17 meV. We see that, in contrast with silicon, the shape of the

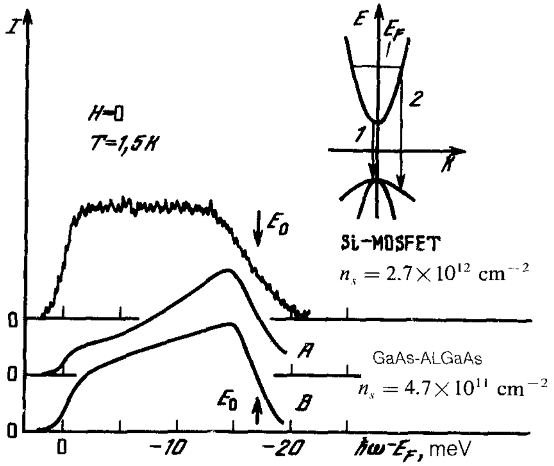

FIG. 4. $2D$-electron-emission lines measured in Si-MIS structure and in a single GaAs-AlGaAs heterojunction at the same Fermi energy of electrons, $E_F \approx 17$ meV. The energy-level diagram of the recombination in momentum space is shown in the inset.

emission lines (A and B) of the heterojunctions does not directly reflect the energy distribution of the single-particle density of states, because the quasimomentum conservation law in the case of direct-gap semiconductors requires that the quasimomenta of the recombining electrons and holes be equal (within the photon momentum). Since the thermal momentum of the photoexcited holes is much lower than the Fermi momentum of $2D$ electrons ($k_F \sim E_F^{1/2} \sim n_S^{1/2}$) the probability for a recombination decreases as the energy at the bottom of the $2D$ subband increases to the Fermi energy.

We wish to thank V. B. Timofeev for a discussion of the results and B. Ulrich for assistance with the experiment.

[1] K. V. Klitzing, G. Dorda, and M. Pepper, Phys. Rev. Lett. **45**, 494 (1980).
[2] D. C. Tsui, H. L. Stoner, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).
[3] E. Stahl, D. Weiss, G. Weimann *et al.*, J. Phys. **S18**, 783 (1985).
[4] J. P. Eisenstein, H. L. Stermer, V. Narayanamurty *et al.*, Phys. Rev. Lett. **55**, 875 (1985).
[5] J. P. Smith, B. B. Goldberg, P. J. Stiles, and M. Neiblum, Phys. Rev. **B32**, 2696 (1985).
[6] E. Gornik, P. Lassnig, G. Strasser *et al.*, Phys. Rev. Lett. **54**, 1820 (1985).
[7] I. V. Kukushkin and V. B. Timofeev, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 413 (1984) [JETP Lett. **40**, 1231 (1984)].
[8] I. V. Kukushkin and V. B. Timofeev, Zh. Eksp. Teor. Fiz. **93**, 1088 (1987) [Sov. Phys. JETP **66**, 613 (1987)].
[9] I. V. Kukushkin, Sol. State Commun. **65**, 1473 (1988).
[10] I. V. Kukushkin and V. B. Timofeev, Pis'ma Zh. Eksp. Teor. Fiz. **44**, 179 (1987) [JETP Lett. **44**, 228 (1987)].
[11] M. C. Smith, A. Petrou, C. H. Perry, and J. M. Worlock, Surf. Sci. **174**, 136 (1986).
[12] C. H. Perry. J. M. Worlock, M. C. Smith, and A. Petrou, Proc. of the Int. Conf. on High Magnetic Fields in Semicond. Phys., Springer Series in Solid State Sci. **71**, 202 (1987).
[13] F. Meseguer, J. C. Maan, and K. Ploog, Phys. Rev. **B35**, 2505 (1987).
[14] T. T. Berendschot, H. A. Reinen, and H. J. Bluyssen, Sol. State Commun. **63**, 873 (1987).
[15] C. H. Yang, S. A. Lyon, and C. W. Tu, Superlattices and Microstructures **3**, 269 (1987).
[16] I. V. Kukushkin, K. von Klitzing, and K. Ploog, Phys. Rev. **B37**, 2021 (1988).

Translated by S. J. Amoretty