Magnetooptics of incompressible Fermi liquid in ultraquantum limit

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The radiative recombination of 2D electrons with photoexcited holes localized in a monolayer of acceptors has been studied in a GaAs–AlGaAs heterostructure in a strong transverse magnetic field $H \leqslant 28$ T at low temperatures, $T \geqslant 400$ mK. At filling factors $\nu < 1$, a variation of H causes the spectral position of the luminescence line corresponding to the recombination of 2D electrons from the state lower in terms of spin to undergo discontinuous changes along the energy scale at the fractional values $\nu = 2/3, 1/3, 4/5, 3/5, 2/5, 1/5, 1/7$, and $1/9$. These structural features disappear as T is increased. They are attributed to jumps in the chemical potential in the interacting system of electrons upon condensation into an incompressible Fermi liquid.

1. A central problem in the physics of few-dimensional semiconductor systems is that of the ground state of interacting 2D electrons in a strong transverse magnetic field.[1] It has now been solidly established that the ground states of such a system are states of an incompressible Fermi liquid in the quantum limit, up to filling factors $\nu \geqslant 1/7$, and at sufficiently low temperatures T (Refs. 2–4). These states are detected by virtue of the fractional quantization of the Hall resistance.[2] Theoretical studies show that a long-range order (Wigner crystallization) should occur in the electron system at $\nu \leqslant 1/5$ (Ref. 5). Efforts have been made in recent years to move into this exceedingly interesting region: the region of low concentrations, strong magnetic fields, and fairly low temperatures.

The most common tool for studying such systems in semiconductors is magnetotransport. That method runs into serious difficulties, however, in the region $\nu \ll 1$ at very low T because strong-localization effects intensity.[6,3] Strong-localization effects are of less concern in the realm of magnetooptics. It was an optical method which was first used successfully in the case of a 2D-electron channel in a Si field-effect transistor under conditions corresponding to the fractional quantization of the Hall resistance.[7] This method revealed the Coulomb gaps of an incompressible Fermi liquid with $\nu = 8/3$ and $7/3$. In the system which was studied, however, selection rules prevented a study of 2D electrons in the quantum limit at low T. No such limitations prevail in the case of the electron channels in an AlGaAs/GaAs heterostructure.[8] The magnetooptics of 2D electrons in quantum wells based on an AlGaAs/GaAs heterostructure was studied under the conditions of the fractional quantization of the Hall resistance in Ref. 9; an anomalous behavior of the electron–hole recombination line was observed there near $\nu = 2/3$. In the case of a quantum well, the electrons are not spatially separated from photoexcited holes. In such structures, effects of a condensation into an incompressible Fermi liquid may thus be masked by the strong *e–h* correlations (an exciton effect).[10] A better choice for magnetooptics under conditions corresponding to the fractional quantization of the Hall resistance, in our opinion, would be heterostructures in which the 2D-electron channel near an isolated heterojunction is spatially separated with a monolayer of acceptors (a δ-doped heterostructure).[11] Photoexcited holes will localize in this monolayer, and the 2D electrons will recombine with them (see the inset in Fig. 1). We examined this recombination mechanism in the present study.

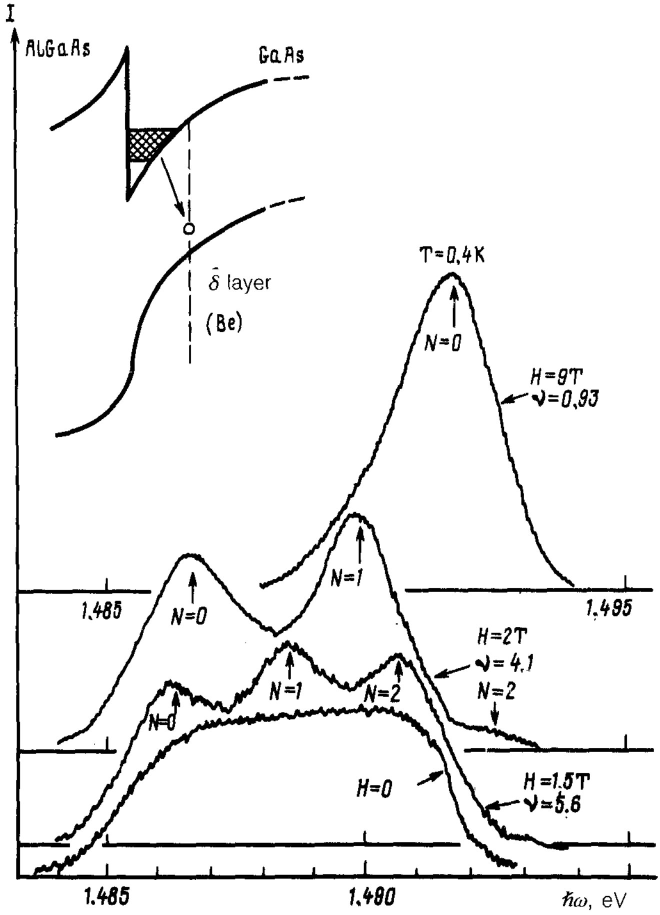

FIG. 1. Luminescence spectra measured at $H = 0$ (the lower spectrum) and at various magnetic fields at $T = 0.4$ K and $n_S = 2.02 \times 10^{11}$ cm^{-2}. The indices of the Landau levels and the filling factors are given here. The inset is a schematic energy diagram of the heterostructure and of the optical transition of interest.

2. We studied several δ-doped GaAs/AlGaAs heterostructures with a GaAs buffer layer about 10^3 Å thick. A monolayer of acceptors (Be) with a concentration of 10^{10} cm^2 was produced in the structures at a distance of 250 Å from the interface. During continuous photoexcitation, the 2D electrons recombine with holes at the acceptors in this monolayer. A corresponding line (a B line) appears in the luminescence spectra in the process.[10] The concentration of 2D electrons in these heterostructures ranged from 6×10^{10} cm^{-2} to 6×10^{11} cm^{-2}; it could be varied by means of photoexcitation, by varying the intensity[12] [the mobilities of the 2D electrons measured in darkness were 3×10^5 and 1.5×10^6 $cm^2/(V\cdot s)$, respectively]. During steady-state illumination, the mobility of the 2D electrons increased substantially.[13]

To determine the concentration of 2D electrons, we used both magnetotransport and magnetooptic Shubnikov-de Haas oscillations.[11] In addition, n_S could be determined by comparing the relative intensities of the recombination emission of 2D electrons from various Landau levels as H was varied (§3).

Measurements were carried out at $T\geqslant400$ mK in magnetic fields up to $H=28$ T. The samples were mounted in a special insert, in which He^3 condensed. The temperatures varied by pumping off the He^3 vapor. The beam from the Ar^{+++} laser used for the excitation was delivered to the sample through an optical fiber; an optical fiber was also used to take the luminescence from the sample to the entrance slit of the spectrometer. The power of the exciting laser beam at the sample did not exceed 1 mW. The heating which resulted did not exceed 0.1 K. The spectral instrument had a resolution of 0.06 meV.

3. Figure 1 shows luminescence spectra measured at $H=0$ and $H\neq0$. In a transverse field H, a Landau-level structure arises, and the intensity of the corresponding lines varies in complete accordance with the variation in ν. This fact was also exploited to determine the concentration of 2D electrons.

Figure 2a, shows $E_N(H)$, i.e., the behavior of the spectral positions of the luminescence lines corresponding to the recombination of 2D electrons with the various Landau levels ($N=0$, 1, 2) as a function of H. In the interval $1<\nu<2$, we see a deviation of the behavior of the spectral position of the $N=0$ Landau level from the linear behavior found at lower fields H ($\nu<2$; the dashed line in Fig. 2a). This deviation results from an intensified exchange interaction of electrons (the so-called g-factor enhancement effect[11]), which occurs at $2>\nu>1$. The amplitude of this deviation is equal to the energy of the exchange interaction of the electrons. We also see from this figure that as H is increased further at low T, there are some additional discontinuous changes in the spectral position of the emission line, which occur in a narrow I interval near the fractional values $\nu=4/5$, 2/3, 3/5, 2/5, and 1/3. The amplitude of these jumps is small in comparison with the characteristic cyclotron energy, which sets the basic scale of the changes in the spectral position of an emission line as H is varied:

$$E_0(H)=E_g+1/2\cdot\hbar\omega_c.$$

Accordingly, Fig. 2b shows in larger scale the changes in the position of the emission line, $E_0(H)$, in a magnetic field. These changes are reckoned from the linear depen-

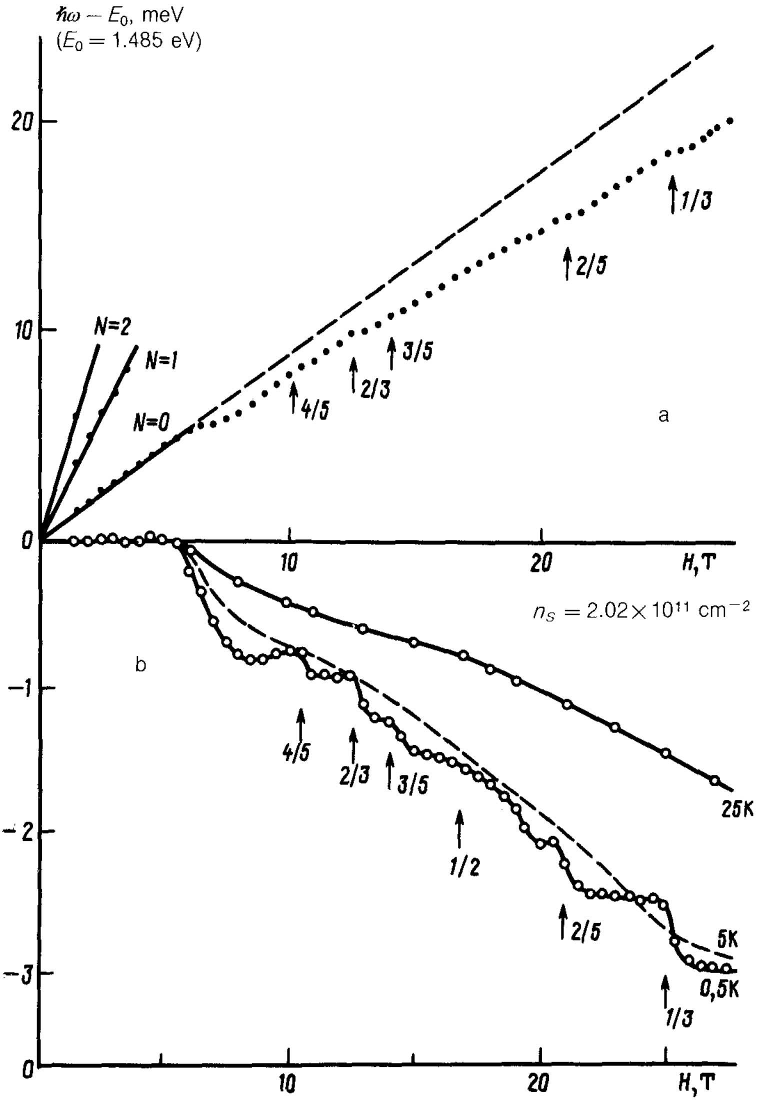

FIG. 2. a: Energy position of the peak of the line corresponding to the recombination of an electron from the lower spin state versus the magnetic field (the energy is reckoned from the bottom of the quantum-size band). At filling factors $\nu > 2$ there is fan of Landau levels ($T = 0.47$ K, $n_S = 2.02 \times 10^{11}$ cm^{-2}). b: Changes in the energy position of the peak of the same line with respect to the dashed straight line in Fig. 2a, upon a variation in H at several temperatures: $T = 0.47$ K, $T = 5$, and $T = 25$ K. The arrows show the fractional filling factors ($T = 0.47$ K, $n_S = 2.02 \times 10^{11}$ cm^{-2}).

dence measured in weak magnetic fields and then extrapolated to large fields H (the dashed line in Fig. 2a). The deviations of $E_0(H)$ from the dashed line are seen to decrease (Fig. 2b) with increasing T, and at $T > 30$ K (at $T > 5$ K for the better structures) the $E(H)$ curve becomes strictly linear and corresponds to the dashed line in Fig. 2. Also shown in this figure are plots of $\Delta E_0(H)$ measured at 0.5, 5, and 25 K. It can be seen from this figure that the jumps $\Delta E_0(H)$ near $\nu = 4/5$, 2/3, 3/5, 2/5, and 1/3 are observed only at T, disappearing at $T > 5$ K. The structural feature at $\nu = 1/3$ and $H = 25$ T disappears at $T = 8$ K; this effect corresponds to a large value of the Coulomb gap and agrees with the magnetotransport data: $\Delta_k \approx 6$ K for $\nu = 1/3$ and $H = 24$ T (Ref. 14). It can also be seen from Fig. 2b, that near $\nu = 1/2$ the behavior $E_0(H)$ is anomalous; this anomalous behavior, however, is observed over a fairly wide range of magnetic fields and is only slightly sensitive to the temperature. We therefore believe that the structural feature at $\nu = 1/2$ is of a different physical nature.[15,16]

We attribute the discontinuous behavior of the spectral position of the emission line at fractional values of ν to jumps in the chemical potential in the system of 2D electrons as they condense into an incompressible Fermi liquid.[17] As in the case of Si metal-insulator-semiconductor (MIS) structures, the amplitude of the jump on the plot of $E_0(H)$ near the fractional values of ν corresponds to the magnitude of the jump in the chemical potential ζ. According to the theory of an incompressible Fermi liquid,[17] the value of $\Delta\zeta$ for $\nu = p/q$ is related to the size of the Coulomb gap Δ_k by $\Delta\zeta = q\Delta_k$.

The physical meaning here is that a unit change in the number of electrons is accompanied by the creation (or absorption) of q quasiparticles (excitations with a fractional charge $\theta^* = e/q$), whose energy is separated from the ground state by a gap Δ_k.

The behavior $E_0(H)$ observed here corresponds completely to the behavior which we observed in Si MIS structures, and it supports the interpretation based on the argument that the jumps in $E_0(H)$ near fractional values $\nu = p/q$ are associated with the creation (if $\nu < p/q$) or absorption (if $\nu > p/q$) of excitations upon a unit decrease in the number of 2D electrons in the course of recombination with a hole.

In a structure with a low concentration $n_S = 0.6 \times 10^{11}$ cm^{-2} we were able to reach filling factors $\nu = 1/12.5$. In this case, at $T = 420$ mK, we observed jumps at $\nu = 2/3$, 1/3, 1/5, 1/7, and 1/9 on the plot of the spectral position of the emission line versus H. As the temperature was raised, these jumps disappeared in succession, starting at large values of q. The state of an incompressible Fermi liquid with $\nu = 1/9$ has been observed here for the first time.

Figure 3 shows luminescence spectra measured near $\nu = 1/3$, 1/5, 1/7, and 1/9. We see that there is no significant splitting in the spectra. A careful analysis has shown that, in general, there is a slight broadening of the recombination line near fractional values of ν, accompanied by a slight decrease in the peak intensity. An additional knee appears in the luminescence spectrum, on the low-energy side, beginning at $\nu \leqslant 1/5$. This knee gradually grows with increasing H, while it disappears if the temperature is raised ($T \geqslant 1.5$ K). At the same time (at $\nu < 1/5$), the integral emission intensity begins to decrease sharply. These structural features are not related in any direct way to the incompressible Fermi liquid. They are nevertheless exceedingly interesting, since they are associated with the possible appearance of a long-range order in the system of interacting electrons. This question will be discussed in a separate publication.

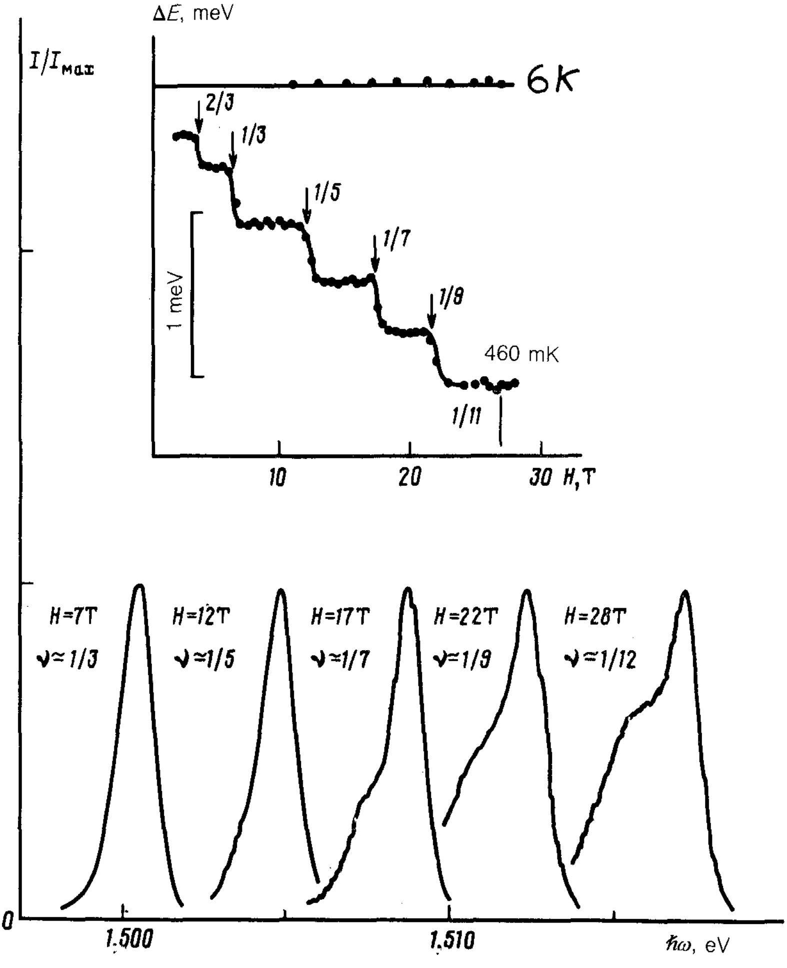

FIG. 3. Shape of the luminescence line measured in various magnetic fields at $T = 420$ mK for a sample with a 2D-electron concentration $n_S = 5.6 \times 10^{10}$ cm^{-2} (the spectra have been normalized in terms of intensity). The inset shows the deviations of the spectral position of the luminescence line of the same sample ($T = 0.46$ K) from the spectral position of this line at $T = 6$ K.

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