Spectroscopic observation of Wigner crystallization of 2D electrons in a strong transverse magnetic field

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A new line appears in the radiative-recombination spectra of 2D electrons in GaAs/AlGaAs heterostructures in a strong transverse magnetic field at low temperatures ($T \sim 0.4$ K) upon the attainment of a critical filling factor $\nu_c = 0.28$. The behavior of this line as a function of the magnetic field, the temperature, and the disorder is linked with a Wigner crystallization in a system of interacting electrons.

1. In an interacting system of 2D electrons in a strong transverse magnetic field, at sufficiently low temperatures, states of an incompressible Fermi liquid are ground states.[1-3] These states correspond to a fractional filling of quantum states ($\nu = 1/q$, where q is an odd integer). They are observed in magnetotransport by virtue of a fractional quantization of the Hall resistance.[1,4-7] Our recent magnetooptic experiments have shown[8] that states of an incompressible Fermi liquid are ground states up to a filling factor $\nu = 1/9$. In the same experiments, Coulomb gaps between the ground states of the incompressible Fermi liquid and the continuum of quasiparticle excitations with fractional charges ($e^* = e/q$, $q = 3, 5, 7, 9$) were determined by an optical method.[8]

Theoretical work predicts that a long-range order should arise in a system of electrons in the quantum limit, at $\nu < 1/3$, and a crystallization (Wigner crystallization) should set in.[9] Studying the radiative recombination of 2D electrons with photoexcited holes at filling factors $\nu < 1$ (at which all the electrons are in the lower spin state), we observed that when the critical values $\nu_c < 0.28$ were reached, a new line appeared in the luminescence spectra. In the present letter we are reporting that the appearance of this line in the spectra and the properties of this line upon variations of the magnetic field and the temperature can be linked with a Wigner crystallization.

2. Some specially prepared GaAs/AlGaAs heterostructures[8] were used for a study of the spectra of the radiative recombination of 2D electrons with photoexcited holes localized in a δ-doped monolayer of acceptors (Be atoms) 25 nm away from the interface. In the course of this recombination, a correspondiing line arises in the luminescence spectra during photoexcitation.[10] An energy diagram of the heterostructure and the optical transition of interest are shown in inset in Fig. 1. The density of 2D electrons in these heterostructures was 6×10^{10}–2.5×10^{11} cm^{-2} and could be varied by varying the photoexcitation power density.[11] The mobility of the 2D electrons measured in darkness was $\mu \simeq 10^6$ cm^2/(V·s). It increased noticeably during steady-state exposure to light.[10,11] The high quality of the structures was confirmed by magnetotransport measurements in darkness and during steady-state illumination. These measurements revealed states of an incompressible Fermi liquid at $\nu = p/q (q = 3$ and $5)$. The samples were mounted in a cryostat, in which He^3 condensed. Optical fibers were used to bring the light to the sample and to take it away. The temperature was monitored with an RuO_2 thermoresistance. In magnetic fields up to $H = 28$ T, without illumination, the temperature was 340 mK; during steady-state illumination with the beam from an Ar^+ laser (at a power of 0.1–1 mW), the temperature rose to 400–600 mK. The luminescence spectra were detected with a cooled GaAs photomultiplier and analyzed with a triple monochromator with a resolution of 0.06 meV. The density of 2D electrons was monitored with the help of the Shubnikov oscillations of the magnetoresistance and also by a magnetooptic technique.

3. Figure 1 shows intensity-normalized luminescence spectra corresponding to the radiative recombination of the 2D electrons with the photoexcited holes. These spectra were measured for one of the samples with a 2D-electron density $n_S = 5.4 \times 10^{10}\ \mathrm{cm}^{-2}$ during steady-state illumination in various magnetic fields. Along with the fundamental line I_1, which is a known line and which corresponds to a recombination of elec-

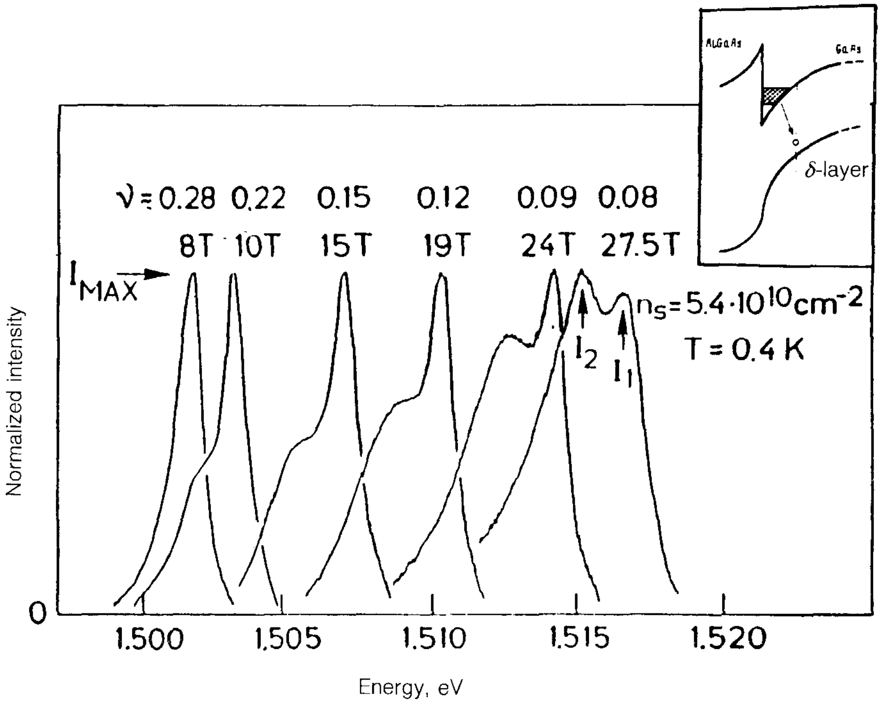

FIG. 1. Spectra of the radiative recombination of 2D electrons with photoexcited holes in a monolayer of acceptors. The spectra were recorded in various magnetic fields for a sample with a 2D-electron density $n_S = 5.4 \times 10^{10}\ \mathrm{cm}^{-2}$ at $T = 400\ \mu$ (the spectra have been normalized to the same peak intensity). The inset shows an energy diagram of the heterostructure and the optical transition of interest.

trons from the lower spin state,[8] a new line, I_2, appears in the spectrum when a certain magnetic field is reached. This line increases with increasing H, and at filling factors $\nu \simeq 0.1$ it dominates the spectrum. The line I_2 is shifted in the low-energy direction, so the splitting between I_1 and I_2 is 1.4 meV. An important point is that the appearance of line I_2 in the spectrum is accompanied by a simultaneous and rapid decay of the overall luminescence intensity in this region. The effect is illustrated by Fig. 2, which shows the overall luminescence intensity and also the intensity ratio I_2/I_1 as a function of H. The decrease in the overall luminescence intensity and the intensification of line I_2 set in at the same magnetic field value, H_c. Measurements on samples with various densities n_S revealed that H_c increases linearly with n_S. The effects which we have described here are thus independent of n_S in the density range studied, and they are observed at filling factors $\nu < \nu_c = 0.28$. It is important to note that the intensity of line I_2 falls off sharply near $\nu = 1/5$, $1/7$, and $1/9$ (Fig. 2b), where a condensation into an incompressible Fermi liquid occurs. At the same fractional fillings, the overall luminescence intensifies because of the intensification of line I .

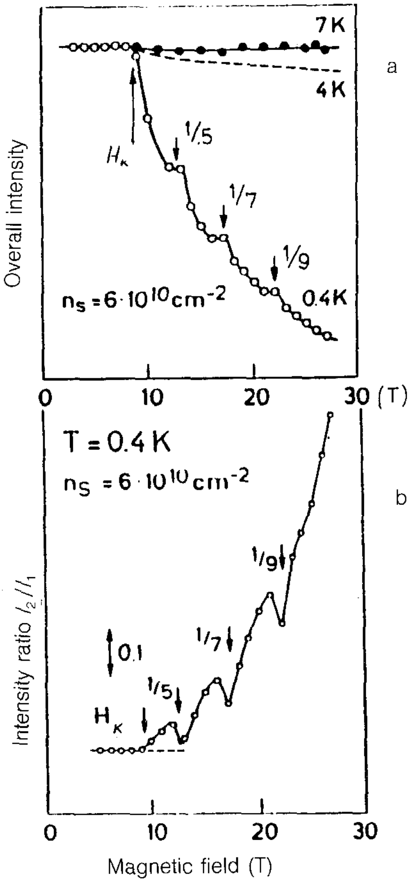

FIG. 2. a—Overall intensity of luminescence lines I_1 and I_2 as a function of the magnetic field ($T = 0.4$, 4, and 7 K; $n_S = 6 \times 0^{10}$ cm^{-2}; b—ratio of the intensity of luminescence lines, I_1 /I_2, as a function of the magnetic field ($n_S = 6 \times 0^{10}$ cm^{-2}, $T = 0.4$ K).

Line I_2 is very sensitive to the temperature. Figure 3 shows the temperature dependence of the intensity ratio I_2/I_1 measured at $H = 26$ $T(\nu = 0.09)$. At temperatures above the critical value, line I_2 disappears from the spectrum (at $H = 26$ T, this critical value is $T_c = 1.4$ K). At the same time, the overall luminescence intensity increases and goes back to its original value, measured at $H < H_c$ (Fig. 2a). The critical temperature depends very strongly on the filling factor: It increases with decreasing ν at $\nu < \nu_c$, but at the fractional values $\nu = 1/5$, $1/7$, and $1/9$, the critical temperature T_c decreases sharply.

4. We attribute the appearance of the new line, I_2, in the spectra, accompanied by a simultaneous and sharp decrease in the overall luminescence intensity, to a crystallization effect in the system of interacting electrons. According to this interpretation, lines I_2 and I_1 correspond to a radiative recombination of 2D electrons from the crystalline and liquid phases, respectively at ($\nu = 1/5$, $1/7$, and $1/9$, the Fermi liquid is incompressible). The fact that I_2 lies at a lower energy than I_1 means that the ground state of the crystalline phase is the lowest state. The disappearance of I_2 at $\nu = 1/5$, $1/7$, and $1/9$ indicates that at these fractional fillings the ground state of this system is nevertheless the incompressible Fermi liquid. The fact that I_2 does not disappear completely from the spectra at these fillings may be a result of variations in the density n_S over the sample. Finally, the sharp decrease in the overall luminescence

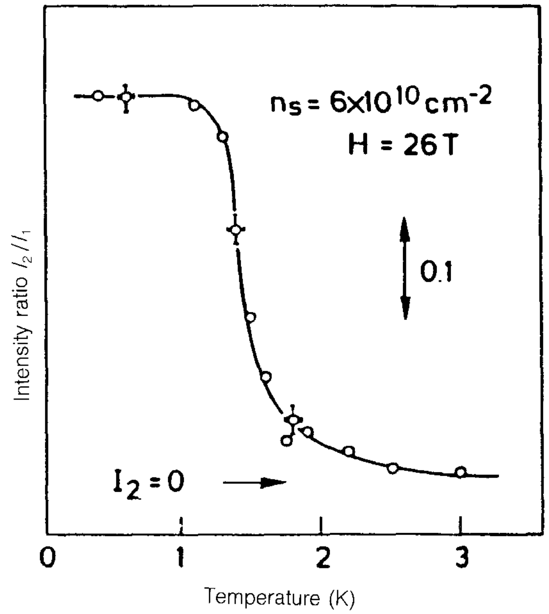

FIG. 3. Temperature dependence of the ratio of the intensities of the luminescence lines I_2/I_1, measured for a sample with a 2D-electron density $n_S = 6 \times 10^{10}$ cm^{-2} at $H = 26$ T.

intensity is a consequence of a pronounced localization of electrons under crystallization conditions. The reasoning here is that in a magnetic field the size in the 2D plane of the wave functions of the electrons and holes participating in the recombination is determined by the magnetic length. In the perpendicular direction, in contrast, the magnetic field has little effect on the wave functions of the recombining particles. With increasing H, the overlap of the wave functions of the strongly localized electrons and holes evidently decreases. The localization of the electrons in this case is of natural origin, stemming from the appearance of a crystal (or a polycrystalline medium), which becomes pinned at irregularities of the random potential. Correspondingly, the overall luminescence intensity falls off sharply with increasing H. As the temperature is raised above the critical value, in contrast, as the crystal melts, and as the electrons are delocalized, the overall luminescence intensity becomes independent of the strength of the magnetic field (Fig. 2a).

The phase diagram of the crystal–liquid transition is interesting. According to an interpretation in the literature,[12] the crystal–liquid equilibrium line in the T–ν plane originates at $\nu<\nu_c$ and varies in a monotonic way. Specifically, T_c increases with decreasing ν. According to our observations, the crystal–liquid phase diagram is cut by gaps at $\nu = 1/5$, $1/7$, and $1/9$, where the states of the incompressible Fermi liquid turn out to stabler. This question will be examined in detail in a separate publication.

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