Novel Magneto-Optical Behavior in the Wigner-Solid Regime

H. Buhmann,(1) W. Joss,(1) K. v. Klitzing,(2) I. V. Kukushkin,(2),(3) A. S. Plaut,(2) G. Martinez,(4)
K. Ploog,(2) and V. B. Timofeev(3)

(1)*Hochfeld-Magnetlabor, Max-Planck-Institut für Festkörperforschung,*
BP 166X, F-38042 Grenoble CEDEX, France
(2)*Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Federal Republic of Germany*
(3)*Institute for Solid State Physics, Academy of Sciences of the U.S.S.R.,*
142432, Chernogolovka, U.S.S.R.
(4)*Service National des Champs Intense–Centre National de la Recherche Scientifique,*
BP 166X, 38042 Grenoble CEDEX, France

(Received 7 August 1990)

Below a critical filling factor ($\nu_c=0.28$) and critical temperature ($T_c=1.4$ K at 26 T) an additional line has been observed in the luminescence spectrum of a GaAs-Al$_x$Ga$_{1-x}$As heterojunction; it grows in intensity with decreasing ν, dominating the spectrum at $\nu<\frac{1}{11}$. Its appearance is accompanied by a strong reduction in overall integrated intensity, while its relative intensity decreases sharply at $\nu=\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$. The lack of correlation between ν_c and the disorder-related properties of the system indicates the intrinsic nature of the line which we propose signals the formation of a pinned Wigner solid.

PACS numbers: 73.20.Dx, 73.40.Kp, 78.20.Ls, 78.65.Fa

One of the most important outstanding questions in low-dimensional physics is the nature of the ground state of the interacting two-dimensional (2D) electrons in a perpendicular magnetic field (H). In the extreme quantum limit, at fractional filling factors $\nu=n_sh/eH$ (where n_s is the electron concentration) the ground state is known to be an incompressible Fermi liquid.[1-3] However, on further reducing ν, a phase transition is expected to occur at $\nu=\nu_c$ to the energetically favored Wigner solid. Theoretically predicted values of ν_c are sensitive to the approximations used in the calculations and have therefore ranged from $\frac{1}{3}$ to $\frac{1}{10}$.[2,4-7] So far, experimentally, this changeover has not been unambiguously identified.

Up to now magnetotransport[8-10] and radio-frequency spectroscopic techniques[11] have been used to investigate this phase transition between the liquid and Wigner-solid states. From transport measurements, it is now well established that at $\nu=\frac{1}{3}$ and $\frac{1}{5}$ the ground state of the system is still an incompressible Fermi liquid, giving rise to a quantized Hall resistance and the corresponding minimum in the diagonal resistivity. And even at $\frac{1}{7}$, evidence of a fractional state has been reported.[10] The radio-frequency absorption measurements,[11] on the other hand, suggest that the value of the critical filling factor for Wigner crystallization is $\nu_c=0.23$.

In this paper we describe magneto-optical experiments, also performed in this extreme quantum limit, on a GaAs-Al$_x$Ga$_{1-x}$As ($x=0.28$–0.32) single heterojunction. We have previously shown[12] that condensation of the 2D electrons into an incompressible Fermi liquid at $\nu=\frac{1}{3}$, $\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ is accompanied by discontinuous changes in the spectral position of the luminescence line at these ν. Here we report the observation of a new luminescence line appearing at $\nu<\nu_c$ and below a critical temperature (T_c, which depends on ν) which weakens in intensity at $\nu=\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ and which we associate with the formation of a Wigner solid.

In Fig. 1 we show luminescence spectra recorded at two different concentrations $n_s=5.4\times10^{10}$ and 6×10^{10} cm^{-2} at various magnetic fields. A detailed description of the sample and the experimental setup, as well as a discussion of the low-field data can be found elsewhere.[12] It can be seen that in both cases above a certain magnetic field (H_c) an additional line (I_2) appears, shifted by ~1.4 meV to lower energy, which grows as the field is increased until at $\nu<\frac{1}{11}$ it dominates the spectrum. Its appearance is accompanied by an abrupt decrease of the integrated luminescence signal.

In Fig. 2 both the intensity ratio I_2/I_1 [Fig. 2(b)] and the total integrated intensity [Fig. 2(a)] are plotted as a function of magnetic field for two different concentrations. It can be seen from this figure that for a given concentration, the value of H_c obtained from both plots is practically identical. It is our belief that at exactly $\nu=\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$, when the 2D electrons condense into an incompressible Fermi liquid, the intensity of the new line actually drops to zero. That an increase in the integrated intensity is observed at this point is due to a simultaneous enhancement in the intensity of the I_1 line.

The most important property of the new line is that it can be characterized by two critical parameters— ν_c and T_c. These can be determined from the plots presented in Fig. 3, in which it can be seen that H_c depends linearly on the concentration of 2D electrons. From the slope of the dependence of H_c on n_s, we obtain $\nu_c=0.28\pm0.02$. In Fig. 3(b), the dependence of the ratio I_2/I_1 on temperature, measured at $H=26$ T ($\nu=0.09$), is shown.

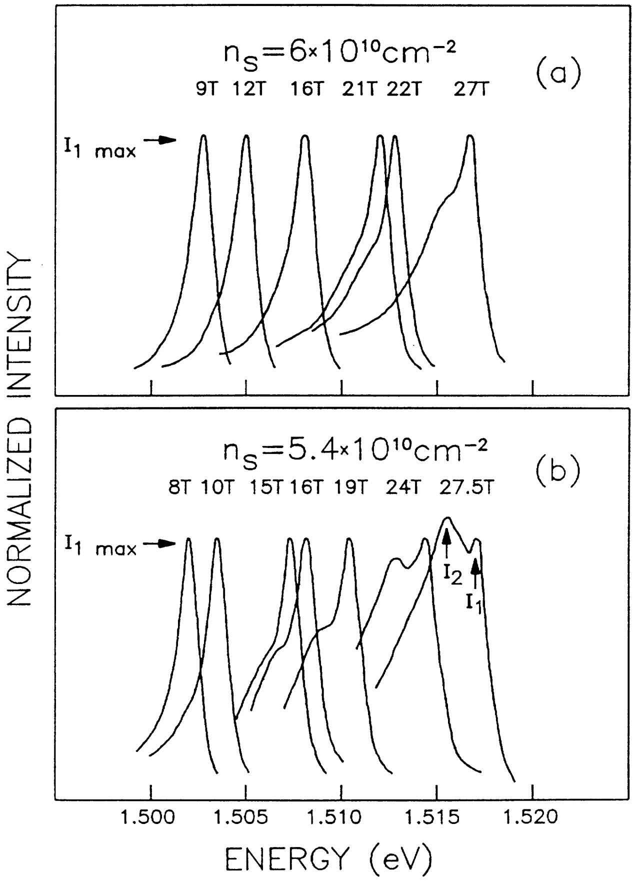

FIG. 1. Luminescence spectra measured for two different concentrations at 0.6 K and at various magnetic fields. Note the nonmonotonic increase of I_2 at (a) 22 T ($\nu \simeq \frac{1}{9}$) and (b) 16 T ($\nu \simeq \frac{1}{7}$).

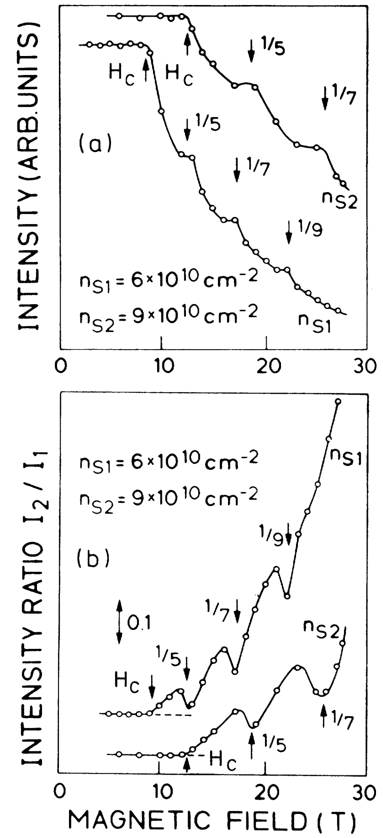

FIG. 2. The dependence on magnetic field of (a) the integrated luminescence intensity and (b) the intensity ratio I_2/I_1, measured at 0.6 K for two different concentrations.

The line I_2 disappears from the luminescence spectrum abruptly at a critical temperature, which at this ν is $T_c = 1.4$ K.

We associate the appearance of an additional line in the emission spectra and the accompanying abrupt decrease in the integrated intensity with the formation of a (most probably polycrystalline) pinned Wigner solid. In accordance with this interpretation, the two lines I_1 and I_2 correspond to radiative recombination of 2D electrons from the liquid (at $\nu = \frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ the liquid becomes incompressible) and solid phase, respectively. That I_2 lies lower in energy than I_1 agrees with the expected lower energy of the solid state compared to that of the liquid one. We conclude from the tendency of the new line to vanish from the luminescence spectra at $\nu = \frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ and from the simultaneous enhancement in intensity of I_1 that at these fractional values of ν the ground state of the system is still an incompressible Fermi liquid. That I_2 does not completely disappear from the luminescence spectrum at these ν may be due to a small amount of inhomogeneity in the concentration which is unavoidable in a real system. In such a case, local values of ν in different parts of the sample will not be exactly identical.

The extent of the wave functions of the localized electrons in the 2D plane is defined by the magnetic length, $l = (\hbar/eH)^{1/2}$. In our case the holes participating in the recombination process are bound to acceptors and are thereby localized in all three dimensions. Thus as the magnetic field is increased and the electrons become more localized in the plane parallel to the interface, the probability of an electron finding itself in the vicinity of a hole decreases, causing a reduction in the luminescence intensity. In less-high-quality structures, in which the Landau-level width, determined from the luminescence linewidth, was larger than 3 meV, and where we did not observe the above described features that we associate with Wigner crystallization, the luminescence intensity started decreasing already at higher ν (just below $\nu = 1$) and the reduction itself was not as strong. At 1.3 K the magnetic-field onset of this luminescence drop moved to a slightly higher field compared to that at 0.6 K [Fig.

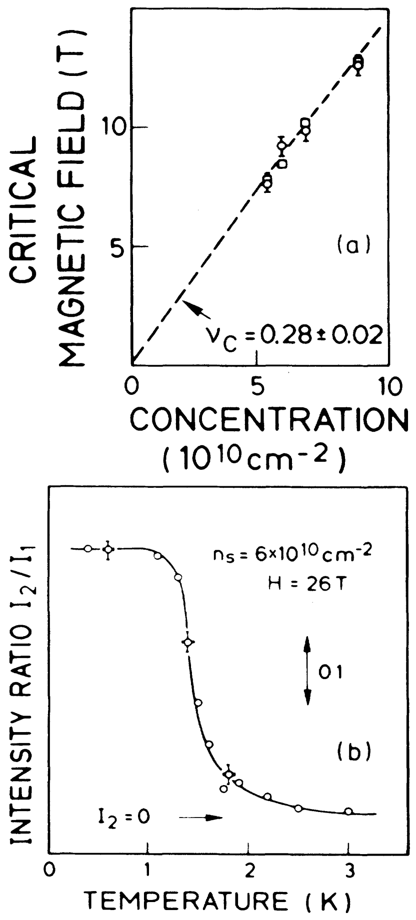

FIG. 3. (a) The dependence of H_c on n_s measured from $I_2/I_1(H)$ (circles) and from the dependence of the integrated intensity on magnetic field (squares). (b) The temperature dependence of the intensity ratio I_2/I_1. T_c has been taken as the temperature at which I_2/I_1 drops to half its maximum value.

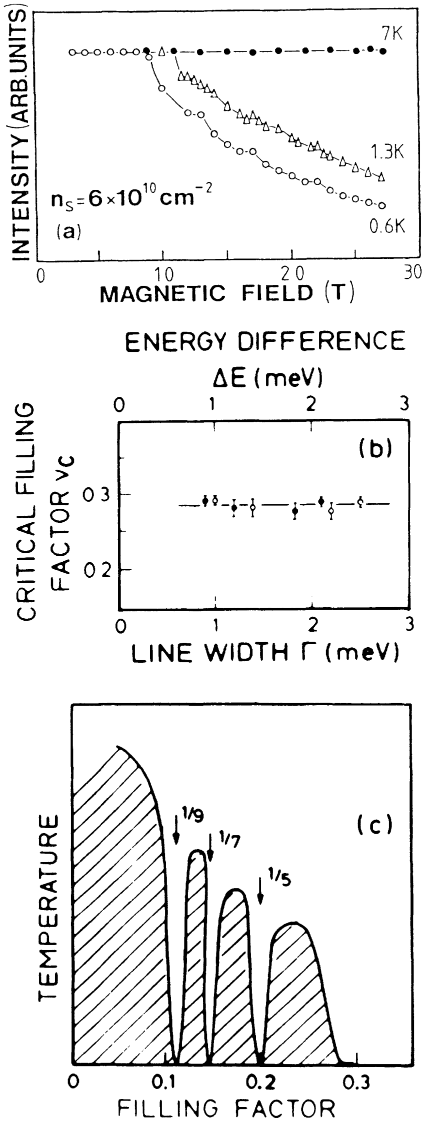

FIG. 4. (a) The dependence of the integrated luminescence intensity on magnetic field measured at different temperatures. Note that H_c moves to higher fields on raising the temperature. (b) The dependence of ν_c on the disorder parameters (defined in the text) ΔE (open symbols) and Γ (solid symbols). (c) Suggested qualitative form of the phase diagram $T_c(\nu)$.

4(a)]. We therefore conclude that 1.3 K is above T_c for ν just smaller than ν_c. At even higher temperatures above T_c where the electrons become mobile no reduction in luminescence was observed at all [Fig. 4(a)]. We therefore believe that strong magnetically induced localization is responsible for the sudden drop in integrated luminescence intensity below $\nu = \nu_c$. It is most important, however, to demonstrate that this localization has an intrinsic origin rather than that of disorder. Quantitatively, disorder can be characterized by the Landau-level width Γ (for example at $\nu = 1$). Additionally we have observed that at low temperatures and below $\nu = 2$, the spectral position of the luminescence line deviates from a linear dependence on H and that this deviation, ΔE, is also sensitive to the amount of disorder present.[12] At higher temperatures, the dependence of the energy position of the luminescence line on magnetic field remains linear. Since ΔE is proportional to H, the size of this deviation, at a set magnetic field, can also be used as a measure of the disorder present in the system. The dependence of ν_c on ΔE and Γ measured for different n_s is presented in Fig. 4(b) where it is clearly illustrated that ν_c shows no dependence on these disorder-related parameters in the region of interest (for $\Gamma > 3$ meV and $\Delta E > 3$ meV the features associated with Wigner crystallization were not observed). This thus confirms the intrinsic nature of the observed localizationlike phenomena, thereby ruling out localization on random potential fluctuations as the cause.

Preliminary results indicate that the critical temperature strongly depends on the filling factor, dropping to zero for $\nu > \nu_c$ and also at $\nu = \frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$, thereby producing the observed oscillations of the I_2 line intensity [see Fig. 2(a)] in the vicinity of these ν. Qualitatively we presume that the phase diagram, $T_c(\nu)$, has the form shown in Fig. 4(c), where the features around $\nu = \frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ are where our results differ most from radio spectroscopic data.[11] On the other hand, the values of ν_c obtained from these two experiments are in good agreement (note that in magnetotransport[9] an unusual enhancement of the resistivity is also observed to occur around $\nu = 0.23\text{–}0.28$). Comparing the absolute values of T_c obtained from the luminescence and radiofrequency experiments, one finds that our value (measured under similar conditions) is approximately 4 times higher than theirs. A higher sensitivity of our method (which is a local probe) to the appearance of a small amount of the crystal phase in the system could explain this discrepancy. The coexistence of two phases is indicated by the presence of two lines in the luminescence spectrum even at the lowest temperature and for $\nu < \frac{1}{11}$. This may be due to the quasiequilibrium nature of the system under continuous illumination. In other words, the small lifetime of the electrons due to recombination may itself be hindering the freezing process.

In summary, we have investigated by magneto-optics, for the first time, a dilute system of 2D electrons in the extreme quantum limit (down to $\nu = \frac{1}{13}$). An additional luminescence line, appearing below a critical value of filling factor and temperature, has been found, which we associate with the formation of a pinned Wigner solid.

We gratefully acknowledge the support of P. Wyder and G. Arnaud, J. Dumas, A. Fischer, M. Hauser, S. Sala, J.-C. Vallier, and C. Warth. One of us (I.V.K.) would like to thank the Alexander von Humboldt Stiftung for financial support.

---

[1] D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1982).

[2] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983).

[3] For a recent review, see T. Chakraborty and P. Pietil'inen, *The Fractional Quantum Hall Effect* (Springer-Verlag, New York, 1988).

[4] P. K. Lam and S. M. Girvin, Phys. Rev. B **30**, 473 (1984).

[5] D. Levesque, J. Weiss, and A. H. MacDonald, Phys. Rev. B **30**, 1056 (1984).

[6] S. T. Chui, T. M. Hakim, and K. B. Ma, Phys. Rev. B **33**, 7110 (1986).

[7] S. Kivelson, C. Kallin, D. P. Arovas, and J. P. Schrieffer, Phys. Rev. B **36**, 1620 (1987).

[8] E. E. Mendez, L. L. Chang, M. Heiblum, L. Esaki, M. Naughton, K. Martin, and J. Brooks, Phys. Rev. B **30**, 7310 (1984).

[9] R. L. Willet, H. L. Störmer, D. C. Tsui, L. N. Pfeiffer, K. W. West, and K. W. Baldwin, Phys. Rev. B **38**, 7881 (1988).

[10] V. J. Goldman, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. **61**, 881 (1988).

[11] E. Y. Andrei, G. Deville, D. C. Glattli, F. I. B. Williams, E. Paris, and B. Etienne, Phys. Rev. Lett. **60**, 2765 (1988).

[12] H. Buhmann, W. Joss, K.v. Klitzing, I. V. Kukushkin, A. S. Plaut, K. Ploog, G. Martinez, and V. B. Timofeev, Phys. Rev. Lett. **65**, 1056 (1990).