PHYSICAL REVIEW B VOLUME 45, NUMBER 8 15 FEBRUARY 1992-II

# Magneto-optical evidence for depinning of the Wigner crystal by an electric field

I.V. Kukushkin,* N.J. Pulsford, K. von Klitzing, K. Ploog, R.J. Haug, and S. Koch
*Max-Planck-Institut für Festkörperforschung, D-7000, Stuttgart 80, Federal Republic of Germany*

V.B. Timofeev
*Institute for Solid State Physics, Academy of Sciences of the U.S.S.R., 142432, Chernogolovka, U.S.S.R.*
(Received 03 December 1991)

We investigate the influence of an electric field on the radiative recombination of two-dimensional electrons in the Wigner-solid regime. We find a threshold enhancement of the intensity of the luminescence accompanied by the appearance of noise, which we associate with a sliding of the pinned Wigner solid by the electric field. Our results indicate that the melting of the Wigner solid occurs in two steps and can be characterized by two critical temperatures.

The liquid-solid phase transition in a two-dimensional (2D) system has attracted considerable theoretical interest over the last sixty years. Much of this interest stems from the reduction in the dimensionality which leads to novel properties of the solid phase and its melting behavior when compared to the more familiar three-dimensional (3D) case.[1] The solid phase is unusual in that an infinite crystal is unstable with respect to long-wavelength ($q \approx 0$) phonon oscillations. However, Monte Carlo calculations[2] demonstrate that stability may be achieved by the formation of a polycrystalline domain structure, which has a mean domain size which decreases with increasing temperature.

Recent experiments[3-9] have probed the condensation of electrons in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions into a 2D solid phase (Wigner crystal). In this system, the electron density is high and a strong magnetic field perpendicular to the 2D layer is required to induce the crystallization. Transport measurements[5,7] on the solid phase reveal low electric-field thresholds in the electrical conductivity and signal noise, which are associated with the Wigner crystal domains depinning out of the disorder potential at the heterojunction interface. The depinning threshold signifies a rigid solid phase of electrons (a fluid phase cannot be pinned) and its disappearance with increasing temperature is identified with the melting of the Wigner crystal.

In a previous paper,[6] we studied the optical properties of 2D electrons in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions in the regime of the Wigner crystallization. We found that below a critical filling factor ($\nu_c$=0.28) and below a critical temperature ($T_c$=1.4 K at 26 T) an additional line appeared in the luminescence spectrum which we associated with the formation of a pinned Wigner solid. In this work, we correlate previous electrical and optical measurements by studying the effect of an electric field on the luminescence spectrum. We observe an electric field threshold enhancement in the optical intensity of the additional line which is accompanied by an appearance of noise in the luminescence signal. We interpret this behavior in terms of the electric-field depinning of the Wigner crystal domains and note the clear link with the transport measurements.[5,7] By modulating the electric field, we are able to detect the additional line independently from the main luminescence line and find a two-step melting process of the Wigner solid with increasing temperature.

The samples studied are high quality GaAs-$Al_{1-x}Ga_xAs$ heterojunctions with a $\delta$-doped layer of Be acceptors in the GaAs buffer layer.[6] An electric field is applied by two diffused indium dots $\sim$ 2.5 mm apart on a sample measuring 3x1.5 $mm^2$. The luminescence was measured inside a dilution refrigerator using an optical fiber access and we ensured that the sample was uniformly illuminated during the measurement. In Fig. 1(a), we show two luminescence spectra measured for a heterojunction with an electron concentration of 5.5x$10^{10}$ $cm^{-2}$ at $B$=16 T ($\nu$=0.135) under zero applied voltage and under a voltage of 5 mV. Under zero voltage, the $I_2$ line, which we associate with the formation of the pinned Wigner solid, shows up as a low energy shoulder to the main $I_1$ line. In the electric field, the intensity of the $I_2$ line increases several times whereas the main $I_1$ line (corresponding to the liquid phase) remains the same.

The selective enhancement of the weaker $I_2$ line in the electric field allows it to be separated from the main $I_1$ line by recording differential luminescence spectra with a low-frequency voltage modulation ($f$=10–60 Hz). Differential spectra are shown in Fig. 1(b) and only a single asymmetric peak at the energy of the $I_2$ line is observed. The dependence of the intensity of this peak on the modulation voltage is shown in Fig. 2(a): there is a threshold at $E_T$=2 mV followed by a sharp increase over the voltage range 2 to 3.5 mV. Above the threshold, the signal becomes very unstable and the noise level, measured as the average deviation of the differential signal from its mean value, is plotted in Fig. 2(b). Both the differential intensity and signal noise show threshold increases in the electric field. A Hall bar sample was also measured under

 

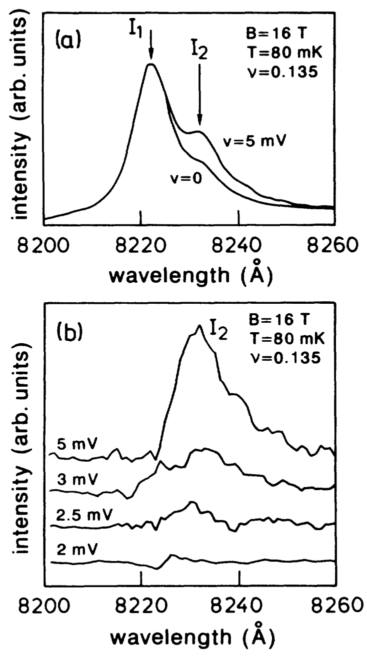


FIG. 1. (a) Luminescence spectra measured at $B$=16 T and $T$=80 mK under zero applied voltage and under an applied voltage of 5 mV. (b) Differential luminescence spectra obtained for various applied voltages. The peaks labeled $I_1$ and $I_2$ correspond to liquid and solid phases, respectively.

similiar experimental conditions and displayed a strong instability in the resistance $\rho_{xx}$ near the threshold.

The threshold behavior of the luminescence signal and its noise level (as well as the observed instability of $\rho_{xx}$) is similar to the transport measurements of Goldman *et al.*[5] of an electric-field threshold in the conduction and of related noise generation. They explained their results in terms of the depinning of the Wigner crystal by the electric field. In our case, a depinning of the Wigner crystal leads to an increase in the luminescence intensity. We associate this with the ineffectiveness of a pinned Wigner crystal in radiative recombination.[6] In a strong magnetic field, the extent of the 2D electron wave function in a pinned Wigner solid is defined by the magnetic length. The holes participating in the recombination process are bound to acceptors and the combined localization of both the electrons and holes makes the luminescence efficiency of the pinned Wigner solid very low. However, an electric field depinning of the Wigner solid domains results in the collective motion of the 2D electrons and thereby leads to an increase in the luminescence intensity of the solid line. The noise is due to the instability of the depinning process near threshold[10] and has been observed in the depinning of both charge-density waves[11] and of the classical electron solid on liquid helium.[12]

In order to understand the electron phase diagram, it is important to identify which phase—liquid or solid—forms the ground state for the electronic system. In Fig. 3, the relative spectral positions of the $I_1$ (liquid) and $I_2$ (solid) lines are plotted. The energy ($\Delta E$) is given by the measured shift of the points from the cyclotron energy $\frac{1}{2}\hbar\omega_c$ extrapolated from the low-field points. The downward cusps in the dependence of the liquid line[13] at fractional filling factors $\nu=\frac{1}{3}$, $\frac{1}{5}$, and $\frac{1}{7}$ reflect the formation of an incompressible Fermi liquid separated by an energy gap from the excited states.[14] No corresponding structure is seen in the solid line ($I_2$) as many-body correlation effects are not expected to produce an incompressible ground state in this phase.

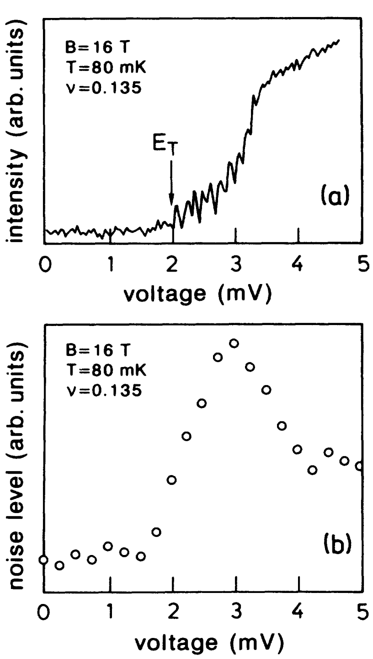


FIG. 2. The dependence of (a) the intensity and (b) the noise level of the $I_2$ line in the differential spectrum on applied voltage.

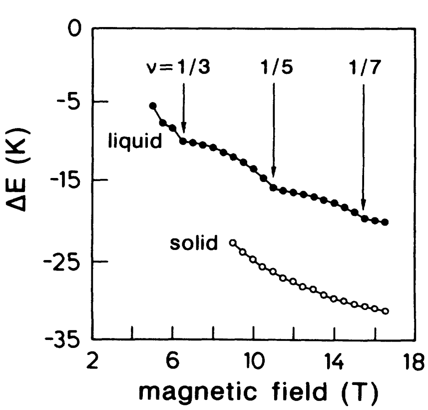


FIG. 3. The spectral positions of the $I_1$ (liquid) and $I_2$ (solid) lines as a function of magnetic field. The energy ($\Delta E$) is the shift relative to the cyclotron energy increase $\frac{1}{2}\hbar\omega_c$.

Theoretical calculations predict that the formation of an incompressible Fermi liquid at $\nu=\frac{1}{5}$, $\frac{1}{7}$, and $\frac{1}{9}$ lowers the energy of the liquid phase to below the solid phase.[15,16] This implies that the liquid phase forms the ground state at these fractions whereas away from these fractions (and below a critical filling factor), the solid phase is expected to be stable. The presence of the incompressible Fermi liquid and the consequential melting of the solid phase has been observed in the vicinity of $\nu=\frac{1}{5}$ using transport measurements.[4] In the optical measurements, both the liquid ($I_1$) and solid ($I_2$) lines are present in the spectra implying that the two phases coexist and this is thought to be either a dynamic effect under the illumination or due to a small amount of inhomogeneity in the 2D electron concentration. However, in either case, the intensities of the two luminescence lines should reveal the relative stabilities of the two phases and hence the ground state of the system. In Fig. 4, the differential intensity of the $I_2$ line for a voltage modulation of 5 mV is plotted as a function of magnetic field. The line appears below a critical filling factor $\nu_c=0.27$ and has intensity minima at $\nu=\frac{1}{5}$ and $\frac{1}{7}$. The onset at $\nu_c=0.27$ represents the boundary below which the Wigner crystal is stable in this sample. The intensity minima at $\nu=\frac{1}{5}$ and $\frac{1}{7}$ are matched by intensity maxima in the liquid line $I_1$ (Ref. 6) and the complimentary oscillations in the intensities of the two peaks support the formation of the liquid phase at these fractions.

Our previous measurements showed that the $I_2$ luminescence line exists up to a relatively high critical temperature $T_c=1.5$ K.[6] Such a high value of $T_c$ strongly differs from transport and radio-frequency measurements[3–5,7] which report critical temperatures in the range 100–500 mK. In Fig. 5, we show the temperature dependence of the differential intensity of the $I_2$ line down to 60 mK for a filling factor $\nu=0.135$ and a voltage modulation of 5 mV. The curve is marked by two temperature thresholds at which the intensity drops sharply: at the first threshold $T_{c1}=350$ mK there is a 30% decrease and this is followed by a second threshold at a higher temperature $T_{c2}=1.2$ K. The classical 2D melting temperature for this electron concentration is 420 mK (Ref. 1) and it therefore seems reasonable to assign the first threshold to the melting of the Wigner solid. The transition temperature is expected to drop below the classical melting temperature as the filling factor increases. The assignment of the second threshold is not clear. The presence of two distinct thresholds might indicate two separate phase transitions. Indeed, 2D melting theory predicts a possible intermediate "hexatic" phase between the liquid and solid phases.[1] This phase is characterized by quasi-long-range orientational order and has physical properties similiar to a liquid crystal. However, the depinning threshold persists beyond $T_{c1}$ and the description of the electrons in this temperature range as a nonrigid liquid crystal is clearly invalid. Another possible explanation of the existence of the $I_2$ line above $T_{c1}$ would be to accept that the melting temperature depends on the electron solid domain size and hence with increasing temperature from $T_{c1}$ to $T_{c2}$, the mean domain size drops to zero. Monte Carlo simulations find that the mean domain size decreases with increasing temperature.[2] However, a continuous decrease in domain size, although accounting for the additional luminescence line existing to well above the classical melting temperature, would be expected to give a continuous decrease in its intensity and this conflicts with the presence of two sharp thresholds in the temperature dependence. Neither proposed mechanism can fully account for the observed two-step intensity decrease and further study is required to identify the structure of the electron phase in this regime.

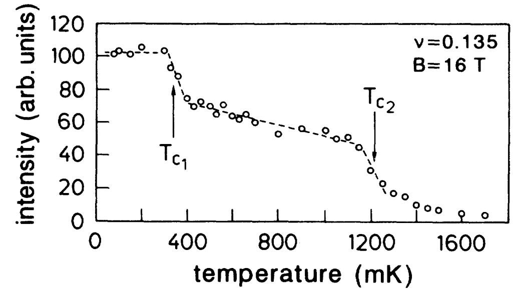


FIG. 5. The temperature dependence of the $I_2$ line intensity for a 5-mV voltage modulation showing two sharp decreases at $T_{c1}$ and $T_{c2}$. The dashed line is a guide for the eye.

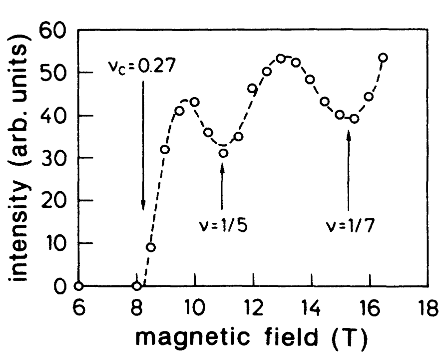


FIG. 4. The integrated intensity of the $I_2$ line for a 5-mV voltage modulation as a function of magnetic field. The positions of filling fractions $\nu=\frac{1}{5}$ and $\frac{1}{7}$ are indicated.

In conclusion, we have studied the influence of an electric field on the luminescence from 2D electrons in the Wigner solid regime. The electric-field threshold behavior, the intensity minima at $\nu=\frac{1}{5}$ and $\frac{1}{7}$, and the presence of a critical temperature close to the classical melting temperature all indicate radiative recombination from electrons in a pinned Wigner solid.

I.V.K. would like to thank the Alexander von Humboldt Stiftung and N.J.P. would like to acknowledge the Royal Society for financial support.

*Permanent address: Institute for Solid State Physics, Academy of Sciences of the U.S.S.R., 142432, Chernogolovka, U.S.S.R.

[1] 2D melting is reviewed by K.J. Strandburg, Rev. Mod. Phys. **60**, 161 (1988).

[2] R.W. Hockney and T.R. Brown, J. Phys. C **8**, 1813 (1975).

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

[4] H.W. Jiang, R.L. Willett, H.L. Stormer, D.C. Tsui, L.N. Pfeiffer, and K.W. West, Phys. Rev. Lett. **65**, 633 (1990).

[5] V.J. Goldman, M. Santos, M. Shayegan, and J.E. Cunningham, Phys. Rev. Lett. **65**, 2189 (1990).

[6] H. Buhmann, W. Joss, K. von Klitzing, I.V. Kukushkin, A.S. Plaut, G. Martinez, K. Ploog, and V.B. Timofeev, Phys. Rev. Lett. **66**, 926 (1991).

[7] F.I.B. Williams, P.A. Wright, R.G. Clark, E.Y. Andrei, G. Deville, D.C. Glattli, O. Probst, B. Etienne, C. Dorin, C.T. Foxon, and J.J. Harris, Phys. Rev. Lett. **66**, 3285 (1991).

[8] B.B. Goldberg, D. Heiman, A. Pinczuk, L. Pfeiffer, and K. West, Surf. Sci. (to be published).

[9] A.J. Turberfield, S.R. Haynes, P.A. Wright, R.A. Ford, R.G. Clark, J.F. Ryan, J.J. Harris, and C.T. Foxon, Surf. Sci. (to be published).

[10] S.N. Coppersmith, Phys. Rev. Lett. **65**, 1044 (1990).

[11] Reviewed in G. Grüner, Rev. Mod. Phys. **60**, 1129 (1988).

[12] H.W. Jiang and A.J. Dahm, Phys. Rev. Lett. **62**, 1396 (1989).

[13] V.M. Apal'cov and E.I. Rashba, Pis'ma Zh. Eksp. Teor. Fiz. **53**, 420 (1991) [JETP Lett. **53**, 442 (1991)].

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

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

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