PHYSICAL REVIEW B VOLUME 49, NUMBER 19 15 MAY 1994-I

Character of the phase transition at the two-dimensional electron-liquid-to-solid boundary

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(Received 14 February 1994)

Nonlinear threshold electric transport has been studied at $T \simeq 30$ mK near the collective insulating transition in a dilute two-dimensional (2D) electron system in high-mobility Si MOSFET's. We found that the threshold electric field becomes steplike at the critical density, both when $H = 0$ and when $H \neq 0$. This steplike onset indicates a weak first-order phase transition at the 2D electron-solid-to-liquid phase boundary.

The conducting and insulating phases in the strongly interacting dilute two-dimensional (2D) electron system have recently become a focus of experimental and theoretical interest.[1] There is now much experimental evidence for the solidification of the dilute 2D electron system into a collective 2D solid, which shows many features of the pinned Wigner lattice. The liquid-to-solid transition occurs in the high-mobility Si metal-oxide-semiconductor field-effect transistors[2–5] (MOSFET's) and GaAs-Al(Ga)As heterojunctions.[6–10] In the mK temperature range the thermal kinetic energy k_BT is much less than the Fermi energy E_F (where $E_F \simeq 5$ K at a typical electron density $n_s = 8 \times 10^{10}$ cm^{-2} in a dilute 2D system), and the physics of the electron solid (ES) is quantum mechanical in nature. This is in contrast to the 2D system of electrons above liquid helium.[1]

In Si (100), due to the strong Coulomb interaction, the low zero-point energy, the two-valley electron system, and the stabilizing pinning force of the impurities at the Si-SiO_2 interface, the quantum ES begins to form as soon as the magnetic field is increased.[5] The quantizing magnetic field in the range 0–5 T, i.e., *through the range of integer filling factors* $\nu > 1$, affects the liquid-to-solid phase boundary and induces quantum oscillations.[11] This results in reentrant insulating transitions[2–4] when the electron density n_s is fixed and the magnetic field is being swept. In GaAs-Al(Ga)As, an ES is induced by a strong magnetic field and forms in the range of *low fractional filling factors* $\frac{1}{7} \leq \nu \leq \frac{1}{3}$. As the field continues to increase, the ES is interrupted then by an incompressible Laughlin-liquid state at exactly fractional fillings. This again results in reentrant insulating transitions around fractional filling factors when the magnetic field is swept at fixed electron density.[8–10]

Despite intensive experimental[2–10] and theoretical studies[1,12–25] of the electron solid, there has not been much focus on elucidating the nature of quantum melting. The melting of the classical electron crystal was found to be second order both in numerical simulations for the ideal ES (Ref. 26) and experimental studies for electrons above liquid He.[27] Classical melting in 2D is often described in a language of dislocations.[28–32] For the quantum case, Chui and Esfarjani[19] exploited the Casimir effect and provided a natural link with the classical dislocation picture; a phase diagram in good agreement with experimental results at high fields is obtained.[13] A second-order phase transition may be expected generally when the dislocation density is low; if the dislocation density is high and the core dislocation energy is small, melting might then occur as a first-order phase transition.[31,32] For the quantum electron lattice in zero field, the core energy is much reduced due to hybridization effects.[18] One thus expects a first-order transition. An alternative reason in favor of this comes from Landau-type arguments: for melting transitions *cubic* invariants can be constructed from the order parameters ρ_G, the Fourier transforms of the electron density at reciprocal-lattice vectors $\mathbf{G}$. Thus a first-order transition results. This argument is not applicable to 2D *finite-temperature* situations because there is no *long-range* order. However, at zero temperature this argument does hold: the Wigner transition is expected to occur at *zero temperature* as the density is varied.[25,33,34]

In this paper we study the threshold depinning electric field close to the transition point. Any signature of the solid phase and, particularly the threshold electric field vanishes in this region. Therefore, in order to detect very weak dc voltages at the insulating transition, we used an improved experimental technique when compared with that used in Ref. 4. The noise level was decreased to a few μV at 10^{13} Ω input resistance. We found a sharp steplike change in the threshold field, suggestive of a first-order transition. We now describe our results in detail.

The present measurements were done with two high-mobility Si-MOSFET samples from two different wafers: sample 1 with peak mobility $\mu^{\mathrm{peak}} = 3.6 \times 10^4$, and sample 2 with $\mu^{\mathrm{peak}} = 5.5 \times 10^4$ cm^2/V s. The samples have a Hall-bar geometry; the top view is shown in the inset of Fig. 1. The source-drain distance is 5.0 mm, the distance l between the two potential contacts A and B is 2.5 mm, and the sample width is 0.8 mm. The samples were immersed into a ^{3}He-^{4}He liquid mixture in a dilution refrigerator, providing a temperature of 30–40 mK. Both samples exhibited a well-pronounced collective in-

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sulating phase[5] and reentrant metal-insulator transitions in the magnetic field.[4] The collective insulating phase begins at decreasing electron density below a critical value $n_c(H)$, which depends sinusoidally on a magnetic field in the range $H \leq 5$ T.[11] The main difference between the two samples was in the n_c value at $H = 0$: $n_c = 8.0\times10^{10}$ cm^{-2} for sample 1 and 7.7×10^{10} cm^{-2} for sample 2.

Figure 1 shows typical threshold current-voltage dependencies in the vicinity of n_c. The threshold electric field E_t was determined from the voltage drop extrapolated from the linear wings of the I-V curves and the known intercontact distance; the homogeneity of the current distribution over the sample area in the regime of a high sample resistance was established in Ref. 4.

As expected, the threshold electric field E_t, shown in Figs. 2(a)–2(c), far from the critical boundary follows a $\frac{3}{2}$ power law both at zero and nonzero magnetic field. The insets in Figs. 2(a) and 2(b) display the density dependence of E_t near the transition $\delta n_s = n_c - n_s \ll n_c$. In all three figures a step $\Delta E_t \sim 100$ μV/cm is clearly observed at the critical point, both at zero and nonzero magnetic field. The inset of Fig. 2(c) shows the oscillatory $n_c(H)$ boundary;[11] the measurements of the threshold voltage in a magnetic field were done at two points, corresponding to the $n_c(H)$ maxima at $H = 1.55$ T (filling factor 2.7), and an arbitrary point at $H = 1.08$ T. The estimated statistical uncertainty of the present measurements is equal to the dot size if not shown by an error bar. The steps in E_t are everywhere larger by at least a factor of 5, and cannot be attributed to the error in E_t or n_c. Moreover, the procedure used here to determine E_t from the I-V curves (see Fig. 1) provides a low estimate because of the limited current range and broadening of the transition when approaching the critical point. The possible inhomogeneity of the electron density over the sample area cannot itself produce the step in E_t, but could, in principle, decrease its observable value. The steplike onset in E_t was not seen earlier, since it was below the resolution level of previous measurements.[4,5,35] There is no hysteresis observed either in the I-V curves or in E_t vs n_s over the discussed range of parameters and the dependencies displayed in Figs. 2 are entirely reproducible.

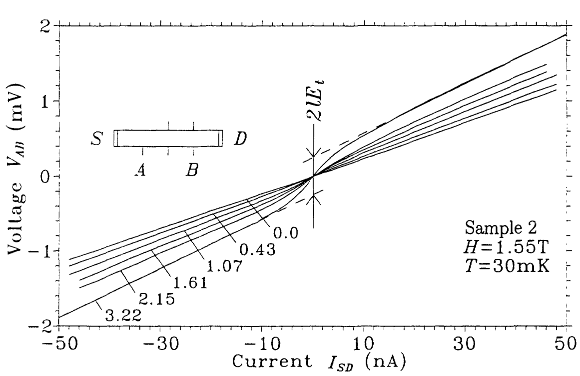

FIG. 1. Typical nonlinear current-voltage dependencies, taken with four-probe dc technique in the vicinity of the critical point, in the ES phase. Dashed lines and arrows explain the procedure used to extract E_t from the I-V curves. The inset shows the sample top view. S and D are the current probes, A, B are potential probes. The $\delta n_s = n_c - n_s$ value for each I-V curve is shown in units of 10^9 cm^{-2}.

Conventional studies of the pinning of the charge-density wave[36] focus on the shear mode becuase of its low frequency. For the systems of experimental interest, numerical studies[20,25] indicate that the longitudinal mode dominates. Because of the long-range nature of the interaction, the shear mode is coupled by a very small matrix element to the impurities.

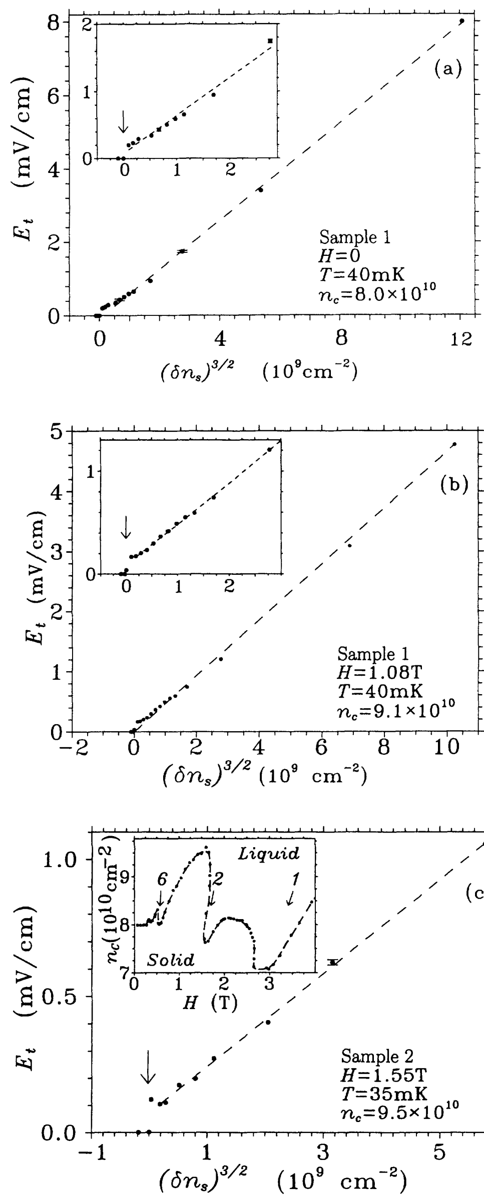

FIG. 2. Threshold electric field vs deviation in the electron density from the critical point. (a) At zero magnetic field; sample 1. (b) At field $H = 1.08$ T; sample 2. (c) At field $H = 1.55$ T corresponding to the n_c maxima ($\nu \simeq 2.7$); sample 2. The insets in (a) and (b) show an expanded region around $\delta n_s = 0$. Vertical arrows indicate location of the critical points. The inset in (c) shows the critical electron density n_c vs magnetic field (Ref. 11) for sample 1. The tilted arrows indicate filling factors for the major features.

The measured threshold electric field is much smaller than the classical estimate $m\omega^2 a_0$ (here ω is the pinning frequency; a_0 is the lattice constant).[37] In experiments[5,35] E_t was found to vanish as

$$E_t \propto (n_c - n_s)^{1.5-1.7} \quad (1)$$

in agreement with the theoretically predicted $\frac{3}{2}$ power law, which is based on the idea that transport is due to the creation of dislocation pairs through quantum tunneling.[12] The basic idea of this picture can be understood as follows. There is an energy barrier Δ to create a dislocation pair in the solid phase. Associated with this barrier there is a decay (tunneling) length of the order of $d \approx \sqrt{\hbar^2/2m^*\Delta}$ where m^* is the effective mass for the relative motion of the dislocation pairs. In the presence of an external electric field, if the energy gained within the tunneling length is equal to Δ, the dislocation pair will be created and tunneling will occur. This thus provides for an estimate $E_t d \propto \Delta$. Since $d \propto \Delta^{-0.5}$, and $\Delta \propto \delta n_s$, thus $E_t \propto (\delta n_s)^{1.5}$. Experimentally, E_t drops discontinuously to zero at the transition. This can be interpreted to correspond to a discontinuous change in Δ, consistent with a first-order transition.

A more detailed consideration of the depinning[12] shows that the pinning frequency also comes into the picture. As we showed[20] for parameters corresponding to the experimental systems the pinning frequency is dominated by the compressibility. Near the solid-liquid transition, the shear mode may go soft. However, the compressibility does not change much. Thus the effect on the threshold field will be small. On the other hand, in the presence of a *strong magnetic field*, the low-lying magnetophonon mode affects both the shear and the longitudinal elastic response function.[38] In that case the threshold behavior of the depinning field is not governed solely by the gap and different threshold behavior has indeed been observed experimentally.[39]

We close with a more detailed discussion of the energy barrier Δ. The energy of a dislocation pair $E_p(r)$ a distance r apart is of the order of $E_{ec} - E_h + C\ln(r)$ where E_{ec} is classical core energy, E_h is the hybridization energy,[18] C is a sum from an elastic and a quantum zero-point correction.[19] The melting transition is expected to occur when the smallest value of $E_p(r)$ becomes negative. In the presence of impurities, the strain field of a dislocation is of finite range equal to $r_m = s/\omega$, the electron crystal sound velocity divided by the pinning frequency. The barrier Δ is an average of E_p over distances up to the tunneling length d. When the transition is approached, the threshold electric field decreases and d increases. We expect Δ to approach the minimum $E_p(r)$ and thus is indeed related to the melting transition.

In summary, we performed precise measurements of the threshold electric-field conduction at the collective insulating transition in the 2D electron system at zero and nonzero magnetic fields. The threshold electric field was found to begin in a steplike fashion at the critical electron density. The step magnitude $E_t \sim 100$ μV/cm was below the resolution of previous measurements. These data indicate a weak first-order phase transition occurs at the electron-liquid-to-solid critical boundary.

This work has been supported by grants from the Russian Foundation for Fundamental Research, and by the "Nederlandse Organisatie voor Wetenschappelijk Onderzoek (N.W.O)." One of the authors (V.M.P.) acknowledges hospitality and support from the High Field Magnet Laboratory, University of Nijmegen, and University of Groningen.

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[1] For a review see *Physics of the 2D Quantum Electron Solid*, edited by S.-T. Chui (International, Cambridge, MA, 1993).
[2] M. D'Iorio, V. M. Pudalov, and S. G. Semenchinsky, Phys. Lett. A **150**, 422 (1990).
[3] S. V. Kravchenko, J. A. A. J. Perenboom, and V. M. Pudalov, Phys. Rev. B **44**, 13 513 (1991).
[4] M. D'Iorio, V. M. Pudalov, and S. G. Semenchinsky, Phys. Rev. B **46**, 15 992 (1992).
[5] V. M. Pudalov, M. D'Iorio, S. V. Kravchenko, and J. W. Campbell, Phys. Rev. Lett. **70**, 1866 (1993).
[6] E. Y. Andrei, G. Deville, D. C. Glattli, and F. I. B. Williams, Phys. Rev. Lett. **60**, 2765 (1988).
[7] R. L. Willett, H. L. Stormer, and D. C. Tsui, Phys. Rev. B **38**, 7881 (1988).
[8] R. L. Willett, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, K. West, and K. W. Baldwin, Phys. Rev. B **38**, 7881 (1989).
[9] V. J. Goldman, M. Santos, M. Shayegan, and J. E. Cunningham, Phys. Rev. Lett. **65**, 2189 (1990).
[10] H. W. Jiang, R. L. Willett, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. West, Phys. Rev. Lett. **65**, 633 (1990).
[11] V. M. Pudalov (unpublished).
[12] S. T. Chui, Phys. Lett. A **180**, 149 (1993).
[13] S. T. Chui and K. Esfarjani, Phys. Rev. B **44**, 11 498 (1991); **45**, 11 441 (1992).
[14] K. Esfarjani and S. T. Chui, Phys. Rev. B **42**, 10 758 (1990).
[15] K. Esfarjani and S. T. Chui, J. Phys. Condens. Matter **3**, 5825 (1991).
[16] S. T. Chui, Europhys. Lett. **20**, 535 (1992).
[17] S. T. Chui and K. Esfarjani, Phys. Rev. Lett. **66**, 652 (1991).
[18] K. Esfarjani, S. T. Chui, and X. Qiu, Phys. Rev. B **46**, 4638 (1992).
[19] S. T. Chui and K. Esfarjani, Europhys. Lett. **14**, 361 (1991).
[20] S. T. Chui, J. Phys. Condens. Matter **5**, L405 (1993).
[21] D. Levesque, J. J. Weis, and A. H. MacDonald, Phys. Rev. B **30**, 1056 (1984).
[22] P. K. Lam and S. M. Girvin, Phys. Rev. B **30**, 473 (1984).
[23] X. Zhu and S. G. Louie, Phys. Rev. Lett. **70**, 335 (1993).
[24] R. Price, P. M. Platzman, and S. He, Phys. Rev. Lett. **70**, 339 (1993).
[25] S.-T. Chui and B. Tanatar, Bull. Am. Phys. Soc. **38**, 472 (1993).
[26] R. Morf, Phys. Rev. Lett. **43**, 931 (1979).
[27] G. Deville *et al.*, Phys. Rev. Lett. **53**, 588 (1984).
[28] J. M. Kosterlitz and D. Thouless, J. Phys. C **6**, 1181 (1973).

[29] D. Nelson and B. I. Halperin, Phys. Rev. B **19**, 2457 (1979).
[30] A. P. Young, Phys. Rev. B **19**, 1855 (1979).
[31] S. T. Chui, Phys. Rev. B **28**, 178 (1983).
[32] For a review see I. Lyuksyutov, A. G. Naumovets, and V. L. Pokrovsky, *Two-Dimensional Crystals* (Academic, New York, 1992) [Russian edition: *Dvumernye Cristalli* (Naukova dumka, Kiev, 1988)].
[33] M. Kawaguchi and M. Saitoh, Solid State Commun. **88**, 765 (1993).
[34] B. Tanatar and D. M. Ceperley, Phys. Rev. B **39**, 5005 (1989).
[35] V. M. Pudalov, M. D'Iorio, and J. W. Campbell, in Proceedings of the International Conference on Low Temperature Physics, Eugene, 1993 [Physica B (to be published)].
[36] B. G. A. Normand, P. B. Littlewood, and A. J. Millis, Phys. Rev. B **46**, 3920 (1992).
[37] H. Fukuyama and P. A. Lee, Phys. Rev. B **17**, 535 (1978).
[38] K. Esfarjani and S. T. Chui, Solid State Commun. **79**, 387 (1991).
[39] Y. P. Li, T. Sajoto, L. W. Engel, D. C. Tsui, and M. Shayegan, Phys. Rev. Lett. **67**, 1633 (1991).