PHYSICAL REVIEW B VOLUME 49, NUMBER 3 15 JANUARY 1994-I

Hall insulator in a two-dimensional electron system in silicon in the extreme quantum limit

S. V. Kravchenko and J. E. Furneaux
Laboratory for Electronic Properties of Materials and Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73019

V. M. Pudalov
Institute for High Pressure Physics, Troitsk, 142092 Moscow District, Russia

(Received 30 August 1993)

We report diagonal- and Hall resistance measurements of the localized two-dimensional electron system in silicon in the high-field extreme quantum limit. The Hall resistance has been found to be almost independent of temperature and close to its classical value, B/n_sec, while the diagonal resistivity diverges at $T \rightarrow 0$. There is no evidence for nonlocal resistance due to special conductivity paths. These results support existence of the recently predicted Hall insulator state in silicon in a high magnetic field.

A new insulating state for two-dimensional (2D) electron systems was predicted recently: the Hall insulator.[1,2] In this state, both diagonal and Hall conductivities, σ_{xx} and σ_{xy}, tend to zero with decreasing temperature such that $\sigma_{xy} \propto \sigma_{xx}^2$. This gives a diverging diagonal resistivity $\rho_{xx} \rightarrow \infty$ and a *finite* Hall resistivity ρ_{xy} close to its classical value B/n_sec (here B is the magnetic field, n_s is electron density, e is the electron charge, and c is the speed of light). Therefore, this state differs qualitatively from a Mott insulator, in which both ρ_{xx} and ρ_{xy} tend to infinity as $T \rightarrow 0$. According to the global phase diagram for the metal/insulator (M/I) transition proposed in Ref. 2, this behavior is generic for transitions into an insulating state involving 2D systems, exhibiting the quantized Hall effect (QHE). For GaAs/Al$_x$Ga$_{1-x}$As heterojunctions, the Hall insulator state is expected for Landau level filling factor $\nu = n_sch/eB$ around 1/5 for high mobility samples or for ν around 1/3 for samples with lower mobility. For the even more disordered 2D systems in silicon, exhibiting no fractional quantum Hall effect, the transition to the Hall insulator state is expected for filling factors below $\nu = 1$.

Experimental data on GaAs/Al$_x$Ga$_{1-x}$As confirmed that the Hall resistance remains nearly equal to its classical value in the insulating states around $\nu = 1/7$,[3] below $\nu = 1/3$,[4] and around $\nu = 1/5$ (Ref. 5) (the data in Ref. 3 had been obtained before the theory[1,2] appeared). Results are in a good agreement with predictions of theory;[2] however, it was pointed out[4,5] that a finite Hall resistance is also characteristic of transport in the presence of a pinned Wigner solid previously reported for the same conditions (see, e.g., Refs. 6–8). For the 2D system in silicon, the Hall resistance has been studied in low magnetic fields,[9,10] in the presence of a reentrant insulating state. This insulating state is also likely to be caused by the strong Coulomb interaction and was well explained in terms of the formation of a pinned electron solid (Ref. 11, and references therein). In fact, the M/I phase diagram experimentally found in Ref. 10 is inconsistent with the predictions of Ref. 2 and with the picture for QHE/insulator transitions suggested by scaling theory[12] for noninteracting electrons. Therefore, the classical value of the Hall resistance observed in Ref. 10 was explained in terms of dislocation motion within the electron solid.

For these reasons, we concentrate here on the experimental verification of the relatively firm theoretical predictions for the transition from the lowest integer QHE state to an insulator, which occurs with increasing magnetic field. An experimental study of ρ_{xy} and ρ_{xx} for the 2D electron system in high-mobility silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) leads to a confirmation of the Hall insulator state. This study was made well outside the reentrant insulating phase, in the high B extreme quantum limit, where the existence of the electron solid is doubtful even at low temperatures[13] and can be excluded at higher T. We used two Si MOSFET's from different wafers with peak mobilities of 3.1×10^4 cm^2/Vs (Si-1) and 1.9×10^4 cm^2/Vs (Si-2). Both samples have Hall bar geometry and dimensions 5×0.8 mm^2, as shown in the inset to Fig. 1. The four-terminal dc transport measurements were carried out with a high input impedance DVM. Magnetic fields were produced by a Ni$_3$Sn superconducting magnet. Low temperatures were obtained with a dilution refrigerator and measured using a calibrated ruthenium oxide thermometer which has insignificant magnetoresistance (< 1%).

Figure 1 shows a typical dependence of ρ_{xx} and ρ_{xy} on electron density, n_s, in the high magnetic field limit (at Landau level filling factor $\nu < 1$). The data at $n_s \gtrsim 2.20 \times 10^{11}$ cm^{-2} are at the edge of the $\nu = 1$ Hall plateau with $\rho_{xx} = 0$ within our experimental accuracy. When electron density is lowered, ρ_{xx} increases approximately exponentially to about 1 MΩ while ρ_{xy} remains at approximately its classical value, B/n_sec (dashed curve). We were unable to take data at $n_s < 1.78 \times 10^{11}$ cm^{-2} because contact resistance became very high resulting in large noise and irreproducible measurements.

The temperature dependence for both components of the resistivity tensor at two different electron densities

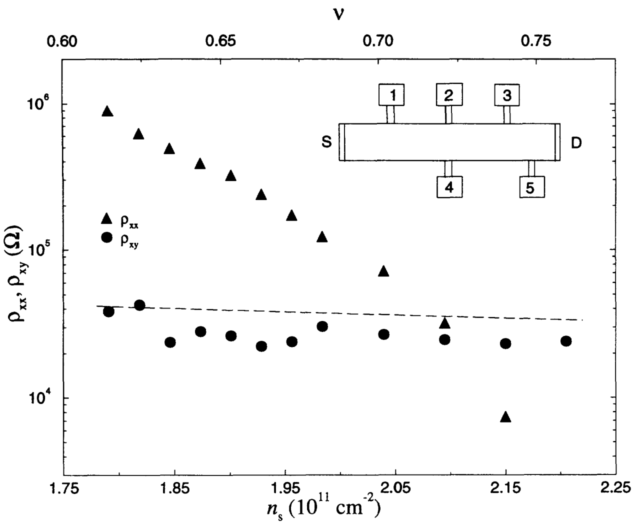

FIG. 1. Diagonal and Hall resistivities vs electron density and filling factor at T = 190 mK and B = 12 T for Si-2. The dashed curve corresponds to the calculated classical Hall resistivity for free electrons. The inset shows a view of the sample.

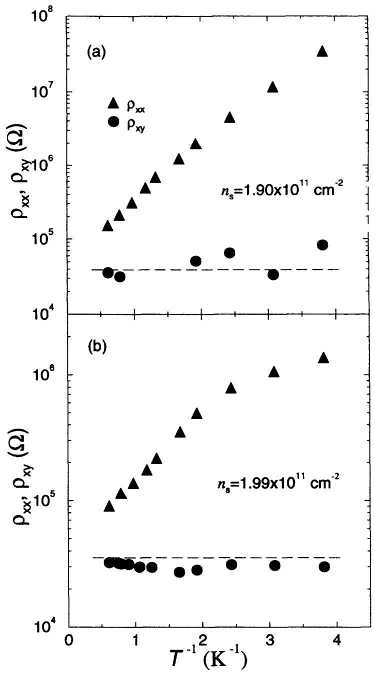

FIG. 2. Temperature dependencies of the diagonal and Hall resistivities for Si-1 at $n_s = 1.90 \times 10^{11}$ cm^{-2}, $\nu = 0.66$ (a) and 1.99×10^{11} cm^{-2}, $\nu = 0.69$ (b) at $B = 12$ T. Dashed lines show the classical Hall resistivities.

is shown in Fig. 2. Again, ρ_{xy} remains nearly constant while ρ_{xx} increases exponentially as the temperature is lowered [at $T \sim$ 500 mK, the slope of $\rho_{xx}(T)$ changes; this effect was previously observed in Ref. 14 and explained there as a possible sign of Wigner crystallization]. The deviations of ρ_{xy} from its classical value, especially pronounced in Fig. 2(a), were irreproducible. These deviations are probably caused by increasing contact noise mentioned above. High contact resistance made it impossible to perform measurements at lower temperatures.

At low temperatures we observe that transport in the insulating phase in the extreme quantum limit is strongly nonlinear similar to measurements reported in Ref. 13; therefore, all the measurements reported here were carried out in the linear regime with electric fields below the nonlinearity threshold. To eliminate the admixture of the diagonal voltage into the Hall voltage, we extracted the antisymmetric contribution from measurements taken in two opposite magnetic field directions.

To measure diagonal and Hall resistances, we used standard geometry applying the current between the contacts S and D (see inset to Fig. 1) and measuring diagonal voltages V_{1-2} or V_{2-3} and Hall voltage V_{2-4}. In principle, in high-quality Si MOSFET's at low temperature and in high magnetic field, nonlocal effects, such as conduction by edge currents, could be significant.[15] This would make it hard to obtain *local* resistivities. Edge currents are not expected to be significant in the regime where $\rho_{xx} \gg \rho_{xy}$.[5] To confirm the insignificance of edge states or other special paths, we applied current between contacts 2 and 4 and measured diagonal voltages V_{1-S}, V_{3-D}, or V_{5-D}. Each of these voltages was consistent with the expectations of a constant resistivity within the sample being less than 1% of typical V_{1-2} values obtained in the standard geometry. Furthermore, the ratios, e.g., between V_{1-S} and V_{1-2}, did not depend on temperature whereas nonlocal conductivity caused by edge currents is known[15] to be extremely temperature sensitive. These measurements demonstrate that the transport is characterized by the resistivity tensor without modifications due to large scale special conductivity channels.

The observed independence of the Hall resistance on temperature and the observed consistency with the classical value in the extreme quantum limit insulator region are consistent with theoretical predictions[1,2] for the Hall insulator. Our results agree also with the global phase diagram proposed for this state in Ref. 2: We see that in our MOSFET's, where the 2D systems have a relatively large disorder potential, the transition to the Hall insulator state proceeds directly from the $\nu = 1$ quantum Hall liquid with increasing magnetic field. (In contrast, a less disordered 2D system is predicted to display a reentrant Hall insulator behavior.) Considering a second possible state of 2D electrons in the extreme quantum limit, an electron solid, we should note that at temperatures below $\sim$ 300 mK, transport properties of the insulating phase in Si MOSFET's in the limit studied here were found[13] to be essentially the same as those in GaAs/Al$_x$Ga$_{1-x}$As heterostructures around $\nu = 1/5$ (Refs. 7 and 8) or in Si MOSFET's in zero[16] and low[9–11] magnetic field. The similarity of transport properties may imply the same ground state for the electrons. The Hall resistance for electron solids seems to be dependent on the particular transport model. It can diverge with lowering temperature[2] if transport is due to activated point defect motion. It can remain close to the classical value if transport is due to the sliding of the electron solid as a whole[4,9], if transport occurs in a polycrystalline state,[4] or if it is due to dislocation motion within the electron solid.[10] At present we cannot make definite conclusions about the microscopic picture of the insulating state with finite Hall resistance at $\nu < 1$ in Si at *low* temperatures. However, at higher temperatures, there is no experimental evidence (such as strongly nonlinear *I-V* characteristics with low threshold voltage) for electron solid formation in Si MOSFET's in the extreme quantum limit. Moreover, estimates for the melting temperature of the electron solid (if any) in Si MOSFET's at infinite magnetic field[17] give $T_m \sim e^2(\pi n_s)^{1/2}/\Gamma_m k_B \epsilon \sim 900$ mK for $n_s \sim 10^{11}$ cm^{-2} [here ϵ is the dielectric constant and $\Gamma_m = 127 \pm 3$ (Ref. 6)]. This sets an upper limit for solid formation at T_m.

In summary, we have experimentally shown that in the extreme quantum limit, the Hall resistance of a two-dimensional electron gas of Si MOSFET's remains independent of temperature and close to its classical value even when ρ_{xx} reaches $\sim 10^8$ Ω. At temperatures below ~ 300 mK, both transport within pinned Wigner solid[4,5,9,10] and a Hall insulator state[1,2] could be responsible for the observed constancy of ρ_{xy} and diverging ρ_{xx}. At higher temperatures, where formation of an electron solid may be excluded, our data indicate development of the insulating state in accordance with the Hall insulator state predicted in Refs. 1 and 2.

We acknowledge useful discussions with Bruce Mason, Ryan Doezema, and George Kravchenko, and experimental assistance from Alison Japikse and Jason Dotter. This work was supported by grants from the National Science Foundation, No. DMR 89-22222 and Oklahoma EPSCoR via LEPM.

---

[1] O. Viehweger and K. B. Efetov, J. Phys. Condens. Mater. **2**, 7049 (1990).

[2] S. Kivelson, D.-H. Lee, and S.-C. Zhang, Phys. Rev. B **46**, 2223 (1992).

[3] V. J. Goldman, M. Shayegan, and D. C. Tsui, Phys. Rev. Lett. **61**, 881 (1988); J. Wakabayashi *et al.*, J. Phys. Soc. Jpn. **57**, 3678 (1988).

[4] S. I. Dorozhkin, A. A. Shashkin, G. V. Kravchenko, V. T. Dolgopolov, R. J. Haug, K. von Klitzing, and K. Ploog, Pis'ma Zh. Eksp. Teor. Fiz. **57**, 55 (1993) [JETP Lett. **57**, 58 (1993)].

[5] V. J. Goldman, J. K. Wang, Bo Su, and M. Shayegan, Phys. Rev. Lett. **70**, 647 (1993).

[6] D. C. Glattli, G. Deville, V. Duburcq, F. I. B. Williams, E. Paris, B. Etienne, and E. Y. Andrei, Surf. Sci. **229**, 344 (1990).

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

[8] H. W. Jiang, H. L. Stormer, D. C. Tsui, L. N. Pfeiffer, and K. W. West, Phys. Rev. B **44**, 8107 (1991).

[9] S. V. Kravchenko, J. A. A. J. Perenboom, and V. M. Pudalov, Phys. Rev. B **44**, 13 513 (1991).

[10] V. M. Pudalov, M. D'Iorio, and J.W. Campbell, Pis'ma Zh. Eksp. Teor. Fiz. **57**, 592 (1993) [JETP Lett. **57**, 608 (1993)].

[11] M. D'Iorio, V. M. Pudalov, and S. G. Semenchinsky, Phys. Rev. B **46**, 15 992 (1992).

[12] D. E. Khmelnitskii, Phys. Lett. A **106**, 182 (1984).

[13] V. T. Dolgopolov, G. V. Kravchenko, A. A. Shashkin, and S. V. Kravchenko, Phys. Rev. B **46**, 13 303 (1992).

[14] S. Kawaji and J. Wakabayashi, Solid State Commun. **22**, 87 (1977).

[15] P. L. McEuen, A. Szafer, C. A. Richter, B. W. Alphenaar, J. K. Jain, A. D. Stone, R. G. Wheeler, and R. N. Sacks, Phys. Rev. Lett. **64**, 2062 (1990).

[16] V. M. Pudalov, M. D'Iorio, S. V. Kravchenko, and J. W. Campbell, Phys. Rev. Lett. **70**, 1866 (1993).

[17] H. Fukuyama and D. Yoshioka, J. Phys. Soc. Jpn. **48**, 1853 (1980).