PHYSICAL REVIEW B VOLUME 57, NUMBER 16 15 APRIL 1998-II

H/T scaling of the magnetoconductance near the conductor-insulator transition in two dimensions

D. Simonian, S. V. Kravchenko, and M. P. Sarachik
City College of the City University of New York, New York, New York 10031

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

(Received 12 January 1998)

For an electron density near the $H=0$ insulator-to-conductor transition, the magnetoconductivity of the low-temperature conducting phase in high-mobility silicon MOSFETs is consistent with the form $\Delta\sigma(H_{||},T)\equiv\sigma(H_{||},T)-\sigma(0,T)=f(H_{||}/T)$ for magnetic fields $H_{||}$ applied parallel to the plane of the electron system. This sets a valuable constraint on theory and provides further evidence that the electron spin is central to the anomalous $H=0$ conducting phase in two dimensions. [S0163-1829(98)52516-7]

Recent experiments[1,2] have demonstrated that the anomalous conducting phase[3] found in the absence of a magnetic field in two-dimensional electron systems in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) is strongly suppressed by an in-plane magnetic field, $H_{||}$. For electron densities near the $H=0$ transition (i.e., for $\delta n \equiv (n_s-n_c)/n_c \ll 1$, $n_c \sim 10^{11}$ cm^{-2}), an external parallel field as low as $H_{||}\sim 4$ kOe causes an increase in the resistivity, changing the sign of $d\rho(T)/dT$ at low temperatures from positive (metallic) to negative (insulating behavior); the resistivity saturates to a constant value for fields $H_{||}$ above $\sim$20 kOe, indicating that the conducting phase has been entirely quenched. We have shown further[4] that a magnetic field suppresses the conducting phase independently of the angle of application with respect to the two-dimensional (2D) electron layer. The total magnetoconductance is the superposition of this term and orbital effects associated with the perpendicular component of the field which give quantum Hall oscillations.[5]

The unexpected conducting phase in two dimensions in the absence of a magnetic field has been observed recently for holes in SiGe quantum wells[7] and GaAs/Al$_x$Ga$_{1-x}$As heterostructures.[8–10] Although considerably smaller, a negative magnetoconductance (positive magnetoresistance) (Refs. 10 and 11) found in these systems has also been attributed to the suppression of the conducting phase. In MOSFETs, as in other systems where a conducting phase has been observed at low temperatures in the absence of a field, estimates[3,7–10] indicate that the energy of interactions between carriers is much larger than the Fermi energy in the range of carrier densities where the conducting state exists.

An in-plane magnetic field affects the spins of the electrons only, and has no effect on their orbital motion. The quenching of the conducting phase by a magnetic field applied parallel to the plane of the electrons thus provides strong indication that the electrons' spins play a central role in the anomalous conducting phase in these two-dimensional systems. We now demonstrate that near the metal-insulator transition, the magnetoconductivity of the $H=0$ conducting phase in high-mobility dilute silicon MOSFETs scales with H/T, obeying the form

$$\Delta\sigma(H_{||},T)\equiv\sigma(H_{||},T)-\sigma(0,T)=f(H_{||}/T). \qquad (1)$$

The maximum mobility of the sample used in these experiments was $\mu^{max}_{T=4.2\text{ K}}\approx 25\,000$ cm^2/Vs. The conductivity was measured in magnetic fields up to 15 kOe applied parallel to the plane of the electrons.

Measurements were taken between 0.25 and 0.9 K with the sample immersed in the ^{3}He-^{4}He mixing chamber of a dilution refrigerator. The electron density was set by the gate voltage at $n_s=9.43\times10^{10}$ cm^{-2}, placing the sample on the conducting side and near the conductor-to-insulator transition ($n_c=8.57\times10^{10}$ cm^{-2}). In the absence of a magnetic field, the resistance was 13.9 kOhm at the lowest measured temperature, $T=0.25$ K.

The magnetoconductivity, $\Delta\sigma(H_{||},T)=\sigma(H_{||},T)-\sigma(0,T)$, is shown in Fig. 1 as a function of temperature for various fixed values of parallel magnetic field. The magnetoconductance is negative, its magnitude increasing with applied field and with decreasing temperature. The noise for small $H_{||}$ derives from the subtraction of two large (and comparable) quantities, $\sigma(H_{||},T)$ and $\sigma(0,T)$. The inset to Fig. 1 shows the magnetoconductivity relative to its zero-field value, $\sigma(0)$, as a function of $H_{||}$ at a temperature of 0.25 K. The magnetoconductance decreases rapidly and begins to saturate above $\sim$13 kOe, consistent with earlier measurements.[1,2] The data for $\Delta\sigma$ can be collapsed onto a single curve by applying a different multiplicative factor to the abscissa for each curve, as illustrated in Fig. 2. The scaling parameter T_0 is plotted in the inset as a function of the Zeeman energy, $g\mu_B H_{||}/k_B$ (in Kelvin). Here g is the g factor (equal to 2 in Si MOSFETs), μ_B is the Bohr magneton, and k_B is the Boltzmann constant. A power-law fit (shown by the solid curve) yields $T_0 \propto H_{||}^{\alpha}$, with $\alpha=0.88\pm0.03$. We note that H/T scaling of the form Eq. (1) requires that $\alpha=1$, corresponding to $T_0=g\mu_B H_{||}/k_B$ (indicated in the inset by the dotted line). We suggest that the deviation of α from unity is associated with the saturation of the magnetoconductance at $H_{||}\gtrsim 13$ kOe shown in the inset to Fig. 1, where one might well expect the scaling to break down. We therefore exclude the data sets at the three largest

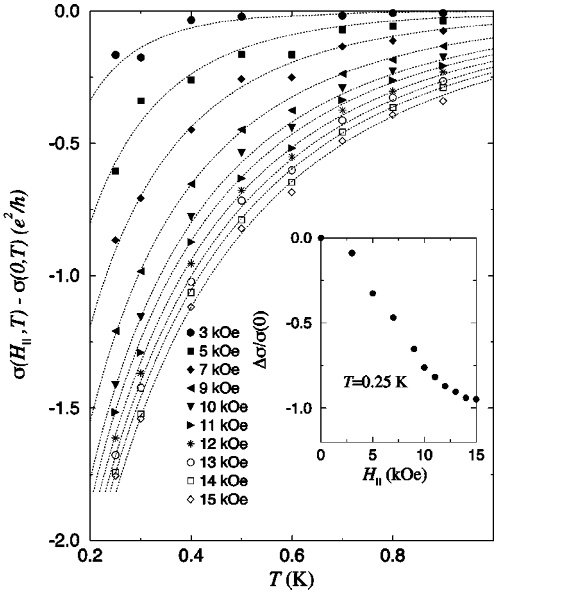

FIG. 1. Magnetoconductivity $\Delta\sigma(H_{\parallel},T)\equiv\sigma(H_{\parallel},T)-\sigma(0,T)$ vs temperature T for several magnetic fields $H_{\parallel}$ applied parallel to the plane of the electrons. The sample is in the conducting phase with an electron density $\delta=(n_s-n_c)/n_c=0.10$. The dotted lines are guides to the eye. The inset shows the magnetoconductivity at $T=0.25$ K relative to its value at $H=0$; $\sigma(0)=0.54e^2/h$. Note the rapid change of $\Delta\sigma/\sigma(0)$ followed by saturation above ≈ 13 kOe.

fields (for which the proximity of the scaling parameter T_0 to saturation is apparent). For in-plane fields in the range $H_{\parallel}=5$–12 kOe, the absolute value of magnetoconductance, $|\Delta\sigma(H_{\parallel})|$, is shown as a function of $(g\mu_B H_{\parallel}/k_B T)^2$ in Fig. 3. For this range of magnetic fields and for an electron

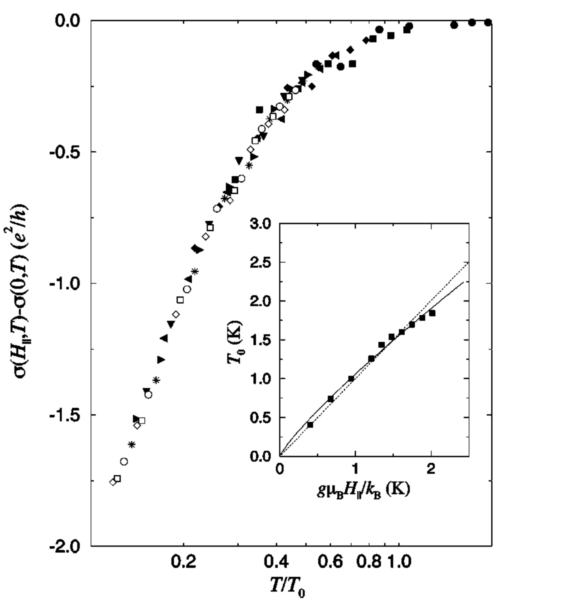

FIG. 2. The magnetoconductance $\Delta\sigma$ as a function of T/T_0. The inset shows the scaling parameter T_0 plotted as a function of $g\mu_B H_{\parallel}/k_B$ (symbols for different fields, $H_{\parallel}$, are the same as in Fig. 1). A power-law fit, shown by the solid curve, yields $T_0\propto H_{\parallel}^{\alpha}$ with $\alpha=0.88\pm0.03$. The dotted straight line corresponds to $T_0=g\mu_B H_{\parallel}/k_B$; deviations from straight-line behavior are attributed to saturation at high fields.

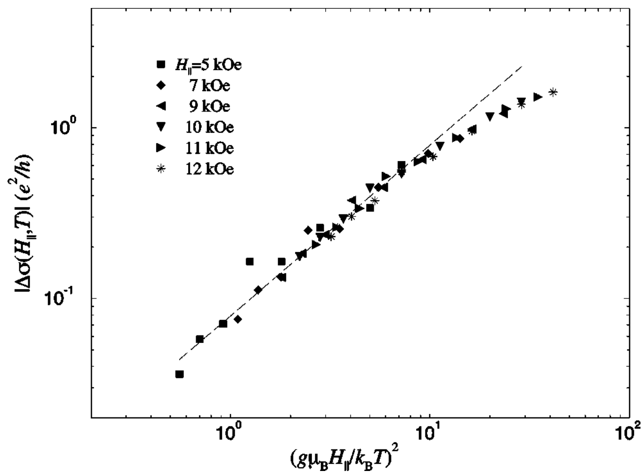

FIG. 3. Magnetoconductance $\Delta\sigma(H_{\parallel},T)$ vs $(g\mu_B H_{\parallel}/k_B T)^2$ on a logarithmic scale for $H_{\parallel}=5-12$ kOe (see the text). The dashed line is a fit to Eq. (7) in Ref. 22, $\Delta\sigma(H,T)=-[0.084e^2/(\pi h)]\gamma_2(\gamma_2+1)(g\mu_B H/k_B T)^2$; $\gamma_2=1.3$.

density fairly close to the critical density, the magnetoconductance scales well with $H_{\parallel}/T$. We note that preliminary experiments indicate deviations from H/T scaling for higher electron densities.[12]

Based on quite general arguments, Sachdev[13] showed that the conductivity near a second-order quantum phase transition is a universal function of H/T for a system with conserved total spin. If the magnetoconductance of our silicon MOSFET does indeed scale with H/T (the dotted straight line in the inset to Fig. 2) rather than H/T^{α} with $\alpha\neq 1$ (the solid curve), this would imply that spin-orbit effects are relatively unimportant near the transition. For a weakly interacting 2D system, Lee and Ramakrishnan[14,15] obtained scaling of the form Eq. (1) associated with the negative $|S_z|=1$ triplet channel contribution to the conductance. We note that the scaling reported here for the 2D system in silicon MOSFETs is remarkably similar[16] to the H/T scaling of the magnetoconductance observed by Bogdanovich *et al.*[17] in three-dimensional Si:B near the metal-insulator transition, where it was attributed to the mechanism of Ref. 15. H/T scaling is also expected within theories that predict various types of superconductivity in a strongly interacting system in two dimensions.[18–20]

Extending earlier work of Finkel'shtein,[21] who showed that a disordered, weakly interacting 2D system can scale toward a metallic phase, Castellani *et al.*[22] have obtained a magnetoconductance $\Delta\sigma(H,T)=-[0.084e^2/(\pi h)]\gamma_2(\gamma_2+1)(g\mu_B H/k_B T)^2$. The coupling constant γ_2 is expected to vary with temperature in the range of validity of the calculation, namely, in the metallic phase and not too close to the critical density. Our observation of simple H/T scaling for a relative density $\delta_n\ll 1$ implies that γ_2 is at most a weakly temperature-dependent quantity near the transition. The fit to the form suggested in Ref. 22 is shown by the dashed line in Fig. 3, and yields $\gamma_2\approx 1.3$, corresponding to intermediate coupling strength.[23] It is interesting that evidence of enhanced conductivity can be seen in ealier measurements by Bishop, Dynes, and Tsui[24] who found an unusually large negative low-temperature magnetoconductance due to electron correlations in silicon MOSFETs with electron densities an order of magnitude above the transition.

To summarize, we have observed scaling of the magnetoconductivity of the form $\Delta\sigma(H_{||},T)=f(H_{||}/T)$ in the anomalous conducting phase of a two-dimensional system of electrons for electron densities near the conductor-to-insulator transition. Our finding of H/T scaling sets a valuable constraint on theories.[18–22,25]

We are grateful to Lenny Tevlin and Subir Sachdev for independently suggesting the scaling analysis presented in this work. We thank D. Belitz, J. L. Birman, Song He, D. I. Khomskii, P. A. Lee, P. Phillips, T. M. Rice, T. V. Ramakrishnan, F. C. Zhang, and S. He for valuable discussions. This work was supported by the U.S. Department of Energy under Grant No. DE-FG02-84ER45153. V.P. was supported by RFBR(97-02-17387) and by INTAS.

[1] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. **79**, 2304 (1997).

[2] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, Pis'ma Zh. Eksp. Teor. Fiz. **65**, 932 (1997) [JETP Lett. **65**, 932 (1997)].

[3] S. V. Kravchenko, G. V. Kravchenko, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, Phys. Rev. B **50**, 8039 (1994); S. V. Kravchenko, W. E. Mason, G. E. Bowker, J. E. Furneaux, V. M. Pudalov, and M. D'Iorio, *ibid.* **51,** 7038 (1995).

[4] S. V. Kravchenko, D. Simonian, M. P. Sarachik, A. D. Kent, and V. M. Pudalov, cond-mat/9709255 (unpublished).

[5] The response to a perpendicular field is considerably more complicated and has been studied by the authors of Refs. 2, 4, and 6.

[6] D. Popović, A. B. Fowler, and S. Washburn, Phys. Rev. Lett. **79**, 1543 (1997).

[7] P. T. Coleridge, R. L. Williams, Y. Feng, and P. Zawadzki, Phys. Rev. B **56**, R12 764 (1997).

[8] M. Y. Simmons, A. R. Hamilton, T. G. Griffiths, A. K. Savchenko, M. Pepper, and D. A. Ritchie, cond-mat/9710111, Physica B (to be published).

[9] Y. Hanein, U. Meirav, D. Shahar, C. C. Li, D. C. Tsui, and H. Shtrikman, Phys. Rev. Lett. **80**, 1288 (1998).

[10] M. Y. Simmons, A. R. Hamilton, M. Pepepr, E. H. Linfield, P. D. Rose, and D. A. Ritchie, Phys. Rev. Lett. **80**, 1292 (1998).

[11] P. T. Coleridge (private communication).

[12] V. M. Pudalov (private communication).

[13] S. Sachdev, Z. Phys. B **94**, 469 (1994).

[14] P. A. Lee and T. V. Ramakrishnan, Rev. Mod. Phys. **57**, 287 (1985).

[15] P. A. Lee and T. V. Ramakrishnan, Phys. Rev. B **26**, 4009 (1982).

[16] Similarities between the two systems were pointed out in Ref. 6.

[17] Snezana Bogdanovich, Peihua Dai, M. P. Sarachik, and V. Dobrosavljević, Phys. Rev. Lett. **74**, 2543 (1995).

[18] D. Belitz and T. R. Kirkpatrick, cond-mat/9705023 (unpublished).

[19] P. Phillips, Y. Wan, I. Martin, S. Knysh, and D. Dalidovich, cond-mat/9709168 (unpublished).

[20] F. C. Zhang and T. M. Rice, cond-mat/9708050 (unpublished); see also Y. Ren and F. C. Zhang, Phys. Rev. B **49**, 1532 (1994).

[21] A. M. Finkel'shtein Zh. Eksp. Teor. Fiz. **84**, 168 (1983) [Sov. Phys. JETP **57**, 97 (1983)]; Z. Phys. B **56**, 189 (1984).

[22] C. Castellani, C. DiCastro, and P. A. Lee, Phys. Rev. B **57**, R9381 (1998).

[23] P. A. Lee (private communication).

[24] D. J. Bishop, R. C. Dynes, and D. C. Tsui, Phys. Rev. B **26**, 773 (1982).

[25] S. He and X. C. Xie, cond-mat/9711195, Phys. Rev. Lett. (to be published).