

Spin polarization of strongly interacting two-dimensional electrons: The role of disorder

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(Received 25 February 2002; revised manuscript received 10 April 2002; published 20 May 2002)

In high-mobility silicon metal-oxide-semiconductor field-effect transistors, the g^*m^* inferred indirectly from magnetoconductance and magnetoresistance measurements with the assumption that $g^*\mu_B H_s = 2E_F$ are in surprisingly good agreement with g^*m^* obtained by direct measurement of Shubnikov-de Haas oscillations. The enhanced susceptibility $\chi^{*\propto}(g^*m^*)$ exhibits critical behavior of the form $\chi^{*\propto}(n-n_0)^{-\alpha}$. We examine the significance of the field scale H_s derived from transport measurements, and show that this field signals the onset of full spin polarization only in the absence of disorder. Our results suggest that disorder becomes increasingly important as the electron density is reduced toward the transition.

DOI: 10.1103/PhysRevB.65.201106

PACS number(s): 71.30.+h, 73.40.Qv, 73.50.Jt

Two-dimensional (2D) systems of electrons¹⁻³ and holes⁴⁻⁶ have attracted a great deal of attention during the last few years. In contrast to expectations for noninteracting⁷ or weakly interacting⁸ electrons in two dimensions, these strongly interacting systems exhibit metallic behavior in the absence of a magnetic field: above some characteristic electron (hole) density, n_c , their resistivities decrease with decreasing temperature. Whether there is a genuine metallic phase and a true metal-insulator transition in these materials continues to be the subject of lively debate.⁹

Experimental results have been obtained in the 2D system of electrons in silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) that indicate that the response to a magnetic field applied in the plane of the electrons increases dramatically as the electron density is decreased toward n_c . Based on a study of the scaled magnetoconductance as a function of temperature and electron density, Vitkalov *et al.*¹⁰ have identified an energy scale Δ that decreases with decreasing density and extrapolates to zero in the limit $T \rightarrow 0$ at a density n_0 in the vicinity of n_c ; this was interpreted as evidence of a quantum phase transition at n_0 . From studies at very low temperatures of the magnetoresistance as a function of electron density, Shashkin *et al.*¹¹ inferred that the two-dimensional system of electrons in silicon inversion layers approaches a ferromagnetic instability at the critical density n_c for the zero-field metal-insulator transition. From a determination of the enhanced spin susceptibility derived from Shubnikov-de Haas measurements down to low densities, Pudalov *et al.*¹² have claimed there is no spontaneous spin polarization for electron densities above $n = 8.34 \times 10^{10} \text{ cm}^{-2} \approx n_c$, although they could not exclude this for lower densities. The possibility that a magnetically ordered phase exists in the limit $T \rightarrow 0$ in dilute two-dimensional silicon inversion layers is intriguing and bears further investigation.

In this paper we show that there is very good agreement between values reported for g^*m^* as a function of electron density in high-mobility silicon MOSFET's obtained directly from measurements of the Shubnikov-de Haas oscillations¹² and those inferred indirectly from magnetoconductance and

magnetoresistance measurements by two different groups using different methods of analysis and the assumption that $g^*\mu_B H_s = 2E_F$.^{10,11,13} Here g^* is the enhanced g factor, m^* is the enhanced electron mass, μ_B is Boltzmann's factor, E_F is the Fermi energy, and H_s is a characteristic field scale determined by different methods from in-plane magnetoconductance¹⁰ and magnetoresistance¹¹ experiments. The enhanced susceptibility $\chi^{*\propto}(g^*m^*)$ exhibits critical behavior of the form $\chi^{*\propto}(n-n_0)^{-\alpha}$. Data from the three experimental groups yield exponents α of 0.23, 0.24, and 0.27, and critical densities between 0.88×10^{11} and $1.04 \times 10^{11} \text{ cm}^{-2}$. We examine the significance of the field scale H_s , and show that this field signals the onset of full spin polarization only in the absence of disorder. Our results suggest that disorder becomes increasingly important as the electron density is reduced toward the transition.

Measurements were taken on three silicon MOSFET's, two of which have mobilities $\mu \approx 25\,000 \text{ V}/(\text{cm}^2 \text{ s})$ and the third $\mu \approx 30\,000 \text{ V}/(\text{cm}^2 \text{ s})$ at 0.3 K. Data were obtained using standard four-terminal ac techniques on samples with split-gate geometry to 12 T at City College and in fields up to 20 T at the National Magnetic Field Laboratory. Data were taken in the linear regime down to 100 mK using small currents on the order of 1–5 nA to prevent overheating the electrons. The Hall voltage was used to align the 2D electron plane parallel to the external magnetic field with an accuracy better than 1° . The change in longitudinal conductivity due to an unintentional Hall component is $\delta\sigma/\sigma = -\rho_H^2/\rho^2$.¹⁴ For a 1° misalignment, the fractional change is less than 10^{-4} at electron density $n = 0.94 \times 10^{11} \text{ cm}^{-2}$, which is negligible.

Measurements of Shubnikov-de Haas oscillations in high-mobility silicon MOSFET's with high electron densities have shown that the magnetic field required to achieve complete polarization of the electron spins is approximately the same as that required to saturate the magnetoresistance to a constant value.¹⁵⁻¹⁷ Similar results have been reported for p -GaAs.¹⁸ For the relatively high densities used in these experiments, the field H_ρ corresponding to saturation of the magnetoresistance is approximately the same as the field H_σ above which there is apparent saturation of the magnetocon-

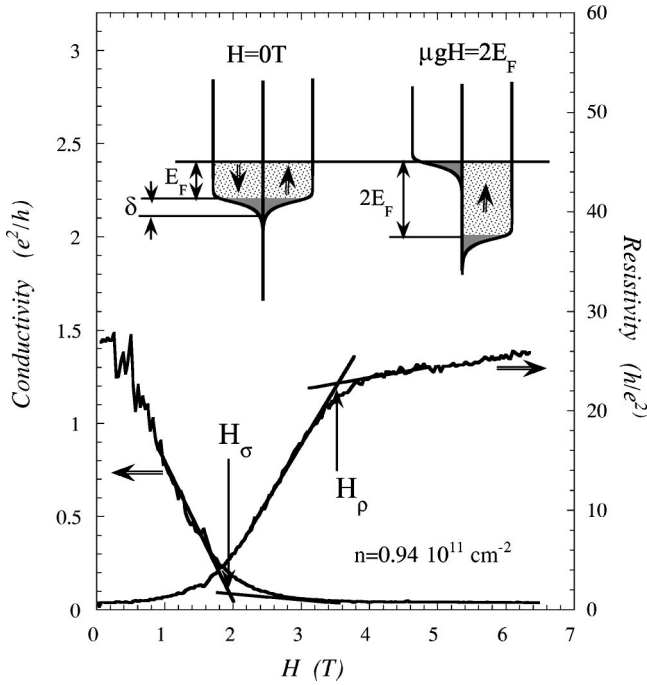


FIG. 1. For a silicon MOSFET with electron density $0.94 \times 10^{11} \text{ cm}^{-2}$, the conductivity (left curve) and resistivity (right curve) are shown as a function of in-plane magnetic field at temperature $T=0.26 \text{ K}$. The saturation fields, labeled H_ρ and H_σ , were obtained from the intersection of a line drawn through the low field data and a line drawn through the high field data, as shown. The insets show schematic diagrams of the electron bands (see text for discussion).

ductance. As we show below, this equivalence breaks down at lower densities. A clear example is illustrated in Fig. 1, where the resistivity and conductivity are shown as a function of in-plane magnetic field for a silicon MOSFET with electron density near the critical density, n_c , for the metal-insulator transition. The saturation field H_ρ derived from the resistivity is considerably larger than the field H_σ above which the conductivity saturates. This can be understood with reference to the band diagrams shown as insets to Fig. 1. In the absence of disorder, all electron states are extended, band tailing plays a negligible role, and full spin polarization is achieved when the Zeeman energy is sufficient to completely depopulate the minority spin band,

$$g^* \mu_B H_{band} = 2E_F, \quad (1)$$

where g^* is the enhanced g factor, μ_B is Boltzmann's factor, H_{band} is the magnetic field required to fully polarize the system in the absence of disorder, and E_F is the Fermi energy. Disorder is weak at high electron densities and one expects $H_{band} \approx H_\rho \approx H_\sigma$.

As the density is decreased and disorder and the band tails become more important, complete spin alignment requires the application of a larger magnetic field to fully polarize the tail states as well as the extended states,

$$g^* \mu_B H_{tail+band} = 2E_F + \delta, \quad (2)$$

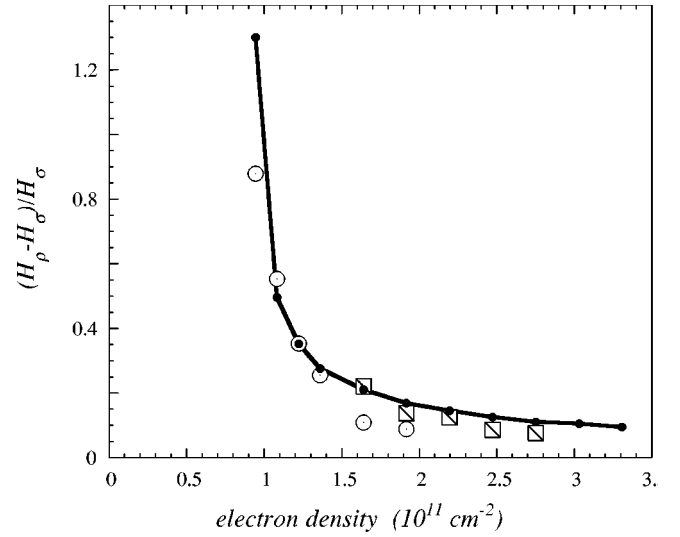


FIG. 2. The fractional difference $(H_\rho - H_\sigma)/H_\sigma$ (open symbols) and $2/\sigma$ (closed symbols) versus electron density; H_ρ and H_σ are the saturation fields deduced from resistivity and conductivity curves, respectively. The open circles and closed symbols refer to data taken at 0.26 K . The open squares are data obtained at 0.1 K on a different MOSFET.

where we have assumed the band tail has an effective energy width δ .¹⁹

Except very near the transition, the number of states in the band tails in the case of samples of reasonably high mobility is much smaller than the number of extended states; at the same time, the energy width δ becomes appreciable as the density decreases and the disorder increases. The field required to align the electrons in the higher mobility band states can thus differ substantially from the magnetic field needed to polarize *all* the electrons.²⁰ While the (small number of) tail states make a minor contribution, the effect of the tail states on the position of the intersection point is much less important for the conductivity than for the resistivity when these are plotted as a function of magnetic field. Consequently, $H_\rho > H_\sigma$ as is evident in Fig. 1. We suggest that $H_\sigma \approx H_{band}$ and $H_\rho \approx H_{tail+band}$.

The fractional difference between H_ρ and H_σ , $\Delta H/H = (H_\rho - H_\sigma)/H_\sigma$, is shown as a function of electron density in Fig. 2; $\Delta H/H$ increases rapidly with decreasing electron density when disorder becomes more dominant. The quantity $2/\sigma$ is plotted for comparison through the following argument. For weak scattering, the parameter δ is of the order of the scattering rate, $\delta \sim \hbar/\tau$. With Eqs. (1) and (2), this gives $\Delta H/H = \delta/2E_F = \hbar/2(E_F\tau)$. Using the expression for the Drude conductivity $\sigma = ne^2\tau/m^*$, and the Fermi energy $E_F/\hbar = (nh)/g_v g_s m^*$ with a valley degeneracy $g_v = 2$ and spin degeneracy $g_s = 2$, one obtains $\Delta H/H = (e^2/h)(2/\sigma)$. The correlation between $\Delta H/H$ and $2/\sigma$ is evident in Fig. 2.

In an earlier paper,¹⁰ we showed that the magnetoconductance of silicon MOSFET's can be scaled onto a single curve by plotting $[\sigma(H) - \sigma(0)]/[\sigma(H=\infty) - \sigma(0)]$ as a function of H/H_s . The parameter H_s obtained by this method is proportional to H_σ discussed above. For high densities where disorder plays a small role, the magnetic field H_σ needed to

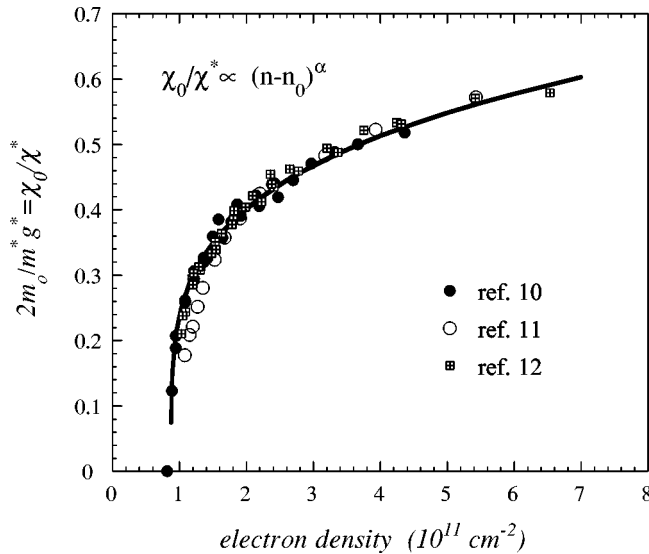


FIG. 3. The inverse of the enhanced susceptibility χ_0/χ^* versus electron density obtained by Vitkalov *et al.*,¹⁰ Shashkin *et al.*,¹¹ and Pudalov *et al.*¹² Data are normalized to the Shubnikov–de Haas values at high densities. The curve is a fit to the critical form $\chi_0/\chi^* = A(n - n_0)^\alpha$ for the data of Ref. 10 (excluding the point shown at $\chi_0/\chi^* = 0$).

saturate the conductivity is very nearly equal to the field required to obtain full spin polarization. At lower densities, the saturation fields deduced from the resistivity and the conductivity are not the same, and we have argued that the difference is associated with the effect of electrons in the states in the band tails. We have suggested that H_σ is the magnetic field required to polarize the band states; the Zeeman energy and g^*m^* are then given by Eq. (1) with $H_{band} = H_\sigma$. The tail states remain unpolarized in $H = H_\sigma$. However, except perhaps very near the transition (or in samples of very low mobility), they represent a small fraction of the electrons, so that the system is close to full spin polarization.

Figure 3 shows $2m_0/m^*g^* = \chi_0/\chi^*$ as a function of electron density n_s obtained from our data,¹⁰ by Shashkin *et al.*,¹¹ and Pudalov *et al.*¹² Here χ^*/χ_0 is the enhanced susceptibility normalized to its free electron value, and χ_0/χ^* is its inverse. The closed circles denote values obtained from scaling our data for the in-plane magnetoconductance and the assumption that $g^*\mu_B H_\sigma = 2E_F$; the open circles were obtained by Shashkin *et al.*¹¹ from magnetoresistance measurements using a different data-fitting proce-

dure and the same assumption as above; the squares are from direct Shubnikov–de Haas measurements of Pudalov *et al.*¹² The data of Shashkin *et al.* decrease somewhat more rapidly at low densities than the others. However, the three sets obtained by different groups using different measurements and different methods of analysis agree surprisingly well. Again, this indicates that the small number of states in the band tails in high-mobility MOSFET's play a negligible role. A fit to the critical form

$$\chi_0/\chi^* \propto (n - n_0)^\alpha, \quad (3)$$

yields the following values for the three data sets considered: for the Shubnikov–de Haas data of Pudalov *et al.*¹² $\alpha = 0.23$, $n_0 = 0.96 \times 10^{11} \text{ cm}^{-2}$; for the magnetoconductance data of Shashkin *et al.*¹¹ $\alpha = 0.27$, $n_0 = 1.04 \times 10^{11} \text{ cm}^{-2}$; and for our data¹⁰ $\alpha = 0.24$, $n_0 = 0.88 \times 10^{11} \text{ cm}^{-2}$.

We have argued above that for high-mobility samples, the difference ($H_\rho - H_\sigma$) is associated with the effect of a small fraction of the electrons in the band tails. The characteristic field H_s obtained in our earlier work was determined from scaling the magnetoconductance, which is a measure of the field required to align the band states while leaving a few electrons in the tail states unpolarized. Shashkin *et al.* determined a field scale by matching magnetoresistance data at low magnetic fields; close examination shows that this procedure does not produce a match at high fields (note that their data are shown on a logarithmic scale, which deemphasizes differences between the curves at high values of magnetic field). Both methods are sensitive to the contribution of the extended state and minimize the effect of the states in the band tails. These procedures yield reliable measures for the behavior of the system at high electron densities where disorder does not play an important role. This accounts for the surprisingly good agreement between the g^*m^* obtained from transport experiments and those found by direct measurement of the Shubnikov–de Haas oscillations. At densities very near the transition (and for very low mobility MOSFET's) one should expect this correspondence to break down as disorder becomes more dominant. We suggest that an understanding of any phase transition that occurs in this regime must incorporate the effect of disorder in a central way.

We thank M. Gershenson and S. V. Kravchenko for providing data for Fig. 3. This work was supported by the US Department of Energy under Grant No. DE-FG02-84ER45153.

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