Indication of the ferromagnetic instability in a dilute two-dimensional electron system

A. A. Shashkin* and S. V. Kravchenko

Physics Department, Northeastern University, Boston, Massachusetts 02115

V. T. Dolgopolov

Institute of Solid State Physics, Chernogolovka, Moscow District 142432, Russia

T. M. Klapwijk

Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands

The magnetic field \( B_c \), in which the electrons become fully spin-polarized, is found to be proportional to the deviation of the electron density from the zero-field metal-insulator transition in a two-dimensional electron system in silicon. The tendency of \( B_c \) to vanish at a finite electron density suggests a ferromagnetic instability in this strongly correlated electron system.

PACS numbers: 71.30.+h, 73.40.Qv, 73.40.Hm

At sufficiently low electron densities, an ideal two-dimensional (2D) electron system becomes strongly correlated, because the kinetic energy is overpowered by energy of electron-electron interactions (exchange and correlation energy). The interaction strength is normally described by the Wigner-Seitz radius, \( r_s \), which is equal to the ratio of the Coulomb and the Fermi energies as calculated for 2D band electrons. In the low-density limit, at \( r_s \gtrsim 35 \), the ground state of the system is expected to be a Wigner crystal characterized by spatial and spin ordering \[ 1 \]. The spin ordering may survive at higher electron densities (lower \( r_s \)) up to the threshold determined by ferromagnetic (Stoner) instability \[ 2 \]. In this strongly-interacting limit (\( r_s \gg 1 \)), all results given by theoretical approaches are very approximate, not to mention that in real 2D electron systems, the influence of disorder needs to be taken into account, which complicates the problem drastically. In strongly disordered 2D systems, the influence of the disorder can dominate the interaction effects leading to a disorder-driven localization, whereas in the least disordered 2D systems, the metal-insulator transition may be caused by interaction effects \[ 3 \].

In magnetic fields parallel to the 2D electron plane, the spin effects should dominate the properties of a 2D electron system once the orbital quantization is quenched. Indeed, the resistance of a 2D electron gas in silicon metal-oxide-semiconductor field-effect transistors (MOSFETs) was found to be isotropic with respect to in-plane magnetic field, \( B \), and rise steeply with the field saturating to a constant value above a critical magnetic field \( B_c \) which depends on electron density \[ 4 \]. Moreover, an analysis of Shubnikov-de Haas oscillations in tilted magnetic fields has established recently that the field \( B_c \) corresponds to the onset of full spin polarization of the electron system \[ 4 \].

In this paper, we study low-temperature parallel-field magnetotransport in a 2D electron system in silicon in a wide range of electron densities, \( n_s \). We find that the saturation (or polarization) magnetic field, \( B_c \), is a strictly linear function of \( n_s \): \( B_c \propto (n_s - n_c) \) where \( n_c \) is the critical electron density for the \( B = 0 \) metal-insulator transition. Since above \( n_c \), the 2D bandtail of localized electrons is negligibly small, as inferred from the low-field/low-temperature Hall effect measurements, vanishing \( B_c \) at a finite electron density gives evidence in favor of the existence of a ferromagnetic transition (at \( n_s = n_c \)) in this strongly correlated 2D electron system.

Measurements were made in a rotator-equipped Oxford dilution refrigerator with a base temperature of \( \approx 30 \text{ mK} \) on high-mobility (100)-silicon samples similar to those previously used in Ref. \[ 6 \]. The resistance was measured by a standard 4-terminal low-frequency technique. Excitation current was kept low enough to ensure that measurements were taken in the linear regime of response. Contact resistances in our samples were minimized by using a split-gate technique that allows one to maintain a high electron density in the vicinity of the contacts regardless of its value in the main part of the sample. In this paper we show results obtained on a sample with a peak mobility close to 3 m\(^2\)/Vs at 0.1 K.

Typical curves of the low-temperature magnetoresistance \( \rho(B) \) in a parallel magnetic field are displayed in Fig. \[ 1 \]. The resistivity increases approximately quadratically with field until it saturates at a constant value above a certain density-dependent magnetic field. In the vicinity of the metal-insulator transition, the magnetoresistance strongly depends on temperature \( T \), as was reported, e.g., in Ref. \[ 6 \]. As one moves away from the transition, however, this temperature dependence weakens and eventually disappears at very low temperatures where the metallic resistivity at \( B = 0 \) saturates and becomes independent of temperature. Therefore, as \( n_s \) is lowered, the low-temperature limit is realized for progressively narrower initial intervals on the curve \( \rho(B) \). The data discussed in this paper are obtained in this...
low-temperature limit where the magnetoresistance becomes temperature-independent.

In Fig. 2 we show how the normalized magnetoresistance, measured at different electron densities, collapses onto a single curve when plotted as a function of $B/B_c$. The scaling parameter, $B_c$, has been normalized to correspond to the magnetic field at which the magnetoresistance saturates (within the accuracy with which the latter can be determined) and hence full spin polarization of the electrons is reached [8]. The observed scaling is remarkably good for $B/B_c \leq 0.7$ in the electron density range $1.08 \times 10^{15} - 1.53 \times 10^{16}$ m$^{-2}$, although with increasing $n_s$ the scaled experimental data occupy progressively shorter intervals on the resulting curve. Both at $B/B_c > 0.7$ and outside the indicated range of electron densities, the scaled data start to noticeably deviate from the universal curve. In particular, the scaling breaks down when one approaches $(n_s < 1.3 n_c)$ the metal-insulator transition which in this sample occurs at zero magnetic field at $n_c = 8 \times 10^{14}$ m$^{-2}$ [9]. This is not surprising as the magnetoresistance near $n_c$ depends strongly on temperature, see above. We note that the observed scaling dependence is described reasonably well by the theoretical dependence of $\rho/\rho(0)$ on the degree of spin polarization $\xi = g_0 \mu_B B / \pi \hbar^2 n_s = B/B_c$ (where both the $g$ factor and the effective mass $m$ may be enhanced due to interactions, see below) as predicted by the recent theory [12] based on the spin-polarization-dependent screening of a random potential deeply in the metallic regime, see Fig. 2.

In Fig. 4, we show the first important and unexpected result of this paper: with high precision, $B_c$ is proportional to the deviation of the electron density from its critical value, i.e., to $(n_s - n_c)$, over a wide range of electron densities. In other words, the field, at which the magnetoresistance saturates, tends to vanish at $n_c$. We emphasize that our procedure provides high accuracy for determining the behavior of the field of saturation with electron density, i.e., the functional form of $B_c(n_s)$, even though the absolute value of $B_c$ is determined not so accurately. Note that at $n_s$ above $2.4 \times 10^{15}$ m$^{-2}$, the saturation of the resistance is not reached in our magnetic field range; still, the high precision of the collapse of the high-density experimental curves onto the same scaling curve as the low-density data allows us to draw conclusion about the validity of the obtained law $B_c(n_s)$ over a much wider range of electron densities.

The fact that the saturation (or polarization) field tends to vanish at $n_c$ would be trivial if the density of the delocalized electrons approached zero at the metal-insulator transition. This crucial point can be verified with the help of the Hall effect measurements in the limit of weak magnetic fields and low temperatures [13]. As seen in the inset to Fig. 4 above $n_c$, the electron density obtained from the Hall effect measurements agrees well with the one determined from Shubnikov-de Haas oscillations, which shows that in the metallic phase, the 2D bandtail of localized electron states is small, i.e., all the electrons are delocalized [17]. Then, the observed tendency for $B_c$ to vanish at a finite electron density gives a sign of the long-awaited ferromagnetic instability in strongly correlated 2D electron systems [18].

Subject to the occurrence of a ferromagnetic (Stoner) instability [2] at $n_s = n_c$, it is easy to calculate the behavior of $B_c$ vs $n_s$ based on the functional form of the exchange and correlation energy which is valid in the strong-interaction limit. Apparently, the Fermi energies of a spin polarized and unpolarized 2D electron system with both interaction and Zeeman energy taken into account must be equal. Writing the exchange and correlation energy in the explicit form, we get for the energy difference at the onset of full spin polarization and at $B = 0$

$$\frac{\pi \hbar^2 n_s}{2 m_b} - \frac{\gamma^2}{\kappa} n_s^{1/2} - \frac{1}{2} g_0 \mu_B B_c = 0, \quad (1)$$

![FIG. 1. Low-temperature magnetoresistance in parallel magnetic fields at different electron densities above the critical density for the $B = 0$ metal-insulator transition. The lowest density curve is outside the scaling region as described in the text.](image1)

![FIG. 2. Scaled curves of the normalized magnetoresistance at different $n_s$ vs $B/B_c$. The electron densities are indicated in units of $10^{15}$ m$^{-2}$. Also shown by a dashed line is the normalized magnetoresistance calculated in Ref. [12].](image2)
where $h$ is the Planck constant, the band mass $m_b = 0.19 m_0$ ($m_0$ is the free electron mass), $e$ is the electron charge, $\kappa$ is the dielectric constant, the Landé $g$ factor in bulk silicon is equal to $g_0 = 2$, and $\mu_B$ is the Bohr magneton. The first term in Eq. (1) is given by the difference of the bare Fermi energies which differ by a factor of two originating from the spin degeneracy (valley degeneracy being taken into account). The interaction (second) term contains the unknown numerical factor $\gamma$ which is positive since the exchange and correlation energy is always negative and its absolute value enhances with spin polarization. Note that the interactions are expected to lead to corrections to both $m_b$ and $g_0$; the problem of the interaction-enhanced effective mass $m$ and $g$ factor lacks a definite answer so far. Note also that the drastic enhancement of the product $gm$ (Fig. 4) determined from the data in Fig. 3 based on the above form of the spin polarization parameter $\xi$ is consistent with the $gm$ value obtained from the analysis of Shubnikov-de Haas oscillations in dilute silicon MOSFETs.

As seen from Fig. 3, the resulting dependence $B_c(n_s)$ with the factor $\gamma = 0.095$ determined from the condition $B_c(n_c) = 0$ describes the experimental finding well enough. Formally, the best description of the experimental data might be obtained with a bit smaller $\gamma = 0.090$, which corresponds to the expected ferromagnetic transition point just below $n_c$, at $n_s = 7 \times 10^{14} \text{ m}^{-2}$. Although the accuracy of the $B_c$ normalization hardly allows one to do so, the conclusions of the paper would still hold for that case. We emphasize, however, that the $B_c(n_s)$ dependence given by Eq. (1) is weakly superlinear, whereas our experiments yield strictly linear dependence. Clearly, theoretical efforts are needed to explore a possible relationship between the Stoner instability and the metal-insulator transition in 2D.

In summary, we have studied the low-temperature magnetoresistance in parallel magnetic fields in a wide range of electron densities above the critical electron density for the zero-field metal-insulator transition, $n_c$. The normalized magnetoresistance is found to scale with $n_s$ defining the scaling parameter, $B_c$, that corresponds to the magnetic field in which the full spin polarization is achieved. Over a wide range of electron densities, this scaling parameter changes in precise accordance with the relation $B_c \propto (n_s - n_c)$. Although in the metallic regime, the bandtail of the localized electrons has been found negligibly small, $B_c$ tends to vanish at a finite electron density. This gives evidence in favor of the existence of a ferromagnetic transition in this strongly correlated 2D electron system.

Recently, a conclusion about possible ferromagnetism in a dilute 2D electron system has been made by another experimental group [2].

We gratefully acknowledge discussions with I. L. Aleiner, A. H. Castro Neto, C. Chamon, B. I. Halperin, D. Heiman, A. I. Larkin, M. P. Sarachik, and S. A. Vitkalov. This work was supported by NSF grants DMR-9803440 and DMR-9988283, RFBR grant 01-02-16424, and Sloan Foundation.

* Permanent address: Institute of Solid State Physics, Chernogolovka, Moscow District 142432, Russia.

[1] E. Wigner, Phys. Rev. 46, 1002 (1934).
[2] E. C. Stoner, Rept. Prog. Phys. 11, 43 (1947).
[3] E. Abrahams, S. V. Kravchenko, and M. P. Sarachik, Rev. Mod. Phys. 73, 251 (2001).
[4] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. Lett. 79, 2304 (1997).
[5] T. Okamoto, K. Hosoya, S. Kawaji, and A. Yagi, Phys. Rev. Lett. 82, 3875 (1999).
[6] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik, and T. M. Klapwijk, Phys. Rev. Lett. 85, 2164 (2000).
[7] R. Heemskerk and T. M. Klapwijk, Phys. Rev. B 58, R1754 (1998).
[8] D. Simonian, S. V. Kravchenko, M. P. Sarachik, and V. M. Pudalov, Phys. Rev. B 58, R1754 (1998).
[9] The $B = 0$ metal-insulator transition point has been determined using the criterion of a sign change of the derivative $d\rho/dT(n_s)$ as well as the alternative methods of vanishing activation energy and vanishing nonlinearity of current-voltage curves as extrapolated from the insulating phase [10]. For our case all of the definitions are equivalent [11].
[10] A. A. Shashkin, V. T. Dolgopolov, and G. V. Kravchenko, Phys. Rev. B 49, 14486 (1994).
[11] A. A. Shashkin, S. V. Kravchenko, and T. M. Klapwijk, cond-mat/000918.
[12] V. T. Dolgopolov and A. Gold, JETP Lett. 71, 27 (2000).
[13] The delocalized electron density could in principle be affected by the application of an insufficiently weak magnetic field [14]. Besides, at relatively high temperatures [15], it may depend on temperature [16].
[14] V. T. Dolgopolov, A. A. Shashkin, M. Wendel, J. P. Kothaus, L. W. Molenkamp, and C. T. Foxon, Phys. Rev. B 55, 7339 (1997).
[15] M. P. Sarachik, D. Simonian, K. Mertes, S. V. Kravchenko, and T. M. Klapwijk, Physica B 280, 301 (2000).
[16] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, JETP Lett. 70, 48 (1999).
[17] The electron density variation due to inhomogeneities in the sample can be estimated from the width of the magnetocapacitance minima in a quantizing magnetic field; it is about $4 \times 10^{13}$ m$^{-2}$ at $n_s \sim 2 \times 10^{15}$ m$^{-2}$ in our samples.
[18] T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. 54, 437 (1982).
[19] F. F. Fang and P. J. Stiles, Phys. Rev. 174, 823 (1968).
[20] S. V. Kravchenko, A. A. Shashkin, D. A. Bloore, and T. M. Klapwijk, Solid State Commun. 116, 495 (2000).
[21] S. A. Vitkalov, H. Zheng, K. M. Mertes, M. P. Sarachik, and T. M. Klapwijk, cond-mat/0009454.