Magnetic Field Suppression of the Conducting Phase in Two Dimensions

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The anomalous conducting phase that has been shown to exist in zero field in dilute two-dimensional electron systems in silicon metal-oxide-semiconductor field effect transistors is driven into a strongly insulating state by a magnetic field of about 20 kOe applied parallel to the plane. The data suggest that in the limit of $T \to 0$ the conducting phase is suppressed by an arbitrarily weak magnetic field. [S0031-9007(97)04107-0]

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Recent experiments in high-mobility Si metal-oxide-semiconductor field effect transistors (MOSFET's) have provided strong evidence that a conducting phase exists in dilute two-dimensional (2D) electron systems in the absence of a magnetic field, in disagreement with predictions of the scaling theory [1] for noninteracting electrons. We attribute this finding to the availability of samples of unusually high mobility, allowing a transition from insulating to conducting behavior with increasing electron density, n_s, at small densities ($n_s \sim 10^{11}$ cm^{-2}). We note that since the Fermi energy $\epsilon_F \propto n_s$ in two dimensions and the electron correlation energy $\epsilon_{ee} \propto n_s^{1/2}$, the ratio ϵ_{ee}/ϵ_F is proportional to $n_s^{-1/2}$; therefore, the lower the electron density, the greater the role of electron-electron interactions. For the 2D electron system in silicon, it has been shown experimentally [2] that the temperature (T) and electric field (E) dependences of the resistivity on the far-insulating side of the transition are consistent with the presence of a Coulomb gap in the density of states, indicating that electron correlations play a significant role. Moreover, comparison of temperature scaling and electric field scaling [3] near the $H = 0$ transition in Si MOSFET's yields a dynamical exponent, $z \approx 0.8$, close to the value $z = 1$ expected theoretically for a strongly interacting system (see, e.g., Ref. [4]), again pointing to the importance of Coulomb interactions. Strong electron-electron interactions may thus be a central feature that allows the existence of a conducting phase in two dimensions. However, the nature of this phase remains unclear.

The influence of a magnetic field applied perpendicular to the plane of the 2D electron system has been studied in detail by Pudalov and co-workers [5] in high-mobility MOSFET's with comparable electron densities. In these studies, the magnetoconductance is largely dominated by orbital effects which lead to the quantum Hall effect. In this Letter we report the results of measurements of the resistivity in a magnetic field applied parallel to the plane; here the magnetic field couples to the spins, but not to the orbital motion. Our results indicate that a parallel magnetic field has a dramatic effect on the transition, entirely eliminating the conduction mechanism responsible for the existence of the $H = 0$ conducting phase above ~20 kOe. Based on our data, we suggest that the conducting phase is suppressed by an arbitrarily weak magnetic field in the limit $T \to 0$. We point out further that the behavior in a magnetic field, as well as the critical behavior in zero field [3,6], bears a strong resemblance to behavior reported near the superconductor-insulator transition in thin metal films [7–9].

We report results of measurements of the linear and nonlinear dc resistivities of three high-mobility Si MOSFET samples ($\mu^{\max}_{T=4.2\text{ K}} \approx 27\,000$ cm^2/V s, labeled sample 1, $\approx 24\,000$ cm^2/V s, labeled sample 2, and $\approx 17\,000$ cm^2/V s, labeled sample 3). As was pointed out in Ref. [3], when the electric field is strong the effective temperature of the electrons is higher than the lattice temperature, so that the resistance is determined by the effective temperature set by the field rather than by the lattice, or bath, temperature. Thus, similar information is obtained from the electric-field dependence of the (nonlinear) resistivity in the limit $T \to 0$ and the temperature dependence of the linear resistivity (in the limit $E \to 0$), as was demonstrated [3] by the behavior near the critical point found in the two cases. Measurements as a function of electric field are easier to perform and entail smaller errors. As in earlier experiments, the electron density was set by adjusting the gate voltage. The resistivity was measured as a function of parallel magnetic field, at various temperatures, and for different values of the electric field (determined by the measuring current). No difference was found for in-plane magnetic fields applied parallel and perpendicular to the measuring current. The samples and measurements are described in more detail in Refs. [3,6].

Figure 1 shows the nonlinear resistivity of sample 3 in units of h/e^2 as a function of electric field in a magnetic field of 5 kOe at a temperature of 0.1 K. Each curve corresponds to a different electron density (gate voltage).

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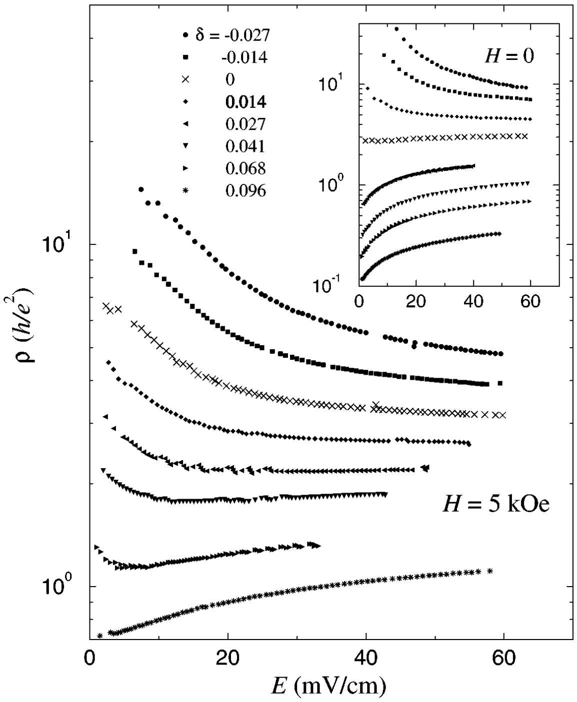

FIG. 1. Resistivity of sample 3 as a function of electric field on a semilogarithmic scale at $H_{||} = 5$ kOe and $T = 0.1$ K. Electron densities are specified relative to the $H = 0$ critical density, $n_c = 8.03 \times 10^{10}\ \mathrm{cm}^{-2}$; $\delta \equiv (n_s - n_c)/n_c$. The inset shows $\rho(E)$ (for sample 1) in the absence of a magnetic field at $T = 0.22$ K, for $\delta = -0.065, -0.050, -0.030, 0, 0.052, 0.10, 0.16,$ and 0.27. The crosses correspond to $\delta = 0$.

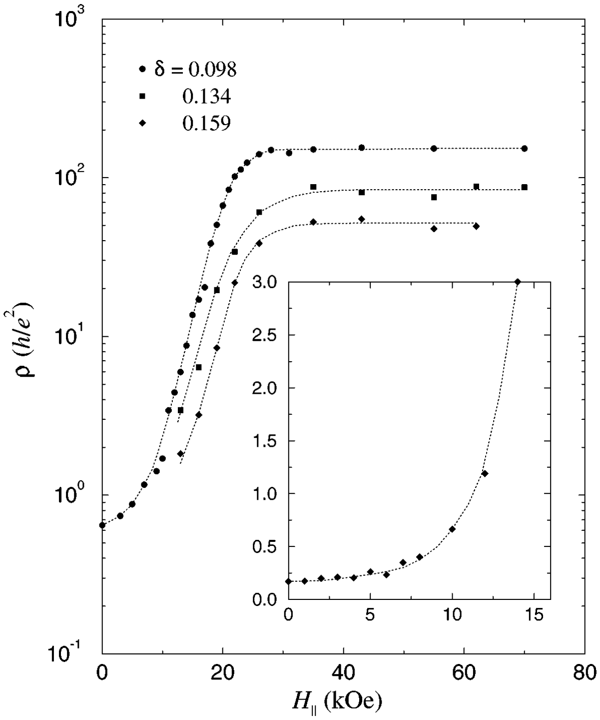

FIG. 2. Resistivity of sample 2 on a logarithmic scale as a function of a magnetic field applied parallel to the plane at $T = 0.25$ K for three electron densities. The inset shows the resistivity on a linear scale in small magnetic field for $\delta = 0.15$ and $T = 0.13$ K.

The inset shows the resistivity of sample 1 as a function of electric field in the absence of a magnetic field for comparable electron densities. In zero magnetic field, the curves clearly separate into two groups: for low electron densities the resistivity increases with decreasing temperature (insulating behavior), while for higher electron densities the resistivity decreases with decreasing temperature (conducting behavior); the resistivity at the transition ($n_s = n_c$) is independent of electric field and approximately equal to $3h/e^2$. As demonstrated in Ref. [3], a single (horizontal) multiplicative factor can be used to obtain scaling. The effect of a parallel magnetic field is clearly shown in the main part of Fig. 1: a magnetic field of 5 kOe drives all curves toward more insulating behavior. Moreover, there is a qualitative change: for some electron densities the resistivity exhibits nonmonotonic behavior, developing a shallow minimum. We shall return to this point below.

The resistivity is shown on a logarithmic scale as a function of magnetic field at a fixed temperature of 0.25 K in Fig. 2 for three different electron densities on the conducting side of the $H = 0$ transition ($n_s > n_c$). The resistivity initially stays approximately constant up to $H_{||} \approx 4$ kOe; data at low fields are shown on an expanded scale in the inset to Fig. 1 for an electron density corresponding to $\delta \equiv (n_s - n_c)/n_c = 0.15$. The resistivity then increases sharply as the magnetic field is raised further, changing by almost 3 orders of magnitude. Above $H_{||} \sim 20$ kOe, it saturates and stays approximately constant up to the highest measured field, $H_{||} = 70$ kOe. A parallel magnetic field has dramatically altered the system, apparently suppressing the conduction mechanism in the anomalous conducting phase entirely in fields above 20 kOe. The behavior is reminiscent of the quenching of superconductivity by a magnetic field (except, of course, that the zero-field resistivity in our case is finite rather than zero). The Zeeman energy, $g\mu_B H_{||}$, at 20 kOe corresponds to a thermal energy $k_B T_H$ with $T_H = 2.7$ K. Note that $T_H \sim T^* \approx 2$ K, where T^* marks the onset of the low-temperature conducting phase in zero field (see the lowest curve of Fig. 4).

Measurements in magnetic fields oriented perpendicular to the plane of the electrons confirm earlier detailed magnetotransport results obtained by Pudalov *et al.* [5] in Si MOSFET's with comparable electron densities and mobilities. Figure 1 of their paper shows that the resistance is essentially constant up to 5 kOe, above which it rises sharply before it is overwhelmed by the quantum Hall effect above ~15 kOe. This puzzling, sharp initial increase has been the subject of some debate. We suggest that its origin is the same as for a parallel field: a conducting phase exists at low temperatures which is suppressed by a magnetic field. Thus, the anomalous $H = 0$ conducting state is driven into a strongly insulating ("normal") state either by $H_{||}$ or by $H_{\perp}$, in a qualitatively similar way.

We now consider whether one can identify a critical parallel magnetic field below which the system is a conductor, and above which it is an insulator. In Fig. 3, we plot the nonlinear resistivity, $\rho(E)$, for a fixed electron density (corresponding to a zero field $\delta = 0.3$) at 0.1 K. Here each curve corresponds to a different value of $H_{||}$. As noted above, the curves are *qualitatively* different from those in zero field shown in the inset in Fig. 1: the curves for $\delta > 0$ display a shallow minimum in finite magnetic field, and it is no longer possible to use a single parameter to collapse them onto two separate branches, insulating and conducting, as was done at $H = 0$ [3,6]. Moreover, there is no universal "critical" value of the resistivity, $\rho(H_{||c})$. This suggests that any finite magnetic field (at $T = 0$) drives the system into the insulating phase.

Finally, Fig. 4 shows the linear resistivity (at $E \rightarrow 0$) as a function of temperature for a fixed electron density on the conducting side of the $H = 0$ transition ($\delta = 0.1$) in several parallel magnetic fields between 0 and 14 kOe. The zero-field curve is typical of a conductor, with resistance dropping sharply as the temperature is decreased below $\approx$2 K, while at $H = 14$ kOe it is strongly insulating. Note that the magnetic field has almost no effect on the resistivity above $T^* \approx 2$ K, while below T^* the effect of $H_{||}^*$ is enormous (as discussed earlier, T^* is the characteristic temperature below which the conducting phase exists in zero field). We note the presence of resistivity minima at intermediate magnetic fields. Again, one-parameter scaling with temperature breaks down, as did one-parameter scaling with electric field (see above).

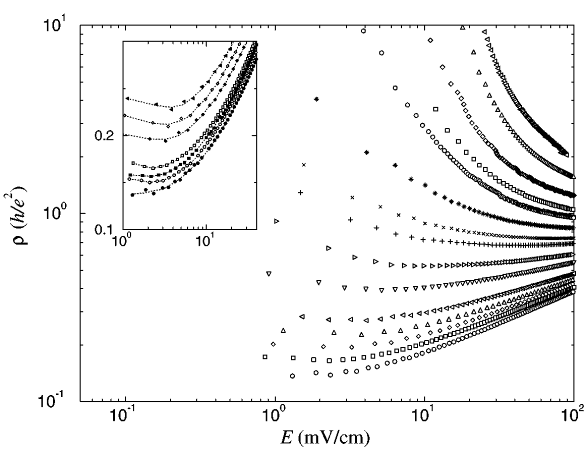

FIG. 3. For sample 2, isomagnetic curves of nonlinear resistivity as a function of electric field on a log-log scale for fixed electron density, $\delta = 0.3$, at $T = 0.10$ K. Each curve corresponds to a different value of parallel magnetic field, $H_{||} = 0$ (bottom curve), 6, 8, 10, 12, 15, 17, 19, 20, 22, 24, 25, 27, 30, and 34 kOe. Minima in the resistivity are clearly illustrated in the inset, where data are shown on a linear scale for $H_{||} = 0$ (bottom curve), 4, 5, 6, 8, 9, and 10 kOe.

The upturn in resistivity at small electric fields (Fig. 3) and at low temperatures (Fig. 4) at intermediate values of magnetic field is reminiscent of the maxima exhibited by the *conductivity* as a function of temperature in the presence of a magnetic field in 3D materials which exhibit a metal-insulator transition, such as Si:P [10]. There the behavior is attributed to the competition between magnetic field-dependent Hartree and field-independent exchange terms, which contribute to the conductivity with opposite sign [10]. The behavior we observe in the 2D system of electrons in silicon MOSFET's is consistent with the theory first proposed by Finkel'shtein, and may derive from a similar effect, which would imply that the low-temperature conducting phase is an "ordinary" metal [11]. We note that the rather sharp change in resistivity from one well-defined value to another, shown in Fig. 2, makes it likely that some sort of collective phase is quenched by the magnetic field. In fact, the isomagnetic curves of Fig. 4 are similar to those in Fig. 1 of Ref. [7] measured near a superconductor-insulator transition driven by a magnetic field in disordered indium oxide films.

The possibility of superconductivity in Si MOSFET's has been considered by Takada [12] and by Hanke and Kelly [13]. More recently, triplet superconductivity has been proposed in this system by Belitz and Kirkpatrick [14], and p-wave superconductivity has been proposed by Phillips and Wan [15]. In addition, various kinds of instabilities in 2D have been proposed theoretically (for a

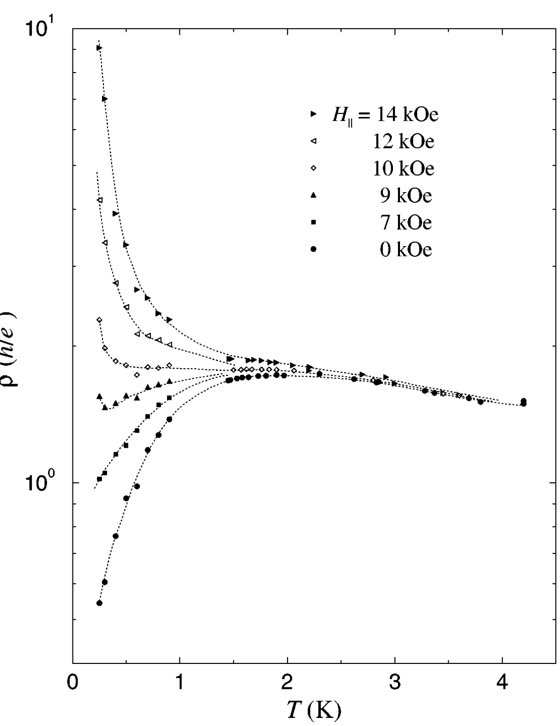

FIG. 4. Resistivity of sample 2 versus temperature in the absence of a field (bottom curve) and in five different parallel magnetic fields. The electron density corresponds to $\delta = 0.10$.

review, see Ref. [16]), including Wigner crystallization, a transition to a ferromagnetic state at low electron densities, single-valley occupancy, and instabilities toward a charge-density or spin-density ground state.

To summarize, we report that a parallel magnetic field suppresses the anomalous conducting phase found at $H = 0$ in the 2D electron system in Si MOSFET's. The resistivity increases by several orders of magnitude at low temperatures, saturating above $\approx$20 kOe. Qualitatively similar behavior is found [5] in a perpendicular field, which couples to orbital motion as well as spin, up to approximately 15 kOe; at higher perpendicular fields the magnetoconductance is overwhelmed by the quantum Hall effect. The fact that a parallel magnetic field has such a dramatic effect indicates that the electrons' spins play a central role. The fact that the Zeeman energy $g\mu_B H$ and thermal energy $k_B T$ that destroy the conducting phase are roughly comparable further supports this possibility. One-parameter scaling with temperature and electric field, found to hold when $H = 0$, breaks down even in a weak magnetic field, suggesting the elimination of the conducting phase by an arbitrarily small H.

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