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Effect of a tilted magnetic field on the anomalous $H=0$ conducting phase in high-mobility Si MOSFET's

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The suppression by a magnetic field of the anomalous $H=0$ conducting phase in high-mobility silicon metal-oxide-semiconductor field-effect transistors is independent of the angle between the field and the plane of the two-dimensional electron system. In the presence of a parallel field large enough to fully quench the anomalous conducting phase, the behavior is similar to that of disordered GaAs/Al$_x$Ga$_{1-x}$As heterostructures: the system is insulating in zero (perpendicular) field, and exhibits reentrant insulator–quantum-Hall-effect–insulator transitions as a function of perpendicular field. The results demonstrate that the suppression of the low-T phase is related only to the electrons' spin. [S0163-1829(98)01331-9]

According to the one-parameter scaling theory of localization for noninteracting electrons,[1] a two-dimensional electron system (2DES) is always insulating at sufficiently large length scales (i.e., in the limit of zero temperature) in the absence of a magnetic field. In high-mobility silicon metal-oxide-semiconductor field-effect transistors (MOSFET's), however, a metal-insulator transition has been observed at a critical electron density, $n_c \sim 10^{11}\mathrm{cm}^{-2}$, and an $H=0$ conducting phase has been shown to exist below ~ 1K.[2] Similar critical behavior has been reported in a p-type SiGe quantum well,[3] and in the hole gas in GaAs/Al$_x$Ga$_{1-x}$As heterostructures.[4,5] At low carrier densities, the interaction energy in these systems is more than an order of magnitude larger than the Fermi energy, so that one does not expect the noninteracting theory of localization[1] to be applicable in its simplest form.

In a disordered 2DES, Khmel'nitskii[6] predicted that the extended states that exist at the centers of each Landau level in large perpendicular magnetic fields should ''float'' up in energy as $H_\perp \rightarrow 0$, leading to an insulating phase at $H=0$. Consistent with this expectation, insulating behavior has been observed in the low-density, strongly disordered 2DES in GaAs/Al$_x$Ga$_{1-x}$As heterostructures.[7,8] In contrast, the low-density 2DES in high-mobility Si MOSFET's exhibits quite different behavior. As $H_\perp \rightarrow 0$, the extended states shift upward from the centers of the Landau levels,[9] as expected. However, instead of ''floating'' up indefinitely with decreasing magnetic field, the states apparently combine at the Fermi level,[9,10] giving rise to the anomalous field dependence of ρ in small magnetic fields first reported in Ref. 11 and shown in the inset to Fig. 1. This behavior is a puzzle, and its physical origin had remained unclear.

We have recently shown that the anomalous low-density–low-temperature conducting phase in silicon MOSFET's is suppressed by a magnetic field applied parallel to the two-dimensional (2D) plane of the electrons:[12,13] as shown in Fig. 2 of Ref. 12, the resistivity increases by several orders of magnitude as the parallel magnetic field is increased to $H_{||} \sim 20$ kOe, above which it saturates to a value that is approximately independent of magnetic field. This prompted us to suggest that the enigmatic behavior in small perpendicular fields is associated with the quenching of the low-temperature conducting phase by a perpendicular field (see the inset to Fig. 1), just as it is quenched by a parallel field (see Fig. 2 in Ref. 12).

From measurements of the resistivity as a function of magnetic field applied at different angles with respect to the plane of the electrons, in this paper we demonstrate that (i) a magnetic field suppresses the anomalous $H=0$ conducting phase in high-mobility silicon MOSFET's, independently of the angle between the field and the plane of the electrons, thereby firmly establishing that the suppression of this phase is associated only with the electrons' spins. (ii) In the presence of a parallel field sufficiently large to quench the anomalous conducting phase in high-mobility silicon samples, the resistivity exhibits, as a function of perpendicular field, all the now-familiar features found in disordered, low-mobility GaAs/Al$_x$Ga$_{1-x}$As heterostructures:[7,8] a giant negative magnetoresistance at low $H_\perp$, the quantum Hall effect (QHE) at Landau-level filling factors $\nu=2$ and 1, and insulating behavior at higher $H_\perp$. We also show that (iii) the suppression of the anomalous conducting phase is not associated with a simple change in disorder potential or electron density, both of which are essentially unaltered by the magnetic field. (iv) The multiple valleys that are peculiar to the conduction band of silicon are not responsible for the low-temperature conducting phase, which is suppressed the same way by a field applied at any angle.

The three silicon MOSFET samples used for these studies have peak mobilities at 4.2 K of $\mu_{4.2K}^{max} \approx 30\,000$ cm^2/V s

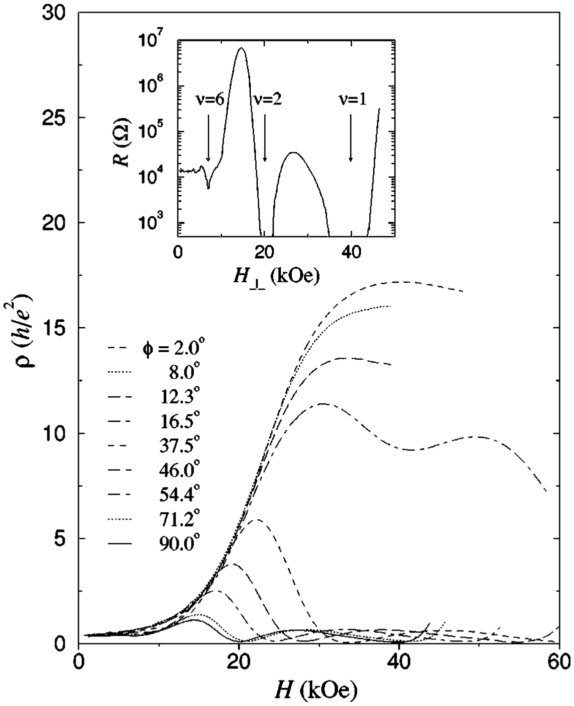

FIG. 1. Resistivity ρ as a function of the total magnetic field for a high-mobility sample B, at $T=0.36$ K and $n_s=1.0\times10^{11}$ cm^{-2}, for nine angles ϕ between the magnetic field and the inversion layer. ρ deviates from the ''main'' curve at smaller magnetic fields as ϕ is increased. The inset shows the resistance R of sample A at $T=35$ mK as a function of perpendicular magnetic field. At electron density $n_s=9.3\times10^{10}$ cm^{-2} this sample is in the conducting state at $H=0$. QHE resistivity minima at filling factors $\nu=1$, 2, and 6 are indicated by arrows (note the absence of a minimum at $\nu=4$, possibly because it is masked by the rapid increase in resistivity). Contrary to expectations, the resistivity decreases rapidly as the field is reduced below $H_\perp\approx15$ kOe, approaching a finite value as $H\rightarrow0$.

(sample A), 25 000 cm^2/V s (sample B), and 8 000 cm^2/V s (sample C). Four-terminal DC transport measurements were taken as a function of a magnetic field applied at different angles with respect to the plane of the electrons. Two Si MOSFET samples were measured in a pumped ^{3}He system equipped with a 12-T magnet and a manual sample rotator. Sample A was studied in a dilution refrigerator in a magnetic field oriented perpendicular to the 2D plane. Excitation currents were between 0.01 and 10 nA; care was taken to ensure measurements were in the linear I-V regime.

For a gate voltage that placed sample B in the conducting state at $H=0$ with a resistivity of ≈10 kΩ at 360 mK, Fig. 1 shows the diagonal resistivity ρ as a function of a magnetic field applied at different angles with respect to the plane of the 2DES. For all angles, $\rho(H)$ follows approximately the same curve up to some value of magnetic field, above which orbital effects leading to QH oscillations become dominant. The resistivity deviates from the ''main'' curve at smaller magnetic fields as the angle between the field and the plane is increased: the larger perpendicular component causes stronger orbital effects which become dominant at a lower total field. We note that small differences in $\rho(H)$ at $H\sim10$ kOe are associated with the emergence of a QHE minimum at filling factor $\nu=6$,[10] which deepens as the perpendicular component of the field becomes larger. The important feature is that the magnetoresistance is the same at all angles up to some field, above which it is overwhelmed by orbital effects. The anomalous $H=0$ conducting phase is thus suppressed in the same manner by a magnetic field applied at any angle.

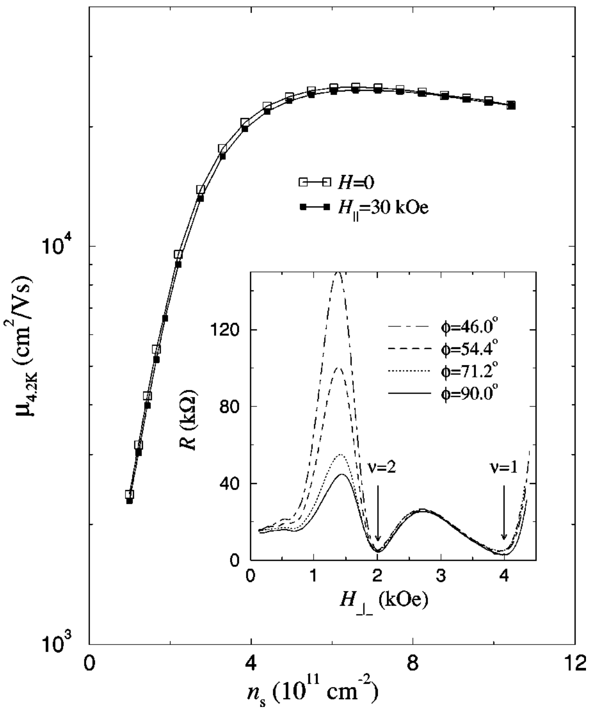

FIG. 2. Mobility at $T=4.2$K vs electron density for sample B in zero magnetic field (open symbols) and $H_{||}=30$ kOe (closed symbols). The inset shows R as a function of $H_\perp$ for four angles between the field and the two dimensional plane; $T=0.36$ K and $n_s=1.0\times10^{11}$ cm^{-2}.

This provides evidence that the conduction-band valleys in silicon do not play an important role. It has been shown[14] that a field applied parallel to the plane of the 2DES in silicon MOSFET's does not affect the splitting of the conduction-band valleys. The absence of any angular dependence implies that valley splitting is not responsible for the suppression of the low-temperature conducting phase by a magnetic field. We thus arrive at the important conclusion that it is the electrons' spin that plays a crucial role. Indeed, among the theoretical suggestions that have been offered as possible explanations of the conducting phase at $H=0$,[15–24] many involve electron spins.[15,17–19,23,24]

We now verify explicitly that a magnetic field does not drive the sample into the insulating phase by simply increasing the amount of disorder (reducing the 4.2-K electron mobility[25]), or by reducing the electron density below its critical value. Figure 2 shows $\mu_{4.2\text{ K}}$ of high-mobility sample B as a function of electron density in $H=0$ and in the presence of a parallel magnetic field, $H_{||}=30$ kOe. These data establish that the mobility is essentially unaltered by a magnetic field.

The inset to Fig. 2 shows the resistance as a function of the perpendicular component of the magnetic field, $H_\perp=H\sin\phi$, as the total field H is swept at four different fixed angles with respect to the electron plane. Note that the parallel field $H_{||}=H\cos\phi$ varies along each curve and is differ-

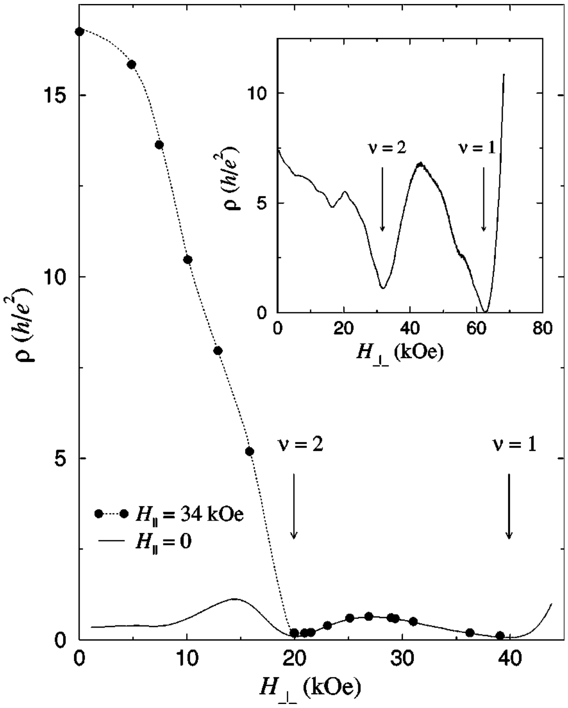

FIG. 3. Resistivity of sample B as a function of $H_\perp$ in the absence of parallel magnetic field (lower curve) and in the presence of $H_{||}=34$ kOe (upper curve). $T=0.36$ K and $n_s=1.0\times10^{11}$ cm^{-2}. The inset shows $\rho(H_\perp)$ for a low-mobility sample C; $T=0.36$ K and $n_s=1.52\times10^{11}$ cm^{-2}.

ent for different angles ϕ. The QHE minima occur at the same $H_\perp$ for all angles, corresponding to different values of the total field. This observation establishes that the magnetic field does not change the electron density in the inversion layer. The dramatic growth with angle of the ρ maximum at $H_\perp\sim15$ kOe can be understood by noting that the $H=0$ conducting state is quenched independently of the field orientation: at a fixed $H_\perp\approx15$ kOe, the total field increases with decreasing ϕ, $H=H_\perp(\sin\phi)^{-1}$, driving the sample closer to the insulating state. Note that an anomalous growth with $H_{||}$ of the resistance peak between $\nu=1$ and 3 has been observed in a p-Si/SiGe heterostructure[27] and was attributed by the authors to the dependence of the ''insulating state width on the ratio between spin and cyclotron splittings.'' We remark that the observation of a $H=0$ conducting state similar to that in high-mobility Si MOSFET's in this system[3] suggests that the strong enhancement of the resistivity in p-Si/SiGe (Ref. 27) may instead be due to the magnetic-field suppression of the anomalous conducting state in the same way as in Si MOSFETs.

In Fig. 3, ρ is plotted as a function of $H_\perp$ in the absence of parallel magnetic field and in the presence of $H_{||}=34$ kOe. The lower curve corresponds to $H_{||}=0$, and exhibits the anomalous behavior of high-mobility Si MOSFET's.[11] Note that the peak at $H_\perp\approx15$ kOe is considerably smaller than that shown in the inset to Fig. 1, because of the higher measuring temperature (360 mK vs 35 mK). The upper curve is the magnetoresistance of the sample in the insulating state, obtained by quenching the $H=0$ conducting state with a parallel field of 34 kOe. In the ''quenched'' phase, high-mobility Si MOSFET's display the familiar reentrant behavior found in disordered, weakly interacting GaAs/Al$_x$Ga$_{1-x}$As heterostructures (see, e.g., Fig. 2 in Ref. 7): the system has an initial large negative magnetoresistance, exhibits the quantum Hall effect at $\nu=2$ and 1, and becomes again insulating at $H\gtrsim42$ kOe. (However, the initial decrease in resistivity is considerably less sharp than in disordered GaAs/Al$_x$Ga$_{1-x}$As.) Note that above $H_\perp\sim20$ kOe, all the data collapse onto a single curve. This confirms once again that the anomalous phase is quenched by a magnetic field applied in any direction (including perpendicular).

The inset to Fig. 3 shows the resistivity ρ of the relatively low-mobility sample C in a perpendicular field. No $H=0$ conducting phase was found in this sample. It is strongly insulating at $H_\perp=0$, and there is an appreciable negative magnetoresistance for $H_\perp\lesssim30$ kOe. The $\nu=1$ and 2 QHE minima are evident, followed at higher field by a transition to an insulator due to the crossing of the last extended state through the Fermi level at $H_\perp\gtrsim65$ kOe. It is interesting that ρ vs $H_\perp$ for sample C appears to exhibit behavior intermediate between the upper and lower curves in the main figure. This suggests that the anomalous low-temperature phase that is so evident in high-mobility samples is also present in a modified, partially quenched form in low-mobility, disordered samples.

In conclusion, we have shown that the suppression by a magnetic field of the $H=0$ conducting phase in high-mobility Si MOSFET's does not depend on the angle between the field and the 2D electron plane. This provides strong evidence that valley splitting does not play an important role, and that the quenching of the anomalous conducting phase in two dimensions is associated with the electrons' spin. We have also demonstrated explicitly that the suppression of the conductivity is not associated with a simple change in sample mobility or electron density, both of which are essentially unaffected by magnetic field. In the presence of large parallel field, the ''quenched'' phase in high-mobility silicon MOSFET's exhibits the reentrant behavior of disordered, weakly interacting GaAs/Al$_x$Ga$_{1-x}$As heterostructures: a large negative magnetoresistance and reentrant insulator–QHE–insulator transitions.[7,8]

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