Magnetoconductivity of Insulating Silicon Inversion Layers

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The normalized in-plane magnetoconductivity of the dilute strongly interacting system of electrons in silicon MOSFET’s scales with $B/T$ for low densities in the insulating phase. Pronounced deviations occur at higher metallic-like densities, where a new energy scale $k_B \Delta$ emerges which is not associated with either magnetic field or thermal effects. $B/T$ scaling of the magnetoconductivity breaks down at the density $n_0$ where the energy scale $k_B \Delta$ vanishes, near or at the critical density $n_c$ for the apparent metal-insulator transition. The different behavior of the magnetoconductivity at low and high densities suggests the existence of two distinct phases.

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According to well established theory, no metallic state can exist in two dimensions for noninteracting [1] or weakly interacting [2] electrons (or holes) in zero magnetic field in the limit of zero temperature. In dilute two-dimensional systems where the interactions are known to be strong, however, experimental studies have revealed an unexpected decrease in the resistance as the temperature is lowered, behavior that is generally a characteristic of metals. This metallic behavior has been observed down to the lowest accessible temperatures at electron [3,4] and hole [5–7] densities above some critical density $n_c$ (or $p_c$). For densities down to approximately $1.5 n_c$, the temperature dependence has been attributed to electron-electron scattering in the ballistic limit ($k_B T >> \hbar/\tau$), confirming the importance of strong e-e interactions in determining the behavior of these systems [8]. However, the behavior observed at lower densities and the nature of the apparent metal-insulator transition are still not understood [9].

A very unusual characteristic of dilute, strongly interacting electron (hole) systems is their strong response to an in-plane magnetic field: the resistivity increases dramatically with increasing field and saturates to a new value above a characteristic magnetic field that depends on density and temperature [9]. Simionian et al. reported that for small to moderate magnetic fields, the magnetoconductivity of silicon MOSFET’s scales as $(B/T)$ for electron densities at and slightly above $n_c$ [10]. From an analysis of the temperature and density dependence of the magnetoconductance of silicon MOSFET’s, Vitkalov et al. [11] have identified an energy scale $(k_B \Delta)$ which extrapolates to zero at a finite density $n_0$ in the vicinity of $n_c$; the behavior of the magnetoconductivity was attributed to an increase in the magnetic susceptibility $\chi \propto (g^* m^*)$ and the approach to a zero temperature quantum phase transition at $n_0$ (here $g^*$ and $m^*$ are the renormalized Lande-g factor and effective mass, respectively). Shashkin et al. [12] found similar results; moreover, based on measurements of Shubnikov-de Haas oscillations and in-plane magnetoresistivity, these authors recently [13] reported that the sharp increase in the susceptibility is associated with an increase in the effective mass while the $g$-value remains essentially constant as the electron density approaches $n_c$. These findings all suggest critical behavior and the approach to a quantum phase transition.

In this paper we report the results of an investigation of the magnetoconductivity of the dilute two-dimensional system of electrons in a high-mobility silicon MOSFET in the insulating phase. We find that the in-plane magnetoconductivity scales with $(B/T)$ for electron densities near and below $n_0$. Pronounced deviations from this simple scaling form become evident in the metallic regime at higher densities: in agreement with our earlier findings [11], scaling in the metallic phase requires the inclusion of an additional energy scale $(k_B \Delta)$. The different behavior of the magnetoconductivity at low and high densities suggests the existence of two distinct phases.

The sample used in these studies is a high-mobility silicon MOSFET ($\mu_{\text{peak}} \sim 20000/V\text{s}$ at 0.5 K). Contact resistances were minimized by using a split-gate geometry that allows a higher electron density to be established in the vicinity of the contacts than in the 2D system under investigation. Data were taken by standard four-terminal ac techniques for electron densities above $1.2 \times 10^{11} \text{cm}^{-2}$, and by dc techniques for lower densities. Experiments were performed at temperatures between 0.25 K and 4 K in magnetic fields up to 10 T; data were taken in the linear regime using small currents to avoid overheating the electrons. The critical density of the sample is $\approx 0.90 \times 10^{11} \text{cm}^{-2}$. 
FIG. 1. (a) Resistivity of a silicon MOSFET at four temperatures, as labeled, as a function of electron density. The curves cross at the critical density $n_c = 0.9 \times 10^{11} \text{ cm}^{-2}$. (b) Conductivity as a function of applied in-plane magnetic field at different densities, as labeled; $T \approx 0.25 \text{ K}$. The top four magnetoconductance curves are at metallic densities, and the bottom three are insulating.

Figure 1(a) shows the resistivity of the silicon MOSFET as a function of electron density at four different temperatures: the behavior is insulating for densities below the crossing point at $0.9 \times 10^{11} \text{ cm}^{-2}$ (resistivity increasing with decreasing temperature) and metallic above that density. Figure 1(b) shows the conductivity as a function of in-plane magnetic field for different densities at $T \sim 0.25 \text{ K}$; here the top four curves correspond to densities in the conducting range, the fifth is at or near the critical density, and the remaining are in the insulating regime. Consistent with earlier results in silicon and various materials, the magnetoconductivity saturates at a progressively lower applied field as the density decreases.

The enormous response to in-plane magnetic field is a typical feature in these 2D systems [14–17].

FIG. 2. Normalized magnetoconductivity as a function of the scaled field at different temperatures at electron density $n_s = 1.2 \times 10^{11} \text{ cm}^{-2}$. The inset shows the (unnormalized) conductivity versus in-plane magnetic field at various temperatures.

For a fixed electron density in the metallic regime ($n_s > n_c$), the inset to Fig. 2 shows the conductivity as a function of in-plane magnetic field at different temperatures. Following the procedure used in a previous study [11], the normalized magnetoconductivity:

$$
\sigma_{\text{norm}} = \frac{\sigma(B = 0) - \sigma(B)}{\sigma(B = 0) - \sigma(B \rightarrow \infty)}, \quad (1)
$$

is plotted as a function of a scaled magnetic field $B/B_\sigma$. Here $B_\sigma$ is a fitting (or scaling) parameter chosen to obtain a data collapse. Note that the normalized magnetoconductivity (1) is simply the field dependent contribution to the conductivity, $[\sigma(B = 0) - \sigma(B)]$, normalized by its full value, $[\sigma(B = 0) - \sigma(B \rightarrow \infty)]$.

A study of the scaled magnetoconductivity at various temperatures and densities allows a determination of the parameter $B_\sigma$ as a function of temperature and density. Consistent with our earlier analysis [11], $B_\sigma$ satisfies the empirical formula:

$$
B_\sigma = A_n \sqrt{\Delta^2 + T^2}, \quad (2)
$$

where the fitting parameter $A_n$ varies by less than 15% in the range of densities of our experiments. The result of this analysis is shown in Fig. 3, where $\Delta$ is plotted as a function of electron density $n_s$. 

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The parameter $\Delta$ enters on an equal footing with the temperature $T$ and represents an energy scale ($k_B \Delta$) associated with $B\sigma$. In agreement with published results, the plot shown in Fig. 3 indicates that the energy ($k_B \Delta$) extrapolates to zero at a finite electron density $n_0$ close to the critical density $n_c$ that signals the change in temperature dependence of the conductivity from metallic to insulating [11]. That $\Delta = 0$ at $n_0$, and hence, $B\sigma = A_nT$ and $\Delta = 0$ for this density.

The vanishing energy ($k_B \Delta$) signals a diverging correlation time scale $\tau \sim \hbar/(k_B \Delta)$, suggesting that the system is approaching a quantum phase transition in the limit $T \rightarrow 0$.

The results of our current measurements are denoted by black squares in Fig. 3. For the metallic densities above $n_c$, the new measurements provide additional and more precise data that support our earlier conclusions. At low densities, our measurements provide important new information: the energy scale ($k_B \Delta$) remains zero in the insulator down to the lowest density measured, $n = 0.76 \times 10^{11}$ cm$^{-2}$, $\sim 15\%$ below the critical density. This implies that the normalized magnetoconductivity scales strictly with $B/T$ in the insulating phase (see Eq. 2).
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FIG. 5. The normalized magnetoconductivity (see Eq. 1) versus $B/T$ for several electron densities at $T = 0.5$ K. Note that the magnetoconductivity scales with $B/T$ for insulating densities $n_s < n_c$ and does not scale for metallic densities.

To summarize, the normalized in-plane magnetoconductivity of the dilute strongly interacting system of electrons in silicon MOSFET’s scales with $B/T$ in the insulating regime for densities below $n_0$. Deviations occur at higher metallic-like densities, where a new energy scale emerges which is not associated with either magnetic field or thermal effects. The breakdown of $B/T$ scaling of the magnetoconductivity above $n_0$, which is at or near the electron density $n_c$ that signals the change from insulating to metallic temperature dependence of the conductivity, suggests that distinct phases exist above and below $n_0$. Our finding of $B/T$ behavior in the insulating regime sets an important constraint on theory.

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