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#### Response to parallel magnetic field of a dilute two-dimensional electron system across the metal-insulator transition

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The response to a parallel magnetic field of the very dilute insulating two-dimensional system of electrons in silicon metal-oxide-semiconductor field-effect transistors is dramatic and similar to that found on the conducting side of the metal-insulator transition: there is a large initial increase in resistivity with increasing field, followed by saturation to a value that is approximately constant above a characteristic magnetic field of about 1 T. This is unexpected behavior in an insulator that exhibits Efros-Shklovskii variable-range hopping in zero field, and appears to be a general feature of very dilute electron systems. [S0163-1829(99)50932-6]

Until quite recently, it was believed that all two-dimensional systems of electrons (or holes) are necessarily localized in the absence of a magnetic field in the limit of zero temperature. This conclusion was based on the scaling theory for noninteracting electrons of Abrahams *et al.*,<sup>1</sup> was further confirmed theoretically for weakly interacting electrons,<sup>2,3</sup> and received experimental confirmation in a number of materials, including thin films<sup>4</sup> and (high-density) silicon metal-oxide-semiconductor field-effect transistors (MOSFET's).<sup>5,6</sup> In the last several years, however, measurements in very dilute two-dimensional systems have provided evidence of a transition from insulating to conducting behavior with increasing electron (hole) density above some low critical value on the order of  $10^9$ – $10^{11}$   $\text{cm}^{-2}$ .<sup>7–13</sup> At these very low densities the energy of electron-electron interactions exceeds the Fermi energy by an order of magnitude or more, and correlations thus provide the dominant energy in the problem. Dilute, strongly interacting two-dimensional systems are currently the focus of intense theoretical interest, and have elicited a spate of theoretical attempts to account for the presence and nature of the unexpected conducting phase.

One of the most interesting characteristics of the conducting phase is its dramatic response to a magnetic field applied parallel to the plane of the two-dimensional system. For example, the resistivity of very high-mobility silicon MOSFET's increases by almost three orders of magnitude with increasing field, saturating to a new value in fields above  $\sim 2$ – $3$  T.<sup>14,15</sup> A similar effect was observed in  $p$ -GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures<sup>11</sup> confirming that this giant positive magnetoresistance is a general property of dilute conducting two-dimensional (2D) systems.<sup>16</sup> In Ref. 17, it was reported that the metal-insulator transition in Si MOSFET's shifts toward higher electron densities in a parallel magnetic field of the order of a few T, while at higher magnetic fields, the effect saturates. We note that a parallel magnetic field couples only to the spins of the electrons and not to their orbital motion. Spins are thus known to play a crucial role, and it has been suggested that full alignment of the electrons results in the complete suppression of the anomalous conducting phase.

In this paper we report that the response of the very dilute 2D system of electrons in high-mobility silicon MOSFET's

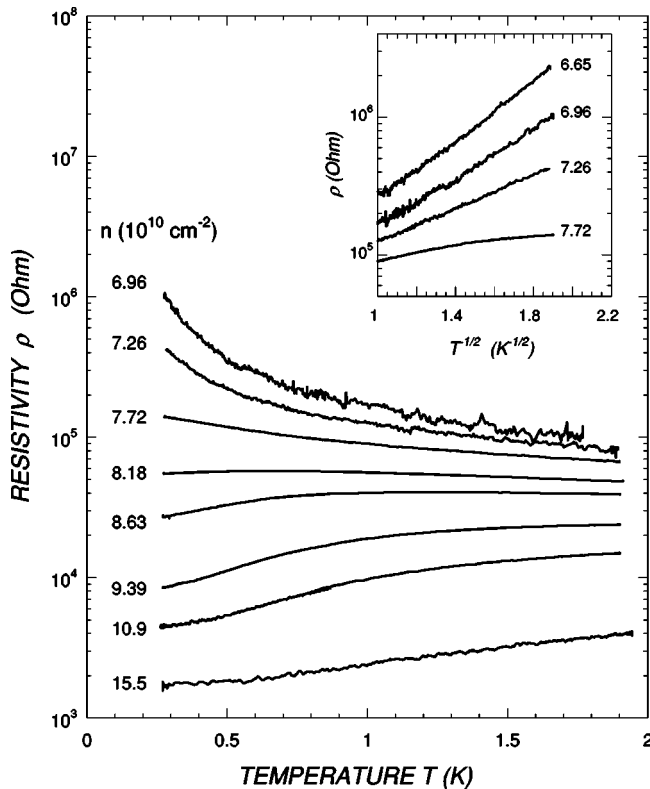


FIG. 1. Resistivity in zero field as a function of temperature for several electron densities, as labeled. The critical density for the conductor-insulator transition is  $7.87 \times 10^{10} \text{ cm}^{-2}$ . For electron densities  $n_s < n_c$ , the inset shows the log of the resistivity versus  $T^{-1/2}$ , demonstrating that Efros-Shklovskii variable-range hopping is obeyed for low densities.

to a parallel magnetic field is qualitatively the same in the insulating phase, varying continuously for electron densities spanning the transition from insulating to conducting behavior. This implies that spins play as crucial a role in the insulating phase as they do in the conducting phase.

The silicon MOSFET's used in these studies were samples with split gates especially designed for measurements at low electron densities and low temperatures similar to those used previously in Ref. 18. The split gates allowed independent control of the electron density in the main channel and in the contact region, allowing a high ( $\sim 10^{12} \text{ cm}^{-2}$ ) electron density to be maintained near the contacts to minimize contact resistance. Sample mobilities at  $T = 4.2 \text{ K}$  were close to  $25\,000 \text{ cm}^2/\text{Vs}$ .

The resistivity is shown in Fig. 1 on a logarithmic scale as a function of temperature for different electron densities  $n_s$  (determined by the voltage applied between the gate and the 2D layer) spanning the metal-insulator transition. The data were taken using low-frequency (typically 0.5 Hz) and low-current ac techniques at higher densities (six lower curves) and low-current dc techniques at lower  $n_s$  (two upper curves); the latter resulted in noisier data. In all cases, care was taken to ensure linearity. The resistivity increases (decreases) with decreasing temperature for low (high) electron densities, signaling a transition from insulating to conducting behavior at a critical electron density  $n_c = (7.87 \pm 0.10) \times 10^{10} \text{ cm}^{-2}$ . The upper two curves in the main figure are clearly in the insulating phase and the third curve from the top is barely insulating.

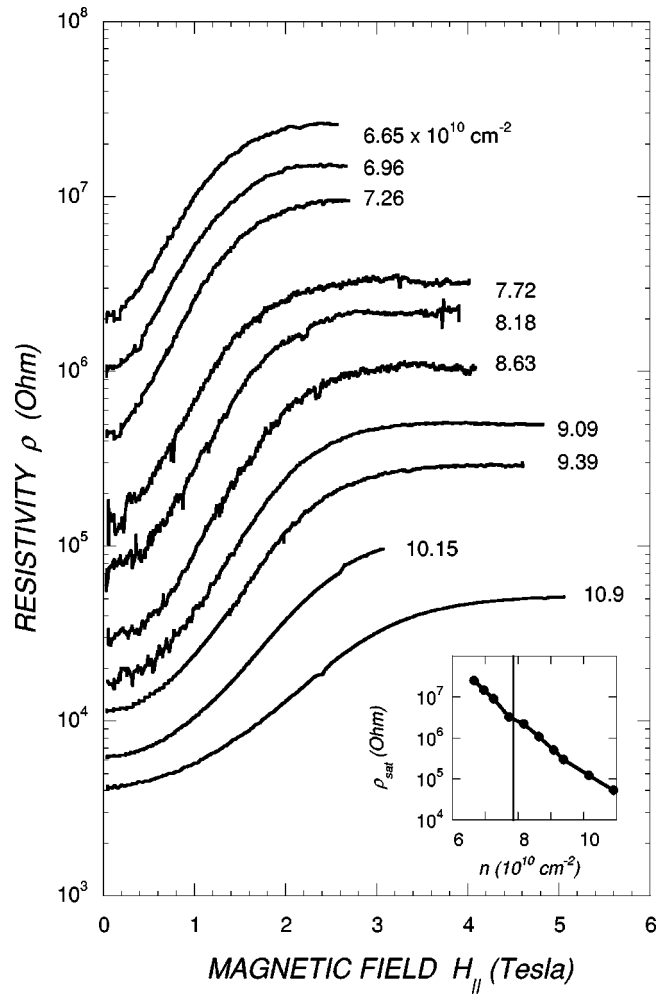


FIG. 2. Resistivity at 300 mK as a function of in-plane magnetic field for different electron densities spanning the conductor-insulator transition. The inset shows the resistivity at saturation,  $\rho_{sat}$ , versus electron density; the vertical line denotes the critical density.

For electron densities spanning the transition, Fig. 2 shows the resistivity at 300 mK as a function of magnetic field applied parallel to the plane of the electrons; the top three curves are insulating in zero field while the remaining curves are in the conducting phase. Again, a low-frequency/low-current ac technique was used at the higher densities (three lower curves) and a low-current dc technique was used at lower  $n_s$ . Measurements have indicated that the overall size of the magnetoresistance is larger at low temperatures and for samples of higher mobility. As reported earlier,<sup>14,15</sup> the resistivity remains approximately constant at small fields, then rises steeply with increasing field by more than an order of magnitude (depending on the electron density) and saturates to a new value for fields above about 2 or 3 T, depending again on electron density. The inset shows  $\rho_{sat}(H_{||})$  as a function of  $n_s$ ; the vertical line denotes our estimate for the critical density  $n_c$ . The surprise here is that the behavior of the magnetoresistance is essentially the same in the insulating phase as in the conducting phase. The response of the resistivity to parallel field evolves continuously and smoothly, with no indication that a transition has been crossed. A similar giant increase of the resistivity in response

to an in-plane magnetic field has been observed recently by Khondaker *et al.*<sup>19</sup> in insulating  $\delta$ -doped GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures.

In agreement with earlier reports,<sup>20</sup> the inset to Fig. 1 shows that in the absence of a magnetic field, the resistivity of these high-mobility silicon MOSFET's for  $n_s < n_c$  obeys variable-range hopping of the Efros-Shklovskii (ES) form,<sup>21</sup>  $\rho(T) = \rho_0 \exp(T_0/T)^{1/2}$ , where  $\rho_0$  was found to be independent of temperature and close to  $h/e^2$ . As expected, departures from this form are evident at higher temperatures (for  $T^{-1/2} < 1.1$ ) as well as for the density  $n_s = 7.72 \times 10^{10} \text{ cm}^{-2}$  very close to the transition. We note that the insulating  $\delta$ -doped GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures that show very strong response to in-plane magnetic field<sup>19</sup> were also found to obey ES hopping with a constant prefactor.<sup>22</sup>

The magnetoresistance of 3D materials that exhibit ES hopping has been found to be net negative in some cases<sup>23</sup> and positive in others.<sup>24</sup> A large, negative magnetoresistance that depends strongly on temperature has been attributed<sup>25,26</sup> to the effect of a magnetic field on the quantum interference between forward-scattering hopping paths. However, this process, as well as all others of orbital origin, is not relevant to the case under consideration, where a magnetic field is applied parallel to the two-dimensional plane of the electrons and couples only to the spins.

Korube and Kamimura<sup>27</sup> have proposed that alignment of the electrons' spins can give rise to a positive magnetoresistance by suppressing hops between singly occupied states via the Pauli exclusion principle. This mechanism yields a resistivity that increases with increasing field and saturates when the spins are fully aligned, consistent with the behavior shown in Fig. 2 for silicon MOSFET's. Albeit considerably smaller, a positive component of the magnetoresistance of In<sub>2</sub>O<sub>3-x</sub> films has been attributed to this mechanism.<sup>28</sup> We point out, however, that the theory of Korube and Kamimura assumes that the electron-electron interaction energy is considerably smaller than the disorder energy, a condition that is unlikely to be satisfied in these high-mobility, low-density silicon MOSFET's.<sup>29</sup> Based on their earlier paper,<sup>30</sup> Si and Varma have suggested that the positive magnetoresistance associated with suppression of the triplet channel contribu-

tion should vary smoothly across the transition. Others have suggested<sup>31,32</sup> that the giant magnetoresistance is due to the breaking of spin singlets in the insulating phase. It is important to note that the similarity of the magnetoresistances in the conducting and insulating phases indicates that they derive from the same or closely connected physics, suggesting a mechanism that is not specific to hopping or to insulators.

Based on transport studies in exceptionally clean  $p$ -GaAs/Al<sub>x</sub>Ga<sub>1-x</sub>As heterostructures with "insulating" densities ( $n_s < n_c$ ), Yoon *et al.*<sup>33</sup> concluded that the insulating phase is associated with the formation of a Wigner crystal rather than with single-particle localization. The possibility that the insulating state at low electron (hole) densities is due to the formation of a pinned Wigner glass was also suggested in Refs. 11 and 34. A very large (many orders of magnitude) increase in the resistance of dilute Si MOSFET's in perpendicular magnetic field observed in Ref. 35 was also attributed to the formation of a magnetically induced Wigner glass. A strong positive magnetoresistance is obtained by Chakravarty *et al.*<sup>36</sup> in a spin liquid phase, which freezes in a continuous phase transition to a Wigner glass; within this model, the magnetic properties are continuous across the transition and the magnetoresistance remains positive in the insulating phase.

To summarize, the magnetoresistance of the 2D system of electrons in silicon MOSFET's varies continuously across the metal-insulator transition, exhibiting unexpected behavior in the insulating phase. The response to a magnetic field applied parallel to the plane of the electrons is dramatic and entirely similar to that found earlier in the conducting phase, indicating that the anomalous behavior associated with the electrons' spins is a general feature of very dilute, strongly interacting 2D electron systems.

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