

Possible metal-insulator transition at  $B = 0$  in two dimensions

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We have studied the zero magnetic field resistivity  $\rho$  of unique high-mobility two-dimensional electron systems in silicon. At very low electron density  $n_s$  (but higher than some sample-dependent critical value  $n_{cr} \sim 10^{11} \text{ cm}^{-2}$ ), conventional weak localization is overpowered by a *sharp drop of  $\rho$  by an order of magnitude* with decreasing temperature below  $\sim 1$ -2 K. No further evidence for electron localization is seen down to at least 20 mK. For  $n_s < n_{cr}$ , the sample is insulating. The resistance is empirically found to scale with temperature both below and above  $n_{cr}$  with a single parameter that approaches zero at  $n_s = n_{cr}$  suggesting a metal-insulator phase transition.

Although the problem of localization in disordered electron systems has been studied both theoretically and experimentally for more than a decade, there remain serious unanswered questions. Abrahams and co-workers predicted<sup>1</sup> that all the electron states in a disordered two-dimensional electron system (2DES) in zero magnetic field are localized at zero temperature. This implies that there is no metal-insulator ( $M$ - $I$ ) transition in an infinite 2D sample. Recently, interest in this and related problems has intensified with studies of the superconductor-insulator transition in ultrathin metal films.<sup>2,3</sup> Furthermore, Azbel predicted<sup>4</sup> that, contrary to Ref. 1, a system of noninteracting 2D electrons in a model disorder potential with a random set of “ $D$ -function” scatterers at zero magnetic field and zero temperature is localized *only* at energies below some mobility edge. At all energies above this edge, extended states exist. According to Azbel,<sup>4</sup> the disagreement between his results and Ref. 1 might indicate that the resistance strongly depends on the range of the scattering centers. For the 2DES in silicon metal-oxide-semiconductor field-effect transistors (MOSFET’s), Azbel’s results might be applicable because the predominant scatterers in these samples, particularly at low electron densities, have been shown<sup>5</sup> to be short range, similar to the model potential.

In the beginning of the 1980s, good agreement between theory<sup>1</sup> and experiment was achieved on samples with rather low mobility. Experimental evidence for logarithmic decrease of conductance with lowering  $T$  was reported in Refs. 6 and 7. For samples with higher mobility, an approximately linear *increase* of conductivity with decreasing temperature was found at temperatures  $\gtrsim 1$  K,<sup>8,9</sup> at electron densities  $n_s \gtrsim 4 \times 10^{11} \text{ cm}^{-2}$ . This was explained by the temperature dependence of the screening function for elastic scattering.<sup>10,11</sup> At low temperatures,  $T \lesssim 1$  K, this increase in conductivity is again limited by weak localization.<sup>9</sup>

Further improvement in the quality of samples has enabled access to a qualitatively new level for this problem, where the electron-electron interaction, rather than

disorder, becomes the dominant parameter. For instance, recent studies of the insulating behavior for new ultrahigh-mobility MOSFET samples<sup>12</sup> produced strong, previously unobtainable evidence that the main mechanism for localization at low  $n_s$  in zero magnetic field is the formation of a pinned electron solid due to these strong electron-electron interactions.

Here we extend these studies to concentrate on slightly higher electron densities where localization is absent at least down to 20 mK. We report interesting unprecedented behavior in similar ultrahigh-mobility (up to  $7.1 \times 10^4 \text{ cm}^2/\text{V s}$ ) Si MOSFET’s. At zero magnetic field and at low electron densities (but higher than some critical value  $n_{cr} \sim 10^{11} \text{ cm}^{-2}$ ), we have found that a conventional weak localization, observed at  $T \gtrsim 1$ -2 K, is overpowered by a *sharp drop of  $\rho$  by an order of magnitude* as the temperature is decreased. We then see no signs of electron localization down to the lowest available temperature, 20 mK. At  $n_s < n_{cr}$ , the resistivity monotonically increases as  $T \rightarrow 0$ , indicating an insulating state studied extensively elsewhere.<sup>12</sup> At  $n_s$  both below and above  $n_{cr}$  we have observed that the resistivity scales with temperature with a single parameter.

Four samples from wafers with different mobilities have been studied: Si-15 with maximum mobility  $\mu_{max}$  of  $7.1 \times 10^4 \text{ cm}^2/\text{V s}$ , Si-12 with  $\mu_{max} = 3.3 \times 10^4 \text{ cm}^2/\text{V s}$ , Si-14 with  $\mu_{max} = 1.9 \times 10^4 \text{ cm}^2/\text{V s}$ , and Si-39 with  $\mu_{max} = 0.5 \times 10^4 \text{ cm}^2/\text{V s}$ . Mobility as a function of electron density for these samples is shown in Fig. 1. All samples are rectangular with a source to drain length of 5 mm, a width of 0.8 mm, and an intercontact distance of 1.25 mm. The resistance was measured using a four-terminal dc technique with a high input resistance digital voltmeter. For each sample we observed the same  $\rho(T)$  characteristics independent of contact configuration. The  $I$ - $V$  characteristics of an electron gas are, in general, nonlinear.<sup>6,7,12</sup> All data discussed here are within the linear  $I$ - $V$  region.

Figure 2 shows  $\rho$  versus temperature for Si-15, Si-12, and Si-14 at different electron densities. At  $T \gtrsim 2$  K,

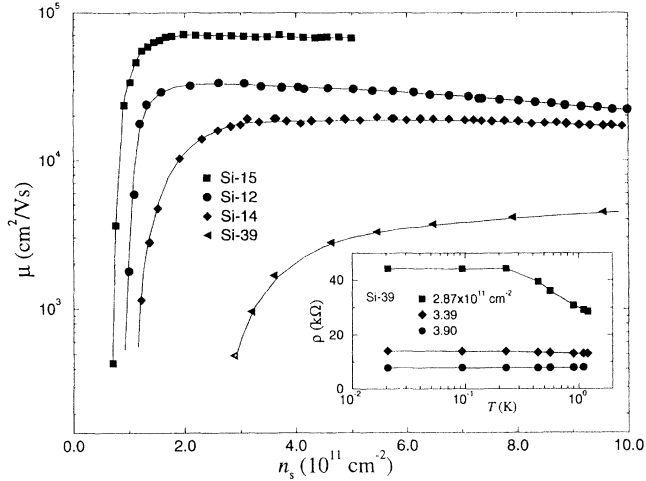


FIG. 1. Mobility vs  $n_s$  for different samples at  $T = 20$  mK (Si-15 and Si-39) and 60 mK (Si-12 and Si-14). Inset shows  $\rho(T)$  for Si-39 at several  $n_s$ .

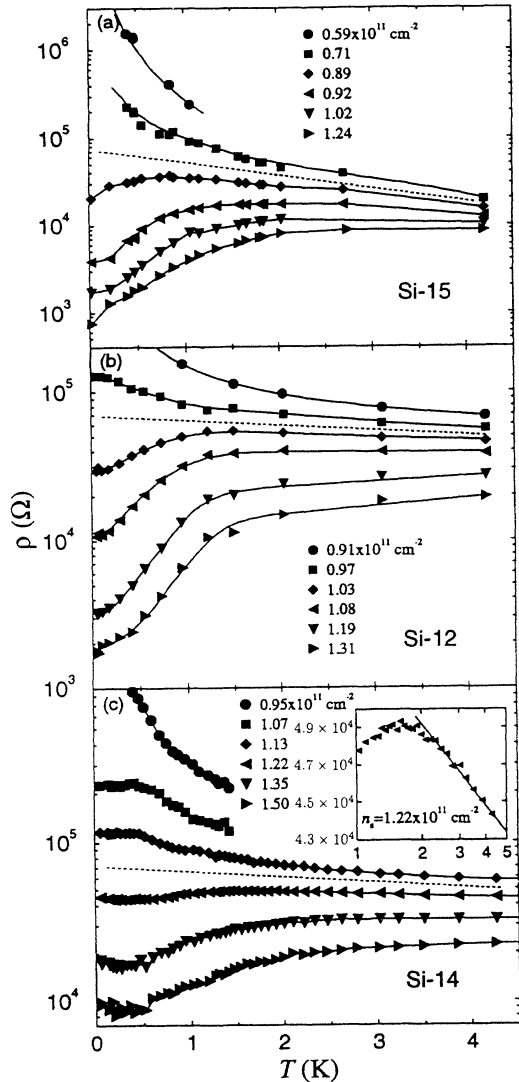


FIG. 2. Resistivity vs  $T$  for electron densities near  $n_{cr}$  for Si-15 (a), Si-12 (b), and Si-14 (c). Inset shows a temperature dependence of  $\rho$  consistent with weak localization ( $\Delta\rho \propto \log T$ ) at temperatures above the drop of  $\rho$ .

temperature dependencies of  $\rho$  dependencies are rather weak:  $\rho$  increases slowly with decreasing temperature consistent with weak localization [ $\Delta\rho \propto \log T$ ; see inset to Fig. 2(c)] for the four upper curves for each sample and stays constant or decreases slightly for the two lowest  $\rho$  curves. But as the temperature is further decreased, for all curves below some “critical”  $\rho(T)$  indicated by dotted lines in Fig. 2,  $\rho$  sharply drops *overpowering the onset of localization visible at higher temperature*. Note that, at  $T \lesssim 1$  K, no further evidence for electron localization is seen at temperatures down to 20 mK for the curves below the critical lines. According to Ref. 7, in low-mobility samples true metallic behavior (i.e.,  $\rho$  independent of temperature or decreasing as  $T$  decreases) never has been seen, and a weak increase of the resistance with decreasing temperature is always present. In contrast, for the curves below the critical lines, at least for Si-15 and Si-12, we observe *strongly* metallic behavior, a strong decrease of  $\rho$  with decreasing temperature. At the same time, for the curves above the critical line, resistivity grows continuously with decreasing temperature, showing a permanently localized state.

For all three samples shown in Figs. 2, one can see a remarkable symmetry of  $\rho(T)$  dependencies about the critical lines, especially for the two curves adjacent to these lines. This is reminiscent of flow lines around a repulsive fixed point at  $T = 0$  similar to that for the quantum Hall effect.<sup>13</sup> Similar behavior has been also reported for the superconductor-insulator transition in disordered metal films.<sup>2,3</sup> Note that the critical lines for samples with different mobility tend to the same  $\rho \sim 7 \times 10^4 \Omega$  as  $T \rightarrow 0$ .

The low- $T$  behavior of  $\rho(T)$  becomes less temperature dependent with decreasing mobility: for example, for Si-14 the characteristic relative drop of the resistivity is approximately three times weaker than for Si-15. Eventually, for the lowest-mobility sample, Si-39, the low-temperature drop does not exist (see inset in Fig. 1). This last  $\rho(T)$  is consistent with that observed in conventional Si MOSFET’s as reported in Ref. 7.

We have performed a one-parameter scaling analysis for the resistivity in the temperature region 350 mK to 4.2 K, above the low-temperature saturation, for the curves lying both below (“metallic” side) and above (“insulating” side) the critical line. The results for the best sample, Si-15, are shown in Fig. 3. One can see that the resistivity can be written in a scaled form, i.e.,  $\rho(T, n_s) \approx \rho(T/T_0(n_s))$ . Resistivities for the metallic side collapse into a single curve except for the curve closest to the boundary with  $n_s = 0.89 \times 10^{11} \text{ cm}^{-2}$ . Resistivities for the insulating side similarly collapse into a single curve. The density dependence of  $T_0$  is shown in the inset. For both metallic and insulating sides,  $T_0$  falls sharply as  $n_s$  approaches the critical electron density,  $n_{cr} \approx 0.85 \times 10^{11} \text{ cm}^{-2}$ . This scaling analysis gives results similar to the beautiful results presented in Ref. 3 for superconductor-insulator transition in disordered Bi films.

The observed absence of localization for  $n_s > n_{cr}$  at  $T \rightarrow 0$ , the sharp well-defined threshold between two types of behavior, and the satisfactory single-parameter

scaling of the resistivity suggest a phase transition. This suggestion is consistent with Azbel's theory.<sup>4</sup> However, our results are not conclusive evidence for the existence of a true  $M-I$  transition in a 2DES at zero temperature due to the finite sample size and finite temperature.

It is impossible to explain the observed sharp drop of  $\rho$  at low  $T$  with the same mechanism (temperature-dependent screening) suggested in Refs. 9–11 as the physical cause for weak decrease in  $\rho$  with decreasing temperature observed at higher  $n_s$  and  $T$ .<sup>8,9</sup> For temperatures less than the collision broadening of the energy levels,

$$T < T_c = \hbar/2\tau k_B \sim 3 \times 10^4 \text{ K V s/cm}^2 \times \mu^{-1}, \quad (1)$$

the singularity in the dielectric function is washed out by collision broadening,<sup>14</sup> and the temperature dependence of  $\rho$  should disappear (here  $\tau$  is the elastic scattering time). In our situation,  $\mu$  gets very low at low  $n_s$  and therefore the cutoff temperature  $T_c$  becomes very high, e.g.,  $\sim 30$  K for  $\mu = 1 \times 10^3 \text{ cm}^2/\text{V}$  whereas the drop of  $\rho$  is observed at  $T \lesssim 1\text{--}2$  K.

Because the observed low-temperature drop of  $\rho$  is so large, and because it overcomes weak localization, it is reasonable to assume that it is caused by the destruction of the dominant scattering mechanism for the 2DES. For low  $n_s$ , this mechanism is ionized impurity scattering.<sup>15</sup> A typical density for ionized impurities in high-mobility samples is  $n_i \sim 10^{10} \text{ cm}^{-2}$ ,<sup>9,12</sup> which corresponds to an average distance between charged scattering centers  $\sim 10^3 \text{ \AA} \gg r_B \sim 20 \text{ \AA}$ , the Bohr radius. Therefore these impurities can be considered independent. A possible single-particle mechanism for the destruction of the ionized impurity scattering could be as follows. In principle, for  $n_i \ll n_s$  one should expect a strong drop of the resistance at temperatures below  $T_b = E_b/k_B$  ( $E_b$  is the binding energy), where the charged scattering centers start to bind electrons: in this case, the scatterers are neutralized by trapped electrons, and, therefore, the scattering of residual free electrons is much weaker than at  $T > T_b$ . The binding energy for a single electron is  $\sim 40$  meV for Si MOSFET's, but screening by free electrons strongly affects this figure. In Ref. 16, where the effect of screening was taken into account, the binding energy was calculated to be a few tenths of meV, making  $T_b \sim T_{cr} \sim \text{few kelvin}$  conceivable but somewhat unlikely. In the framework of this model, it is also difficult to account for the scaling behavior of resistivity and for the striking symmetry of  $\rho(T)$  about the dotted lines in Fig. 2.

Another physical cause for the observed drop in  $\rho$  could be electron-electron interactions which have the largest characteristic energy at electron densities around  $10^{11} \text{ cm}^{-2}$ :

$$\begin{aligned} E_{e-e} &\sim \frac{e^2}{\epsilon} n_s^{1/2} \sim 5 \text{ meV} \gg E_F \\ &= \frac{\pi \hbar n_s}{2m^*} \sim 0.6 \text{ meV} \sim \hbar/\tau \end{aligned} \quad (2)$$

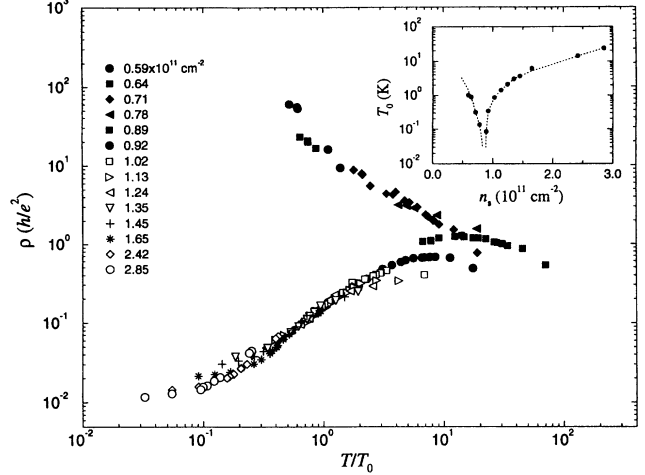


FIG. 3. Scaling behavior of the resistivity for Si-15. Inset shows density dependence of the scaling parameter  $T_0$ .

(here  $E_{e-e}$  is the energy of electron-electron interactions,  $e$  is the electron charge,  $\epsilon$  is the dielectric constant,  $E_F$  is the Fermi energy, and  $m^*$  is the effective mass). In fact, there is strong evidence<sup>12</sup> that the insulating behavior at  $n_s < n_{cr}$  is caused by an electron solid formation due to these strong electron-electron interactions. One could suppose that the state of the system near the  $M-I$  transition, on the metallic side, is an electron liquid dominated by a macroscopic multielectron wave function which suppresses scattering. The existence of such a “liquid crystal” was discussed earlier (see, e.g., Ref. 17) and recently has obtained strong experimental support.<sup>18</sup> The symmetry of  $\rho(T)$  depicted in Fig. 2 and common characteristic temperatures observed for localized and extended state anomalies are indicators of a common mechanism. This favors a many-body mechanism for the low-temperature resistivity drop. This effect would not exist in more disordered samples such as Si-39, where disorder dominates the system at lower densities, destroying the coherence necessary to observe the multielectron collective state.

Finally, we would like to note that the similar destruction of already started localization by decreasing temperature was recently observed at Landau level filling factor  $\nu = 1$  at very low  $n_s$ , on the border of the existence of the quantum Hall effect.<sup>19</sup> There it was considered as evidence for the temperature-induced sinking of the lowest extended state below the Fermi level as  $T \rightarrow 0$ ; in this sense, the effect of temperature was equivalent to the effect of the disorder. If one admits the existence of the mobility edge in zero magnetic field (prohibited by the scaling theory<sup>1</sup> and predicted by Azbel<sup>4</sup>), similar “sinking” of the energy of the mobility edge with decreasing temperature can cause the dramatic drop of  $\rho$  reported here.

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<sup>1</sup> E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, *Phys. Rev. Lett.* **42**, 673 (1979).

<sup>2</sup> A. F. Hebard and M. A. Paalanen, *Phys. Rev. Lett.* **65**, 927 (1990).

<sup>3</sup> Y. Liu, K. A. McGreer, B. Nease, D. B. Haviland, G. Martinez, J. W. Halley, and A. M. Goldman, *Phys. Rev. Lett.* **67**, 2068 (1991).

<sup>4</sup> M. Ya. Azbel, *Phys. Rev. B* **45**, 4208 (1992).

<sup>5</sup> T. Ando, A. B. Fowler, and F. Stern, *Rev. Mod. Phys.* **54**, 437 (1982).

<sup>6</sup> D. J. Bishop, D. C. Tsui, and R. C. Dynes, *Phys. Rev. Lett.* **44**, 1153 (1980).

<sup>7</sup> M. J. Uren, R. A. Davies, M. Kaveh, and M. Pepper, *J. Phys. C* **14**, 5737 (1981).

<sup>8</sup> K. M. Cham and R. G. Wheeler, *Phys. Rev. Lett.* **44**, 1472 (1980).

<sup>9</sup> E. A. Vyrodov, V. T. Dolgoplov, S. I. Dorozhkin, and N. B. Zhitenev, *Zh. Eksp. Teor. Fiz.* **94**, 234 (1988) [Sov.

*Phys. JETP* **67**, 998 (1988)].

<sup>10</sup> F. Stern, *Phys. Rev. Lett.* **44**, 1469 (1980).

<sup>11</sup> A. Gold and V. T. Dolgoplov, *Phys. Rev. B* **33**, 1076 (1986).

<sup>12</sup> V. M. Pudalov, M. D'Iorio, S. V. Kravchenko, and J. W. Campbell, *Phys. Rev. Lett.* **70**, 1866 (1993).

<sup>13</sup> M. M. Pruisken, in *The Quantum Hall Effect*, edited by R. E. Prange and S. M. Girvin (Springer-Verlag, New York, 1987), p. 117.

<sup>14</sup> S. Das Sarma, *Phys. Rev. B* **33**, 5401 (1986).

<sup>15</sup> F. Stern and W. E. Howard, *Phys. Rev.* **163**, 816 (1967).

<sup>16</sup> B. Vinter, *Surf. Sci.* **98**, 197 (1980).

<sup>17</sup> B. I. Halperin and D. R. Nelson, *Phys. Rev. Lett.* **41**, 121 (1978).

<sup>18</sup> G. M. Summers, R. J. Warburton, J. G. Michels, R. J. Nicholas, J. J. Harris, and C. T. Foxon, *Phys. Rev. Lett.* **70**, 2150 (1993).

<sup>19</sup> S. V. Kravchenko, Whitney Mason, J. E. Furneaux, J. M. Caulfield, J. Singleton, and V. M. Pudalov, in *Proceedings of 4th International Symposium on Research in High Magnetic Fields*, Nijmegen, 1994 [Physica B (to be published)].