Metallic Low-Temperature Resistivity in a 2D Electron System Over an Extended Temperature Range

S. V. Kravchenko
Physics Department, Northeastern University, Boston, Massachusetts 02115

T. M. Klapwijk
Department of Applied Physics, Delft University of Technology, 2628 CJ Delft, The Netherlands
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We report measurements of the zero-field resistivity in a dilute 2D electron system in silicon at temperatures down to 35 mK. This extends the previously explored range of temperatures in this system by almost an order of magnitude. On the metallic side, the resistivity near the metal-insulator transition continues to decrease with decreasing temperature and shows no low-temperature upturn. At the critical electron density, the resistivity is found to be temperature independent in the entire temperature range from 35 mK to 1 K.

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Although the behavior suggestive of a zero magnetic field metal-insulator transition (MIT) in two dimensions (2D) was first reported six years ago, it still remains unexplained, with proposed driving mechanisms ranging from contaminations in the oxide to superconductivity, and from percolation to a non-Fermi-liquid state [1,2]. One of the unusual features of dilute 2D systems is a dramatic drop in the resistivity on the metallic side of the transition. This drop becomes apparent below a characteristic temperature $T^* \sim \frac{1}{3} T_F$, where T_F is the Fermi temperature. T^* is rather high but approaches zero at the critical particle density. The relatively high value of T^* prompted classical approaches to the problem [3,4]. If the mechanism behind the unusual behavior is indeed classical, then quantum localization [5] should eventually take over at low enough temperatures, and in this case there will be no zero-temperature metal-insulator transition. This possibility calls for experiments to be done at the lowest temperatures possible.

A decrease of the resistivity with decreasing temperature in 2D systems (metallic behavior) does not by itself necessarily signal the presence of any unanticipated physics. It can be due, for example, to phonon scattering, as it is in p-GaAs/AlGaAs heterostructures at relatively high hole densities $\sim 10^{11}$ cm^{-2} [6]. At these densities, the conductivity is $\gtrsim 300 e^2/h$, and the system may look metallic down to inaccessibly low temperatures because logarithmic quantum corrections to the conductivity are only $\sim e^2/h$ per decade in temperature. But at the particle density, n_s, close to the critical density for the metal-insulator transition, n_c, the conductivity becomes of the order of e^2/h, and the decrease in temperature by a decade should now produce a decrease in conductivity that is comparable to the conductivity itself. Quantum corrections can only be seen at temperatures $T \ll T_F$. In p-GaAs/AlGaAs heterostructures, T_F at or near the critical hole density is very low, and the condition $T \ll T_F$ is hard to fulfill. For example, in Ref. [6], T_F is only about 300 mK [7] at the lowest (still metallic) hole density, and, although temperatures as low as 40 mK have been reached in that paper, the lowest T was of the order of $0.1 T_F$. More convenient systems to reach the condition $T \ll T_F$ at $n_s \sim n_c$ are silicon metal-oxide-semiconductor field-effect transistors (MOSFET's) and p-SiGe heterostructures, where T_F at $n_s = n_c$ is of the order of 5–10 K. However, although occasional data at temperatures as low as 16 mK for Si MOSFET's and 50 mK for p-SiGe were reported, the resistivity at electron-hole densities close to the MIT was carefully studied only down to ^{3}He temperatures (250–300 mK) [1,8,9].

In this Letter, we report studies of resistivity in high-mobility Si MOSFET's at temperatures down to 35 mK which extends the previously explored temperature range by almost an order of magnitude. We concentrate on electron densities near the metal-insulator transition, where the conductivity is $\lesssim e^2/h$. We show that even at these very low values of conductivity, but on the metallic side of the MIT ($n_s > n_c$), the metallic temperature dependence of the resistivity, characterized by $dR/dT > 0$, persists down to the lowest accessed temperatures, which are less than $10^{-2} T_F$ so the condition $T \ll T_F$ is well satisfied. On the insulating side of the transition ($n_s < n_c$), the behavior is always insulating, with $dR/dT < 0$. Between the metallic and insulating behaviors, at $n_s = n_c$, there exists a resistivity, ρ_c, which is practically temperature independent in the entire temperature range from 35 mK to 1 K. If one admits that the MIT-like behavior in two dimensions is merely a result of a competition between quantum localization and a classical decrease of the Drude resistivity, then the existence of such a temperature-independent curve would require cancellation of two unrelated strong mechanisms in a wide temperature range, a coincidence which seems hardly probable.

The samples used in our experiments were specially designed for measurements at low electron densities and low temperatures by use of the so-called split-gate technique.

Narrow (<100 nm) gaps in the gate metallization were introduced near the doped contact areas which allowed for maintaining high electron density near the contacts and therefore dramatically reduced their resistance. In the main part of the sample ($50 \times 120\ \mu m^2$) the electron density was controlled independently. Typical mobility dependence of the electron density, n_s, is shown in the inset to Fig. 1. The peak mobility of this sample was $2.3 \times 10^4\ cm^2/V\,s$ at 4.2 K. In the main part of the same figure, the temperature dependence of the resistivity is shown in the temperature range 100 mK to 9 K. Experimentally, in the same material the higher the peak mobility of the electrons the larger the low-temperature drop of the resistivity. Indeed, in this sample the drop is somewhat smaller than that in the best Si MOSFET's, being only a factor of 6 rather than >10. However, the samples studied in this paper were more convenient to use because of much higher quality of contacts which allowed reliable low-temperature transport measurements at these very low electron densities.

The samples were mounted at the end of a copper finger attached to the mixing chamber of a Kelvinox-100 dilution refrigerator with base temperature of 14 mK. The electron gas was cooled by 16 thick (0.5 mm) copper wires thermally coupled to the cold finger and mixing chamber, and connected to the contacts on the sample holder. Temperature was measured by a ruthenium oxide thermometer placed near the sample and connected to the mixing chamber and the cold finger by the same wires as the sample. Temperature readings by the thermometer were typically 10 mK higher than the temperature of the mixing chamber. To reduce the external noise, three sets of low-pass filters were used: *R-C-R* filters with a cutoff frequency of 40 Hz and two sets of *C-L-C* filters with a cutoff frequency of 500 kHz. Resistivity was measured by a four-terminal dc method, while holding the voltage drop across the whole sample (between two opposite current leads) to be less than 200 μV to ensure that the total power dissipated in the sample was always less than 10^{-13} W. The Fermi temperature was calculated using the electron density determined from the positions of the Shubnikov–de Haas oscillations in a weak perpendicular magnetic field and the value of the effective mass $0.19m_e$. The fact that the electron density does not change upon the application of the magnetic field was checked independently by low-temperature measurements of the Hall voltage and capacitance.

Figure 2 shows the temperature dependence of the resistivity at five different electron densities at temperatures down to 35 mK. The two upper curves display insulating behavior with $dR/dT < 0$ and two lower curves display metallic behavior with $dR/dT > 0$, in the entire temperature interval. The middle curve shows almost no temperature dependence. Deviations from the average value $\rho_c = 2.82h/e^2$ do not exceed $\pm 5\%$ (see the inset); at low temperatures, typically $\lesssim$300 mK, they are not reproducible from one cooldown to another and even in different temperature sweeps. Both above and below the temperature-independent curve the resistivity continues to change strongly down to the lowest temperature reached. This confirms that the temperature of the electron gas continues to change down to the lowest temperatures. Note that the change in the electron density, resulting in a sharp

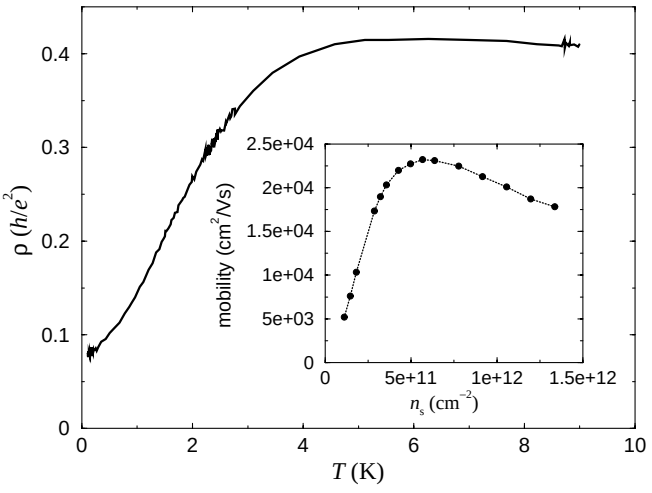

FIG. 1. Resistivity as a function of temperature at $n_s = 1.11 \times 10^{11}\ cm^{-2}$. The inset shows electron mobility vs electron density measured at 4.2 K.

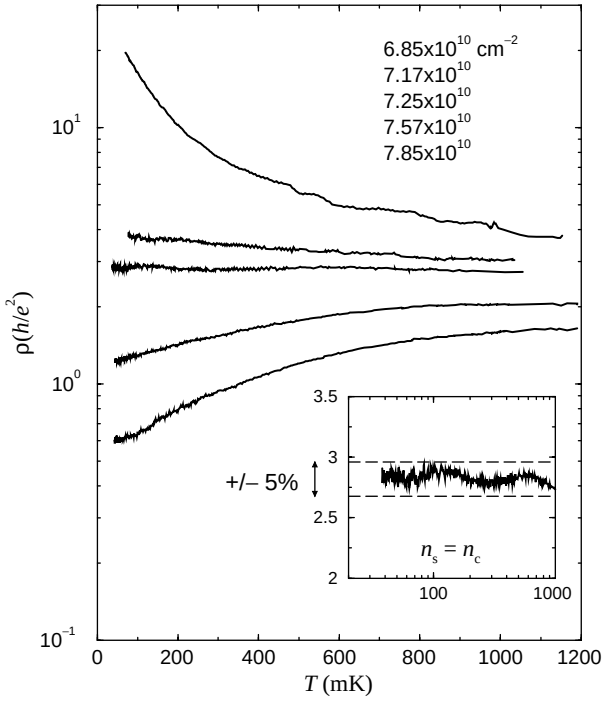

FIG. 2. Resistivity vs temperature at five electron densities as labeled. The inset shows that the middle curve ($n_s = 7.25 \times 10^{10}\ cm^{-2}$) changes by less than $\pm 5\%$ in the entire temperature range.

transition from strongly insulating to strongly metallic behavior, is less than 15%. In particular, a decrease of n_s by only 1% from its critical value is enough to cause a pronounced insulating behavior (see the second curve from the top which could be mistakenly identified as a "tilted separatrix" if the tuning of the electron density were not fine enough). Another obvious necessary condition to observe the flat separatrix is the high homogeneity of the electron density throughout the sample.

In the low-temperature limit, the two lower curves display metallic, near-linear temperature dependence, as shown in Figs. 3(a) and 3(b). The resistivity shows no insulating upturn in the low-temperature limit. The lowest temperature reached corresponds to a ratio T/T_F of less than 8×10^{-3} (see upper x axes in both figures). The almost linear temperature dependence observed near the MIT at these low temperatures is different from the exponential temperature dependence seen at higher temperatures and higher densities [8].

A striking feature of the data is the existence of a temperature-independent curve at $n_s = n_c$ which separates metallic ($dR/dT > 0$) and insulating ($dR/dT < 0$) behaviors. At resistivity levels on the order of or greater than h/e^2, one is in the regime where $k_F l \lesssim 1$ (here k_F is the Fermi vector and l is the mean free path). To illustrate the expected strength of the quantum corrections in this case, in Fig. 4 we plot the experimentally measured $\rho(n_c)$ together with the resistivity calculated from the one-parameter scaling theory (upper curve). We assumed that the single parameter scaling theory of localization holds even in the presence of very strong electron-electron interactions and that the Drude resistivity is temperature independent in this temperature range. We use the standard formula [5]

$$\frac{d\ln\rho(L_\phi)}{d\ln L_\phi} = -\beta(\rho). \tag{1}$$

Here $L_\phi \propto \rho^{-\gamma} T^{-p/2}$ is the phase-breaking length, p and γ are constants taken (after Ref. [4]) to be equal to 3 and 0.5, respectively, and $\beta(\rho)$ is the scaling function approximated as $\beta(\rho) = -\ln(1 + a\rho)$, where $a = 2/\pi$ and ρ is measured in units of h/e^2. The boundary condition is that at $T = 1$ K the calculated resistivity is equal to the measured one: $\rho(1\text{ K}) = 2.82$ [10]. As shown by the dashed curve in Fig. 4, by the time the temperature reaches 100 mK, quantum localization would increase the resistivity by a factor of more than 30.

The observation of a temperature-independent resistivity at $n_s = n_c$ over such a wide temperature range and at temperatures where the electron system is clearly fully degenerate is certainly consistent with the existence of the zero-temperature quantum phase transition. In

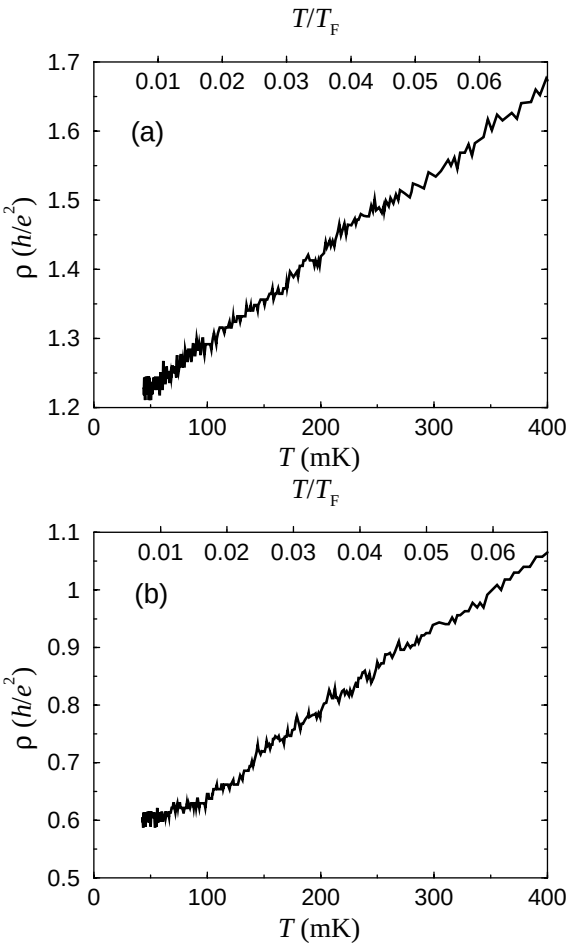

FIG. 3. Resistivities at $n_s = 7.57 \times 10^{10}$ cm^{-2} (a) and 7.85×10^{10} cm^{-2} (b) as functions of temperature (lower x axes) and as functions of the ratio T/T_F (upper x axes).

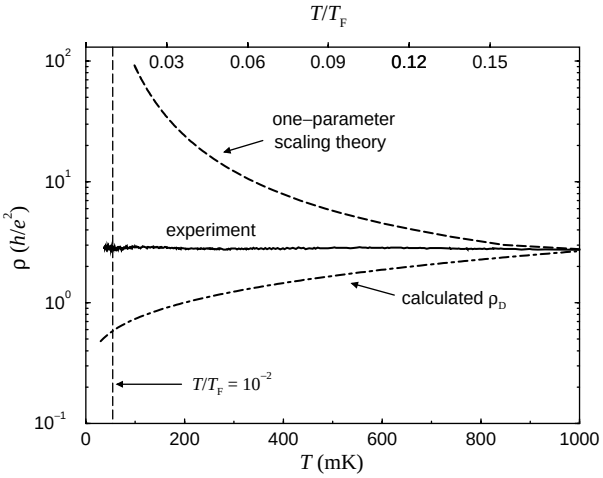

FIG. 4. Resistivity at the separatrix (the middle curve of Fig. 2) as a function of temperature (lower x axis) and as a function of the ratio T/T_F (upper x axis) compared to that calculated using one-parameter scaling theory (the dashed curve); see text. As the dashed line shows, by the time the temperature reaches 100 mK, the resistivity of a "conventional" 2D system would have increased by a factor of more than 30. The dotted-dashed lower curve shows the calculated Drude resistivity required to produce the temperature-independent resistivity between metallic and insulating behaviors.

combination with the results of Ref. [1], where the temperature-independent curve (with essentially the same value of resistivity as in this paper) was observed in the temperature range 250 mK–1.8 K in another 2D system in silicon, we further allege that there is no appreciable temperature dependence at $n_s = n_c$ in the temperature range from 35 mK to 1.8 K, i.e., for temperatures between approximately $6.5 \times 10^{-3} T_F$ in this paper to $0.25 T_F$ in Ref. [1]. At higher temperatures, the resistivity at $n_s = n_c$ starts to decrease slowly with increasing temperature (see, e.g., Ref. [8]). One possible cause of this behavior can be quantum-classical crossover which leads to insulatinglike temperature dependence at temperatures comparable to or greater than T_F [Refs. [3(b)] and [3(c)]].

The existence of a temperature-independent curve between insulating and metallic behaviors was also reported in another 2D system, p-GaAs/AlGaAs heterostructure [11], at temperatures below 150 mK. Above this temperature, the resistivity slowly decreases with increasing temperature similar to its behavior in our system at $T \gtrsim 1.8$ K. Taking into account the much lower value of $T_F \sim 800$ mK [7] in the sample used in Ref. [11] compared to our system, one may suggest that, as in our case, the loss of full degeneracy causes this behavior.

In samples with lower mobility, the temperature-independent curve between metallic and insulating behaviors no longer exists, as can be seen, e.g., in Fig. 4 of Ref. [9]: below a certain temperature ~ 1 K, the curve, which is nearly flat at higher T, turns "insulating." In very disordered samples, the metallic behavior is not seen at all.

Of course, the fact that we have observed no insulating-like upturn of the resistivity in a wide, but still restricted, range of temperatures does not necessarily mean that the system will remain metallic at zero temperature. As has already been mentioned, if the MIT-like behavior observed by us and others were a result of competition between Anderson localization and a temperature-dependent Drude resistivity, $\rho_D(T)$, the localization would eventually dominate at low temperatures. However, the existence of the temperature-independent curve between metallic and insulating behaviors makes this possibility unlikely. Indeed, it would require the Drude resistivity to have a very special temperature dependence (see Eq. (6) in Ref. [4]):

$$\frac{d \ln \rho_D(T)}{d \ln T} = \frac{p}{2} \left(1 - \frac{1}{\beta(\rho_D(T))} \right)^{-1}. \qquad (2)$$

The Drude resistivity calculated by using this equation with the same boundary conditions as before is shown in Fig. 4 by the dot-dashed line. We note that the shape of $\rho_D(T)$ required to produce a temperature-independent curve is determined by the β function, which comes from the scaling theory, and the parameter p, which comes from the relation between L_ϕ and T. It would therefore be a remarkable coincidence if the required $\rho_D(T)$ dependence over a wide temperature range was produced by some classical mechanism not related *a priori* to either β or p [12].

In summary, we have shown experimentally that the strong metallic temperature dependence of the resistivity in silicon MOSFET's survives down to at least 35 mK. This extends the previously explored range of temperatures by almost an order of magnitude. At these temperatures, the system is clearly fully degenerate with the ratio T/T_F being less than 10^{-2}. At the critical electron density, the resistivity is practically temperature independent in the entire temperature interval. These observations put valuable constraints on possible theoretical explanations.

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[1] M. P. Sarachik and S. V. Kravchenko, Proc. Natl. Acad. Sci. U.S.A. **96**, 5900 (1999), and references therein.
[2] E. Abrahams, Ann. Phys. (Leipzig) **8**, 539 (1999), and references therein.
[3] (a) B. L. Altshuler and D. L. Maslov, Phys. Rev. Lett. **82**, 145 (1999); (b) T. M. Klapwijk and S. Das Sarma, Solid State Commun. **110**, 581 (1999); (c) S. Das Sarma and E. H. Hwang, Phys. Rev. Lett. **83**, 164 (1999).
[4] B. L. Altshuler, D. L. Maslov, and V. M. Pudalov, cond-mat/9909353.
[5] E. Abrahams, P. W. Anderson, D. C. Licciardello, and T. V. Ramakrishnan, Phys. Rev. Lett. **42**, 673 (1979).
[6] A. P. Mills, Jr., A. P. Ramirez, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **83**, 2805 (1999).
[7] Based on the effective mass $m^* = 0.37 m_e$; see K. Hirakawa *et al.*, Phys. Rev. B **47**, 4076 (1993).
[8] V. M. Pudalov, G. Brunthaler, A. Prinz, and G. Bauer, JETP Lett. **68**, 442 (1998).
[9] X. G. Feng, D. Popović, and S. Washburn, Phys. Rev. Lett. **83**, 368 (1999).
[10] By choosing this boundary condition we assume that the cutoff temperature at which localization effects become negligible is of the order of 1 K. In reality, it is likely to be higher, and this would lead to even stronger quantum corrections.
[11] Y. Hanein *et al.*, Phys. Rev. B **58**, R7520 (1998).
[12] We stress that Eq. (6) in Ref. [4] is obtained for a very general case, without assuming any particular mechanism for the possible temperature dependence of ρ_D.