A new metal in two dimensions

X. G. Feng*, Dragana Popović*, S. Washburn† & V. Dobrosavljević*
*National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310, USA
†Dept. of Physics and Astronomy, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA

The unexpected discovery[1,2] of the existence of a metallic state at zero temperature in two dimensions has been confirmed in a variety of two-dimensional electron[3–6] and hole[7–10] systems. However, there is still no generally accepted microscopic description of the metallic phase and the metal-insulator transition in two dimensions. The metallic phase has been characterized by an increase of conductivity with decreasing temperature. Both magnetic field[11,12] and an arbitrarily small amount of spin flip scattering by local magnetic moments[13] suppress such a metallic phase, and lead to a decrease in conductivity as the temperature is lowered. Here we show that, in the presence of local moments, this behaviour describes a new and unexpected kind of metal in two dimensions. In addition, we report the discovery of a novel type of a metal-insulator transition, which occurs between this metal and an insulating state as the carrier density is reduced. While the transition is analogous to that observed in some three-dimensional systems, it is unlike any known quantum phase transition in two dimensions.

Our experiment was carried out on Si metal-oxide-semiconductor field-effect transistors (MOSFETs), where the two-dimensional (2D) electron system is formed by confining the electrons to the Si side of the Si-SiO_2 interface. At low temperatures (T), electrons are quantized in the lowest energy state perpendicular to the interface, and are thus forced to move in a plane parallel to it. The electron density n_s is varied by applying voltage V_g to the metallic gate. As a result of disorder (potential scattering by the charges in the oxide and by the roughness of the interface), the 2D density of states of each state perpendicular to the oxide interface acquires a tail of strongly localized states. In some samples, including ours, some of the localized states in the tail of the first excited state may be populated even at low n_s, and act as additional scattering centers for 2D electrons. In particular, since at least some of them must be singly populated due to a large on-site Coulomb repulsion (tens of meV), they act as local magnetic moments. We have shown earlier[13] that the number of these local moments may be varied by applying voltage (V_{sub}) to the Si substrate, as this changes the splitting of the states. In this experiment, we keep V_{sub} constant at +1 V, which leads to a large number of local moments, and hence to the observation of the novel behaviour of the conductivity σ in the entire temperature range studied (up to 4.5 K) for all n_s. The same qualitative behaviour is also observed when the number of local moments is smaller (*e. g.* for negative V_{sub}), and details have been presented elsewhere[13].

Figure 1a shows $\sigma(T)$ for different values of n_s. An excellent fit (dashed lines) to the data is obtained with

$$\sigma(n_s, T) = \sigma(n_s, T = 0) + A(n_s)\, T^2 \qquad (1)$$

over a wide range of n_s as shown, where σ measured at the lowest T (0.3 K) varies over three orders of magnitude below e^2/h (e^2/h – quantum unit of conductance). The data obtained on another sample show that the T^2 dependence continues unchanged down to 0.022 K.

The high quality of the fits allows a reliable extrapolation of the zero-temperature conductivities $\sigma(n_s, T = 0)$, whose finite (*i. e.* non-zero) values mean that, in spite of the decrease of $\sigma(n_s, T)$ with decreasing T, *the 2D system is in the metallic state.* $\sigma(n_s, T = 0)$ obtained from the fits in Fig. 1a is shown in Fig. 1b as a function of $\delta_n = (n_s - n_c)/n_c$, the distance from the metal-insulator transition (MIT). The MIT occurs at the critical density $n_c = 0.55 \times 10^{15}\mathrm{m}^{-2}$, where the Fermi energy $E_F \approx 4$ K and $r_s \approx 22$ (r_s is the average inter-electron separation in units of the effective Bohr radius). We find the power-law behaviour $\sigma(n_s, T = 0) \sim \delta_n^{\mu}$ ($\mu = 2.99 \pm 0.01$), as expected in the vicinity of a quantum critical point[14], such as the MIT. The power law holds over a very wide range of δ_n (up to 5) similar to what has been observed[15] in Si:P near the MIT.

In addition, very general considerations have suggested[16] that the conductivity near the MIT can be described by a scaling form

$$\sigma(n_s, T) = \sigma_c(T) f(T/\delta_n^{z\nu}), \qquad (2)$$

where z and ν are the dynamical and correlation length exponents, respectively, and the critical conductivity

$$\sigma_c = \sigma(n_s = n_c, T) \sim T^x. \qquad (3)$$

We find that $x = 2.55 \pm 0.3$, and show in the inset of Fig. 2 that all the data for $\sigma(n_s, T)/\sigma_c(T) \sim \sigma(n_s, T)/T^x$ are described by a single scaling function $f(T/T_0)$. T_0, which was obtained by collapsing the data in the inset of Fig. 2, is displayed in Fig. 2 as a function of δ_n on both sides of the transition. Again, we find a power-law behaviour, $T_0 \sim |\delta_n|^{z\nu}$, in agreement with Eq. 2. For the metallic side of the transition, $z\nu = 1.32 \pm 0.01$, and for the insulating side $z\nu = 1.4 \pm 0.1$. This value of $z\nu$ is similar to $z\nu = 0.8 - 1.7$ obtained[1,3,13,17,18] in Si MOSFETs for the 2D MIT that occurs in the absence of local moments between an insulator and a metal with $d\sigma/dT < 0$. It

is easy to show using standard scaling arguments[16] that $\mu = x(z\nu)$, *i. e.* that μ can be determined not only from extrapolations of $\sigma(T)$ to $T = 0$ (see Eq. 1 and Fig. 1b) but also based on all data taken at all temperatures and values of n_s for which scaling holds. In this way, we obtain $\mu = x(z\nu) = 3.4 \pm 0.4$, in agreement with the method used above. While the uncertainty in μ obtained from dynamical scaling is comparable in size to those of various critical exponents in other systems ($\approx$5–30%)[19], μ found from zero-temperature extrapolation of $\sigma(T)$ is determined to within 0.3% (Fig. 1b). This is especially remarkable since $\sigma(n_s, T = 0)$ spans four orders of magnitude.

Several striking features of our data stand out.

(1) The temperature dependence of the conductivity follows a precise T^2 form over a very broad temperature range. Such behaviour is well established for metals containing local magnetic moments, and is believed to result from the Kondo effect[20]. In our case, this feature provides the most direct evidence of the presence of local magnetic moments. From a practical point of view, such a simple temperature dependence is crucial for characterising the low temperature state of the system since it allows for an unambiguous extrapolation to $T = 0$.

(2) The local magnetic moments lead to a qualitative modification of the low temperature transport. Similar to the applied magnetic fields, local moments couple to the spin of the conduction electrons. *In contrast* to the magnetic field effect[11,12], the local moments do *not* lead to an insulating behavior at $T = 0$, but instead produce a novel metallic phase characterised by a small but finite conductivity at $T = 0$. The difference between the response to local moments and to applied fields appears to reflect the role of the Kondo effect, which would be suppressed by high enough magnetic fields.

Our data also demonstrate clearly that the mere decrease of conductivity with decreasing T at a given n_s *does not necessarily imply the existence of an insulating state at* $T = 0$. Therefore, without a detailed study of $\sigma(T)$ and without any evidence for scaling, recent observations[21–23] of a change from $d\sigma/dT < 0$ to $d\sigma/dT > 0$ at high n_s do *not* represent an evidence for the second metal-insulator transition as n_s is varied.

(3) In this new metallic phase, the $T = 0$ conductivity *decreases continuously*, and follows a distinct power-law behaviour as the metal-insulator transition is approached. In particular, *metallic* conductivity as small as $10^{-3}e^2/h$ has been observed. This behaviour is in a striking contrast to anything that has been reported in other 2D systems in absence of local magnetic moments. A similar observation in three-dimensional systems[15] has demonstrated the absence of minimum metallic conductivity, and has had a profound impact on shaping the theoretical ideas about the metal-insulator transition.

(4) Our data show an excellent fit to the dynamical scaling described by Eq. 2. It should be noted that such scaling behaviour is not consistent with the simple single-parameter scaling formulation[24]. In standard approaches, "Wegner scaling" suggests[16] that the exponent x in Eq. 3 is expected to take the value $x = (D-2)/z$, and thus to vanish in two dimensions. However, it should be emphasized that $x \neq 0$ does *not* contradict[16] any fundamental principle even for 2D systems. Interestingly, recent work on the 2D MIT in the absence of local moments has found evidence[25] that the *same* scaling form can be used to resolve some apparent violations of the single-parameter scaling. In that case though, the exponent x takes a distinctly different value, presumably reflecting the different universality classes of the two situations owing to the presence or absence of the local moments.

¿From a broader perspective, our results may provide an important new insight into the fundamental nature of the metal-insulator transition. In particular, from a conventional point of view, $D = 2$ has been long regarded as a special situation, since it was believed to represent the *lower critical dimension* D_{lc} for the MIT. While rigorously true for non-interacting electrons, this view finds little microscopic basis once the electron-electron interactions are incorporated[26]. We note that very general considerations suggest[16] that the more general scaling form of Eq. 2 should be valid with $x \neq 0$ not only in $D = 3$, but in fact *in any dimension* $D > D_{lc}$. The very fact that our data exhibit nontrivial scaling with $x \neq 0$ thus immediately suggests that $D = 2$ *is not the lower critical dimension* for the MIT. If this is correct, it would immediately explain the apparently puzzling existence of a metallic phase in two dimensions – a possibility long viewed with skepticism but the one that has been gathering a rapidly increasing experimental support in recent years.

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FIG. 1. **a**, Temperature dependence of the conductivity plotted *vs.* T^2 for different carrier densities and $0.3 < T < 4.5$ K. The dashed lines are fits. σ is shown for n_s from $3.0 \times 10^{15}\mathrm{m}^{-2}$ (top) down to $0.7 \times 10^{15}\mathrm{m}^{-2}$ (bottom) in steps of $0.1 \times 10^{15}\mathrm{m}^{-2}$. **b**, $\sigma(n_s, T = 0)$ *vs.* the distance from the metal-insulator transition. The dashed line is a fit with the slope equal to 2.99 ± 0.01.

FIG. 2. Scaling parameter T_0 as a function of $|\delta_n|$. Open symbols correspond to the insulating side of the transition, closed symbols to the metallic one. The dashed lines are fits with slopes 1.4±0.1 and 1.32±0.01, respectively. Inset, scaling of raw data $\sigma/\sigma_c \sim \sigma/T^x$ in units of $e^2/h\mathrm{K}^{2.55}$. Different symbols correspond to different n_s ranging from $0.3\times10^{15}\mathrm{m}^{-2}$ to $3.0 \times 10^{15}\mathrm{m}^{-2}$. It was possible to scale all the data below about 2 K.

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Correspondence and requests for materials should be addressed to D. P. (e-mail: dragana@magnet.fsu.edu).