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Effect of Local Magnetic Moments on the Metallic Behavior in Two Dimensions

X. G. Feng[1], Dragana Popović[1], and S. Washburn[2]
[1] *National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310*
[2] *Dept. of Physics and Astronomy, The University of North Carolina at Chapel Hill, Chapel Hill, NC 27599*

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The temperature dependence of conductivity $\sigma(T)$ in the metallic phase of a two-dimensional electron system in silicon has been studied for different concentrations of local magnetic moments. The local moments have been induced by disorder, and their number was varied using substrate bias. The data suggest that in the limit of $T \rightarrow 0$ the metallic behavior, as characterized by $d\sigma/dT < 0$, is suppressed by an arbitrarily small amount of scattering by local magnetic moments.

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A metal-insulator transition (MIT) has been observed recently in a variety of two-dimensional (2D) electron [1–4] and hole [5,6] systems but there is still no generally accepted microscopic description of the 2D metallic phase. Some of the relevant properties of the 2D metal include: (a) an increase of conductivity σ with decreasing temperature T (i. e. $d\sigma/dT < 0$) for carrier densities $n_s > n_c$ (n_c – critical density); and (b) a suppression of the $d\sigma/dT < 0$ behavior by magnetic field [7]. The latter suggests the importance of the spin degrees of freedom, which can be probed further by studying the effect of local magnetic moments on the transport properties of the conduction electrons. Indeed, magnetic impurities have been used extensively over the last several decades to probe the properties of metals, and continue to be relevant today in attempts to understand heavy-fermion materials and high-T_c superconductors [8]. In the experiment discussed below, the number of local moments is varied in a controlled way. We show that in the $T \rightarrow 0$ limit the $d\sigma/dT < 0$ behavior is suppressed by an arbitrarily small amount of scattering of the conduction electrons by disorder-induced local moments.

We present results obtained on a 2D electron system in Si metal-oxide-semiconductor field-effect transistors (MOSFETs). In such a device, the disorder is due to the oxide charge scattering (scattering by ionized impurities randomly distributed in the oxide within a few Å of the interface) and to the roughness of the Si-SiO$_2$ interface [9]. For a fixed n_s, it is possible to change the disorder by applying the substrate (back gate) bias V_{sub}. In particular, the reverse (negative) V_{sub} moves the electrons closer to the interface, which increases the disorder. It also increases the splitting between the subbands since the width of the triangular potential well at the interface is reduced by applying negative V_{sub}. Usually, only the lowest subband is occupied at low T, giving rise to the 2D behavior. In sufficiently disordered samples, however, the band tails associated with the upper subbands [10] can be so long that some of their strongly localized states may be populated even at low n_s, and act as additional scattering centers for 2D electrons. Clearly, the negative V_{sub} reduces this type of scattering by depopulating the upper subband. The effect of scattering by electrons localized deep in the tails of the upper subband was first observed as an enhancement of the mobility μ at low n_s with negative V_{sub} [11], and was subsequently studied in more detail by other groups using different measurements and techniques [12]. More recently, we have used one negative value of V_{sub} to enhance μ (reduce the disorder) at intermediate values of n_s, and observed the change from $d\sigma/dT > 0$ to $d\sigma/dT < 0$ for $n_s > n_c$ [2]. Here, however, we present a systematic study of this process as the disorder is varied using V_{sub}. We show clearly that the bare value of high T (Drude) mobility is *not* sufficient to predict the sign and the magnitude of $d\sigma/dT$ at low T but rather that it is the *type* of the disorder that is relevant [13]. In particular, we show that scattering by electrons localized in the tail of the upper subband has a much more profound effect on $d\sigma/dT$ than potential scattering due to oxide charges and surface roughness. This is attributed to spin flip scattering by electrons in localized states that are singly populated due to a strong on-site Coulomb repulsion, and act as local magnetic moments. Large on-site Coulomb interaction has been well documented in systems similar to ours, such as electrons in quantum dots [16], and other materials with strongly localized states [17]. For typical localization lengths of ∼100 Å in Si MOSFETs [9,18], the on-site Coulomb repulsion is ∼10 meV. Therefore, such states will be singly occupied at low n_s [9].

Our measurements were carried out on n-channel Si MOSFETs with the oxide charge density of 3×10^{10}cm^{-2}, determined using standard techniques [9,19]. Other details of the sample structure are given in Ref. [2]. For a fixed V_{sub}, n_s was controlled by the gate voltage V_g and determined in a standard fashion [9,19]. $\sigma(V_g)$ was measured at temperatures $0.3 < T < 4.5$ K for n_s of up to 3×10^{12}cm^{-2} and for -50 V$\leq V_{sub} \leq +1$ V. The effect of V_{sub} on μ at 4.2 K was found [14] to be consistent with earlier work and our interpretation. In particular, for $n_s < n_{max}$ ($n_{max} \sim 5\times10^{11}$cm^{-2} is the density where μ reaches its maximum), an increase of μ is observed [14]

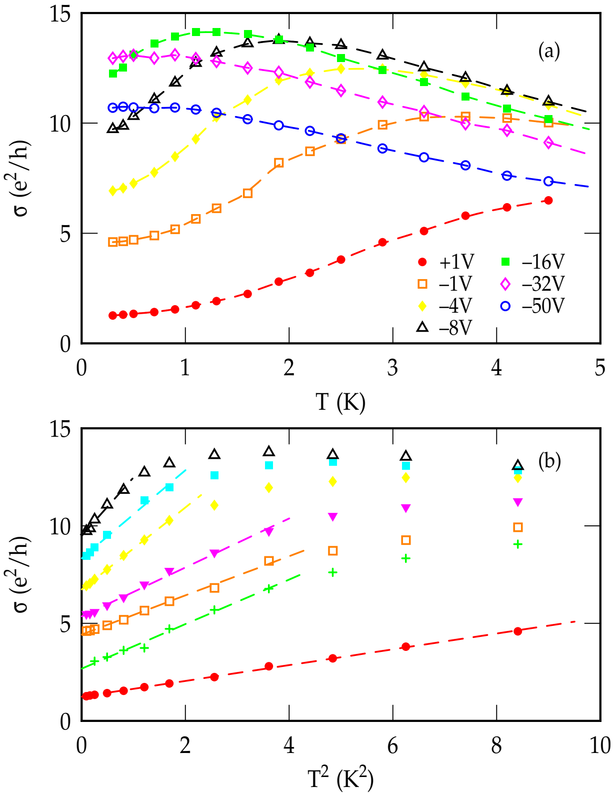

FIG. 1. Temperature dependence of the conductivity σ for $n_s = 3.0 \times 10^{11}\mathrm{cm}^{-2}$. (a) The data are shown for different values of V_{sub} as given on the plot. (b) The data are plotted vs. T^2, and shown for $V_{sub} = +1, -0.5, -1, -2, -4, -6, -8$ V going from bottom to top.

with the negative V_{sub} as a result of the decreased scattering by local moments from the upper subband, and consistent with early work [11]. For $n_s > n_{max}$, μ decreases with (negative) V_{sub}, consistent with the fact that surface roughness scattering is the dominant source of disorder in this range of n_s [9]. This is a result of an increased proximity of the 2D electrons to the interface and, possibly, a reduction in scattering by local moments from the upper subband. The latter could be due to a smaller number of local moments being present in a sample at high n_s (for a given V_{sub}) because of an improved screening by 2D electrons. For sufficiently high negative V_{sub} ($-V_{sub} > 35$ V), the 4.2 K mobility decreases with V_{sub} for all n_s, suggesting that the upper subband has been completely depopulated and that the further increase in V_{sub} leads only to increasing disorder due to potential scattering from roughness at the Si-SiO$_2$ interface.

Fig. 1(a) shows some typical results for $\sigma(T)$ in the $n_s < n_{max}$ range as a function of V_{sub}. The metallic behavior, such that $d\sigma/dT < 0$, spreads out towards lower T with the increasing negative V_{sub}, i. e. as the scattering by local moments is reduced, and it also spreads out towards higher values of n_s (not shown). In other words, $\sigma(T)$ displays a maximum at $T = T_m$, such that T_m shifts to lower T with the (negative) V_{sub}. As $(-V_{sub})$ is increased beyond 35 V, the form of $\sigma(T)$ is no longer very sensitive to changes in V_{sub} even though the disorder due to potential scattering increases. In addition, by comparing the data for $V_{sub} = -50$ V and –1 V, for example, it is obvious that $d\sigma/dT < 0$ behavior is more pronounced (T_m is lower) when scattering by local moments is reduced *even though the 4.2 K mobility is lower* [13]. This demonstrates clearly the need to distinguish between different types of disorder, a fact that has been overlooked in some theoretically proposed phase diagrams [20,21]. For $T < T_m$, σ decreases with decreasing T and, in fact, follows a T^2 form at the lowest T [Fig. 1(b)]. Such $\sigma(T)$ is often considered to be a signature of local magnetic moments, and results from the Kondo effect [8]. Here it represents a direct evidence for the existence of local moments in our samples. A detailed study of this regime has been presented elsewhere [22]. Fig. 1(b) also shows that the range of T ($T < T_m$) where local moments dominate transport becomes smaller as their number is reduced by increasing negative V_{sub}.

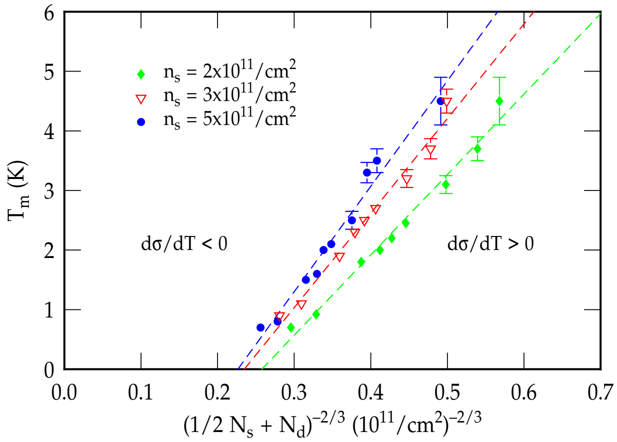

FIG. 2. Position of the maximum T_m in $\sigma(T)$ for different values of n_s as a function of the inverse subband splitting. (The left hand side on the x-axis corresponds to large values of the negative V_{sub}, and the right hand side corresponds to low values of V_{sub}.) The metallic behavior with $d\sigma/dT < 0$ is observable at $T > T_m$. T_m extrapolates to zero (dashed lines) for $V_{sub} \sim -40$ V, corresponding to the subband splitting of the order of 30 meV.

The position of the maximum T_m in $\sigma(T)$ is shown in Fig. 2 for different values of n_s as a function of the inverse subband splitting (N_d is the depletion layer charge density, which increases with the reverse V_{sub}) [9]. The metallic behavior with $d\sigma/dT < 0$ is observable at $T > T_m$ [see Fig. 1(a)]. For a given n_s, T_m extrapolates to zero for a finite value of the subband splitting. This value is slightly higher for higher n_s, consistent with the fact that the number of local moments in the upper subband is also slightly higher (Fermi energy E_F is higher) and, therefore, one needs to apply more V_{sub} in order to depopulate the upper subband. From the data shown in

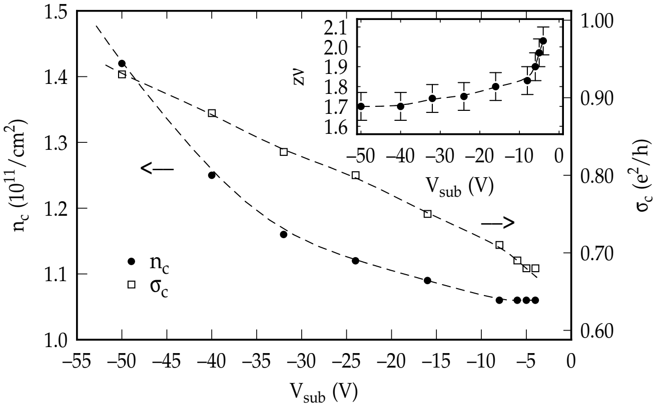

FIG. 3. Critical density n_c and critical conductivity σ_c determined from the data at $T > T_m$ as a function of V_{sub}. The disorder due to potential scattering increases with the negative V_{sub}. Inset: critical exponents $z\nu$ vs. V_{sub} obtained from the same data. Dashed lines guide the eye.

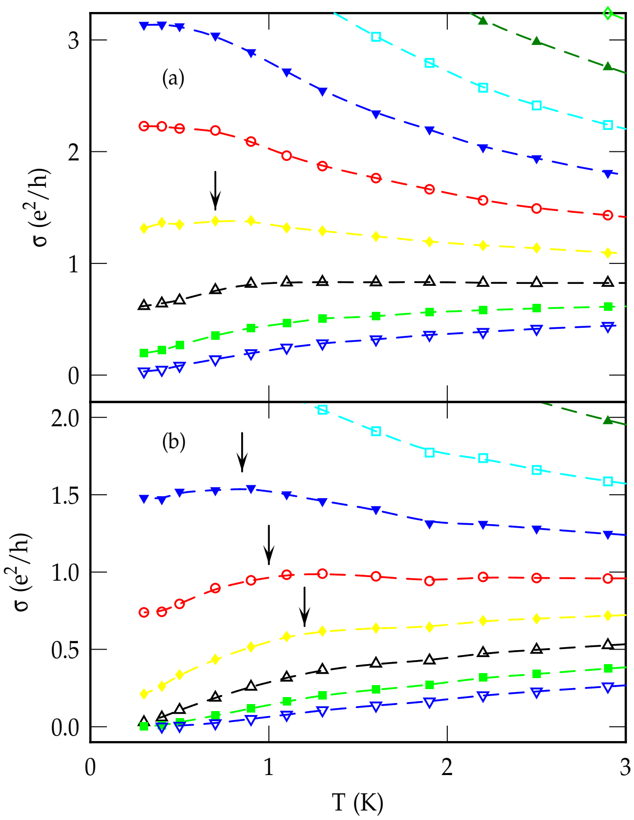

FIG. 4. Temperature dependence of conductivity for n_s from 1.02×10^{11}cm^{-2} (bottom curve) up, in steps of 0.1×10^{11}cm^{-2} and (a) $V_{sub} = -40$ V, (b) $V_{sub} = -50$ V. The arrows indicate the peaks in $\sigma(T)$ for $n_s(10^{11}\text{cm}^{-2}) = 1.42$ and 1.52 for $V_{sub} = -50$ V, and possible peaks for $n_s = 1.32 \times 10^{11}$cm^{-2} at both V_{sub}.

Fig. 2, it follows that T_m goes to zero for $V_{sub} \sim -40$ V in agreement with the measurement of the 4.2 K mobility as discussed above. $V_{sub} \sim -40$ V corresponds to the subband splitting of the order of 30 meV [9]. The extent of the tail of the upper subband derived in this way is consistent with earlier work [12]. Our data, therefore, show that the 2D metal with $d\sigma/dT < 0$ can exist at $T = 0$ only in the absence of scattering by disorder-induced local moments. This is similar to the behavior observed in a magnetic field [7], and consistent with some theoretical models [23–26].

In the presence of scattering by local moments, $d\sigma/dT < 0$ is observable at $T > T_m$, where T_m, of course, can be arbitrarily small. For a fixed V_{sub}, $\sigma(n_s, T)$ for $T > T_m$ exhibits [2] all of the properties of a 2D MIT. Fig. 3 shows the values of n_c and the (apparent) [27] critical conductivity σ_c determined only from the data at $T > T_m$, where scattering by local moments is not significant, as a function of V_{sub}. Both n_c and σ_c increase monotonically with the reverse V_{sub}, i. e. with an increase in disorder due to potential scattering. The increase of n_c and σ_c with disorder observed here on a single sample is in agreement with the same conclusion reached by comparing MOSFETs with different peak mobilities [28]. Fig. 3 inset shows the dependence of the critical exponents $z\nu$ ($z-$ dynamic exponent, $\nu-$ correlation length exponent) on V_{sub}. $z\nu$ was determined by scaling the data in the vicinity of n_c, where $\sigma(n_s, T) = \sigma_c f(T/\delta_n^{z\nu})$ [$\delta_n = (n_s - n_c/n_c)$] [2,27].

Fig. 4(a) shows $\sigma(T)$ for $V_{sub} = -40$ V for a small range of n_s close to n_c. Based on the analysis discussed above, we are confident that for this value of V_{sub} there are no local moments associated with the upper subband in the sample. Indeed, the $\sigma(T)$ curves do not exhibit a maximum in the measured range of T, except possibly where shown in Fig. 4(a). Such a structure might, in fact, be due to local moments associated with the lowest subband. From the theoretical point of view, the possibility of disorder-induced local moment formation in strongly interacting electronic systems has been suggested since the early developments of the theory of interacting disordered systems [29,24] and has been studied, subsequently, using different models [30]. In order to test this idea, we have increased V_{sub} to -50 V, thus increasing the disorder, which is now due only to scattering by the oxide charges and the surface roughness. Fig. 4(b) shows that, for the same n_s, the values of σ are reduced as expected for higher disorder. More importantly, we observe the *appearance of the peak* in $\sigma(T)$ for those n_s for which it was clearly absent in Fig. 4(a). Also, a weak structure (peak) in $\sigma(T)$ for $n_s = 1.32 \times 10^{11}$cm^{-2} has shifted to higher T. This increase of T_m, and the dependence of T_m on n_s as shown in Fig. 4(b), are qualitatively the same as what was observed by increasing the number of local moments associated with the upper subband. These results strongly suggest that an increase in the potential (non-magnetic) scattering has led to the formation of the (additional) local moments in the system. We have also observed similar peaks in $\sigma(T)$ in different Si MOS-

FETs at $T < 0.4$ K but, without a systematic study such as this one, it would have been impossible to determine their origin. We speculate that local moments might exist in other materials as well but that the corresponding T_m might be experimentally inaccessible in high-mobility devices.

Back gate bias was used recently in a 2D hole system [15] to study the effect of the spin-splitting due to the spin-orbit interaction and the inversion asymmetry of the confining potential [31]. It was found that the magnitude of the $d\sigma/dT < 0$ behavior was reduced as the spin-splitting decreased, i. e. as the confining potential became more symmetric. In our samples, we observe the opposite: the triangular confining potential becomes more symmetric with the application of the reverse V_{sub}, and that is exactly when the $d\sigma/dT < 0$ behavior appears. Therefore, even if the effect of the spin-orbit interaction exists in our samples, it does not drive the MIT.

The reverse V_{sub} also reduces the average spatial extent Δz of the inversion layer charge density in the direction perpendicular to the interface (typically, $\Delta z \approx 20 - 30$ Å) [9], leading to an increase of the effective Coulomb interaction [32]. Since r_s (r_s – the average intercarrier separation in units of the effective Bohr radius) is already fairly large ($r_s \sim 15$) for n_s close to n_c (given in Fig. 3), we expect that the further increase in the Coulomb interaction for a fixed n_s would only lead to an insulating behavior (see, e. g. Refs. [20,21]) and not to the metallic behavior with $d\sigma/dT < 0$, as observed. We conclude that the effect of V_{sub} on the effective Coulomb interaction is not the dominant effect in our samples.

Our study shows that the 2D metal with $d\sigma/dT < 0$ can exist in the $T \to 0$ limit only in the absence of scattering by local magnetic moments. Our results emphasize the key role of the spin degrees of freedom in the physics of the low density 2D electron system.

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