Reentrant Insulator-Metal-Insulator Transition at $B = 0$ in a Two-Dimensional Hole Gas

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We report the observation of a reentrant insulator-metal-insulator transition at $B = 0$ in a two-dimensional (2D) hole gas in GaAs at temperatures down to 30 mK. At the lowest carrier densities the holes are strongly localized. As the carrier density is increased a metallic phase forms, with a clear transition at $\sigma \simeq 5e^2/h$. Further increasing the density weakens the metallic behavior and eventually leads to the formation of a second insulating state for $\sigma \gtrsim 50e^2/h$. In the limit of high carrier densities, where $k_F l$ is large and r_s is small, we thus recover the results of previous work on weakly interacting systems showing the absence of a 2D metallic state. [S0031-9007(99)08472-0]

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Evidence has recently emerged suggesting the existence of a metallic state in 2D systems with low disorder, in apparent disagreement with earlier experiments [1] and theoretical expectations [2,3]. In these earlier works it was shown that logarithmic corrections to the metallic conductivity existed at low temperatures in low mobility systems, and it was generally believed that these corrections would also be found in higher mobility samples at lower, unobtainable, temperatures. Recent experiments, using electrons in high quality silicon inversion layers [4] and holes in both SiGe [5] and GaAs [6–8] heterostuctures, have shown a transition from strong localization at conductances $\sigma < e^2/h$ to metallic behavior with increasing carrier concentration, characterized by a significant drop in resistance at low temperatures.

The metallic state has been observed only in 2D systems at low carrier densities, where electron-electron interactions are known to be strong, although it is not known if it persists to the very lowest temperatures. If the metallic state is due to the interactions then it might be expected that as the carrier density is increased these interactions will no longer dominate and the metallic phase will cease to exist. While the first transition from the 2D metallic phase to an insulating state with *decreasing* carrier density has been widely observed [4–10], there has been no equivalent observation of a second transition from metallic to insulating behavior with *increasing* carrier density, which must occur when $k_F l$ is large and $r_s \rightarrow 0$ [2,3]. Here k_F is the Fermi wave vector, l is the elastic mean free path, and r_s is the ratio of the average interparticle Coulomb energy to the Fermi energy.

In this Letter we present experimental evidence for both insulator-metal-insulator transitions as the carrier density is increased in a two dimensional GaAs hole gas. The observation of a second metal-insulator transition at $\sigma \gtrsim 50e^2/h$ ($k_F l \gtrsim 50, r_s \lesssim 6$) bridges the gap between current experimental data from strongly interacting systems and earlier studies which showed the absence of a metallic state in weakly interacting systems [1–3]. Finally we show that the application of a parallel magnetic field weakens the metallic state, and we map out the p_s-$B_\parallel$ phase space over which the 2D metal exists.

The heterostructure used in this study is similar to that described in Ref. [8], consisting of a 200 Å GaAs quantum well with an *in situ* back gate buried 3300 Å below. Two samples, consisting of 450×50 μm Hall bars defined along the $[\bar{2}33]$ direction, were studied and showed similar results. The data presented here are from one sample, which showed identical behavior on three separate cooldowns from room temperature to the base temperature of the dilution fridge (30 mK). Standard four terminal low frequency (4 Hz) ac lock-in techniques were used, with excitations in the range 33–50 μV and 0.05–5 nA for voltage and current bias measurements, respectively. The hole density p_s could be varied from $0-2.3 \times 10^{11}$ cm^{-2} ($r_s > 5$). The peak mobility, obtained at the highest density, was 1.6×10^5 cm^2 V^{-1} s^{-1}, which is 30% lower than the mobility at the same density in Ref. [8].

Figure 1(a) shows the insulator-metal-insulator transition by plotting the differential conductivity [$\sigma'(E) \propto |\partial I/\partial V|_E$] as a function of carrier density for different dc electric fields E applied along the channel. The electric field heats the holes above the lattice temperature, making it possible to distinguish between insulating and metallic states. Insulating behavior in regions I and III is characterized by an increase in the conductivity (or differential conductivity) with increasing temperature (or electric field), whereas a decrease in σ with E or T in region II indicates metallic behavior. While the I → II transition at low carrier densities can be clearly seen, the second II → III transition is less visible since σ' is large and the change in σ' due to the electric field is small. The transitions can be more clearly resolved by examining the change in the differential conductivity $\Delta\sigma'$ due to the electric field [Fig. 1(b)]. We can thus divide the graph into three regimes (indicated by the dotted lines in Fig. 1):

(I) For densities below 7.3×10^{10} cm^{-2} the sample is in the regime of strong localization: σ increases with increasing $|E|$, and $\Delta\sigma' > 0$.

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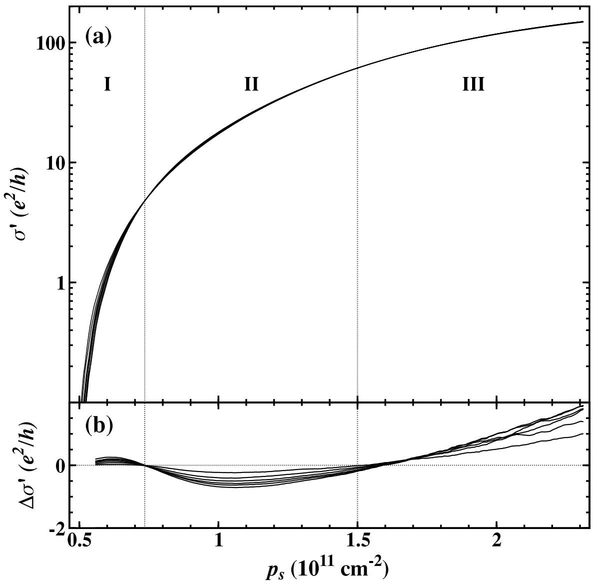

FIG. 1. (a) Differential conductivity, $\sigma' \propto |\partial I/\partial V|_E$ for electric fields of 0, 1.5, 3, 4.5, 6, 7.5, and 10.5 mV/cm, as a function of carrier density ($T = 30$ mK). (b) Change in the differential conductivity $\Delta\sigma'(E) = \sigma'(E) - \sigma'(E = 0)$ as a function of carrier density.

(II) An electric field (i.e., hole temperature) independent point at $\sigma' \simeq 5e^2/h$ ($p_s = 7.3 \times 10^{10}$ cm^{-2}, $r_s \simeq 9$ [11]) separates the strongly insulating regime from the metallic regime, in which $\Delta\sigma' < 0$.

(III) For densities $\gtrsim 1.5 \times 10^{11}$ cm^{-2} ($r_s \lesssim 6$) the sample once again becomes insulating with $\Delta\sigma' > 0$, although the transition between the metallic phase and this second insulating phase at $\sigma \approx 50e^2/h$ is not as well defined as the first transition. Closer inspection shows that the transition moves to higher densities with increasing E, the significance of which will be discussed later.

This reentrant insulator-metal-insulator behavior was also observed in the T dependence of σ, with a clear T-independent transition at $\sigma \simeq 5e^2/h$ (50 mK $< T <$ 1 K), and a second, broader, transition at $\sigma \approx 50e^2/h$.

We now examine the three phases in more detail and plot the temperature dependence of the resistivity for each regime in Fig. 2. At the lowest carrier densities, where $\sigma < e^2/h$, the system is strongly insulating, and there is a large increase in resistivity with decreasing T [Fig. 2(a)]. In this regime, close to the transition, ρ follows the form for Mott variable range hopping: $\rho(T) = \rho_M \exp[(T/T_0)^{-1/3}]$. This behavior is consistent with that observed in previous work on a slightly higher quality sample, where $T^{-1/2}$ behavior was observed deep in the insulating regime [8], with a crossover to $T^{-1/3}$ behavior near the I $\rightarrow$ II transition [12].

Increasing the carrier density causes a transition to metallic behavior, in which the resistivity decreases as the temperature is lowered. For temperatures above 0.3 K there is a weak decrease in resistivity with decreasing temperature. It was not possible to ascertain the functional form of $\rho(T)$ in our earlier data [8], but by extending the measurements to lower T, as shown in Fig. 2(b), we are able to resolve an exponential decrease of the resistivity as $T \rightarrow 0$. This can be quantified by fitting the low temperature ($T < T_0$) resistivity data to the empirical formula [10]: $\rho(T) = \rho_0 + \rho_1 \exp(-T_0/T)$, yielding $\rho_0 = 0.06h/e^2$, $\rho_1 = 0.006h/e^2$, and $T_0 = 0.4$ K. The exponential behavior can be more clearly seen in the inset to Fig. 2(b) where $[\rho(T) - \rho_0]$ is plotted against $1/T$, revealing a linear dependence over more than a decade change in resistivity.

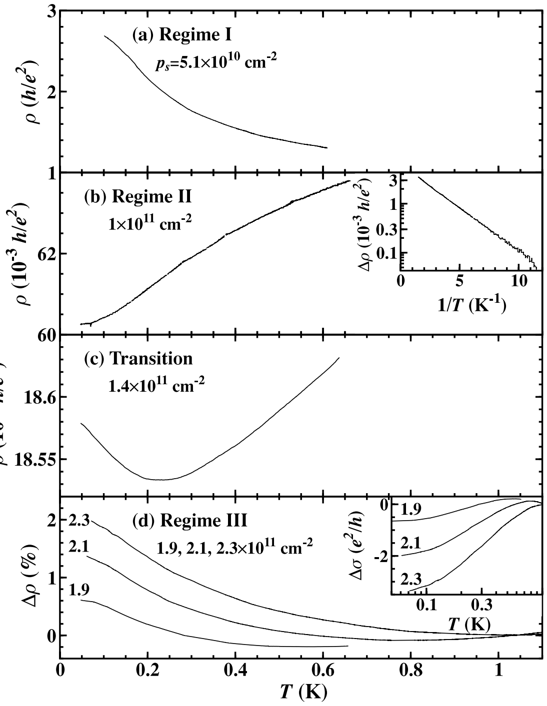

FIG. 2. Temperature dependence of the resistivity in the different regimes. (a) Strongly localized regime: ρ shows hopping conduction. (b) Metallic regime: ρ decreases exponentially as T is reduced. The inset shows an Arrhenius plot of $\Delta\rho = \rho(T) - \rho_0$. (c) Transition between regimes II and III: The metallic behavior is weaker at this higher density, with insulating behavior visible at $T < 0.2$ K. (d) Regime III: The fractional change in resistivity is plotted for three different carrier densities. The inset shows the equivalent change in conductivity on a semilog plot.

We now turn to the main result of this paper—the observation of a *second* insulating state at high densities. As the carrier density is further increased the metallic behavior in regime II becomes less pronounced, and a gradual transition to an insulating state occurs. Figure 2(c) shows the behavior of the resistivity at the second transition, with $p_s = 1.4 \times 10^{11}$ cm^{-2}. At high temperatures metallic behavior is observed ($\partial\rho/\partial T > 0$), but for $T < 200$ mK there is a change in sign of $\partial\rho/\partial T$ as a new insulating state emerges. The presence of both metallic and insulating behaviors at the same carrier density in Fig. 2(c) accounts for the broadening of the transition between the metallic (II) and insulating (III) regimes in Fig. 1(b). We noted earlier that there is also an apparent movement of the II → III transition to higher densities as E is increased. It can now be seen that this occurs because the insulating state persists to higher temperatures as the carrier density is increased. The strengthening of the insulator with increasing density is shown in Fig. 2(d), where the percentage change in resistivity from the $T = 1$ K value is plotted for three different densities. At a density of 1.9×10^{11} cm^{-2} the insulating behavior is visible to 500 mK, and by 2.3×10^{11} cm^{-2} it is observed up to $T = 1$ K.

The possible origins of this insulating behavior are now considered. Increasing the carrier density increases $k_F l$ and reduces the relative importance of many body interactions, since r_s scales as $\sqrt{1/p_s}$. Hence at sufficiently large densities the results of earlier studies of weakly interacting systems should be recovered [1–3]—the 2D system once again becomes insulating. In those earlier studies two separate mechanisms were identified as causing insulating behavior: weak localization due to phase coherent backscattering and weak electron-electron interactions, both of which give rise to a logarithmic correction to the Drude conductivity. To look for such a correction the change in conductance, $\Delta\sigma = \sigma(T) - \sigma(T = 1\text{ K})$, is plotted against the temperature on a log scale for three different carrier densities in the inset to Fig. 2(d). These data are very similar to that observed in previous studies of weakly interacting electron gases in lower mobility silicon inversion layers [1]. At high temperatures there is a deviation from $\log(T)$ behavior, as phonon scattering and temperature dependent screening become important. There is also an apparent saturation of $\Delta\sigma$ at low temperatures (which is not due to unintentional heating effects). It is therefore difficult to unambiguously identify $\log(T)$ behavior as the temperature range is limited and the change in conductance small. Nevertheless, at the largest density, farthest from the II → III transition, $\log(T)$ behavior can be observed over a limited temperature range (150–600 mK).

If the insulating phase in regime III were due to weak localization, then the application of a perpendicular magnetic field $B_\perp = 0.1$ T, which is known to suppress the phase coherent backscattering, would destroy it. This is not observed. Furthermore we find that the low field magnetoresistance is positive, in contrast to the negative magnetoresistance that arises from weak localization.

Weak electron-electron interactions cause a logarithmic correction to the Drude conductivity which is enhanced by a magnetic field due to a lifting of the spin degeneracy and becomes larger with increasing carrier density [3]. This is in qualitative agreement with the data in Fig. 2(d), where the correction $\Delta\sigma$ becomes larger for higher carrier densities. Although the insulating behavior cannot be definitively ascribed to weak interactions, it is significant that the range of temperatures over which $\log(T)$ behavior is observed is largest for the highest densities (at which $r_s \simeq 5$), as we approach the limit for which the theory of Ref. [3] is applicable ($r_s \lesssim 1$).

The observation of insulating behavior at high densities has implications for the existence of a true 2D metal at $T = 0$. The data in Fig. 2(d) demonstrate that as the carrier density is reduced from 2.3×10^{11} cm^{-2} the onset of insulating behavior occurs at progressively lower temperatures. Thus it is not certain that the metallic behavior shown in Fig. 2(b) would not also become insulating at lower, possibly inaccessible, temperatures. The corollary of this would be that there is no true metallic state in 2D, only metalliclike behavior at finite temperatures. However, if the insulating behavior saturates as $T \to 0$, then it is possible that the metallic state is stable, with a window of carrier densities within which a 2D metal can exist. The data shown in Fig. 2(d) do exhibit signs of saturation below 100 mK, although we emphasise that the functional form of $\Delta\sigma(p_s, T)$ is not yet established and that much lower measurement temperatures are needed before the ultimate nature of the 2D metal can be established.

At this point it is appropriate to discuss why the second transition to insulating behavior at high densities has not been observed in other studies. The heterostructure used in this work has a higher degree of disorder than those used previously to examine the 2D metallic state. The peak mobility is 30% lower than in Ref. [8] for the same p_s, with $r_s \simeq 9$ at the I → II transition compared to values of 11, 15, and 24 obtained in Refs. [8], [4], and [6,7], respectively [11]. The disorder has two significant consequences: First, the metallic behavior is weaker, as indicated by the large value of σ at the I → II transition ($\sigma \simeq 5e^2/h$), the smaller drop in ρ as $T \to 0$, and the smaller values of the ratio ρ_1/ρ_0 and the temperature T_0 (which is about half that obtained in other hole gases at the same density [7]). Second, the conductivity at high densities ($\sigma \approx 100e^2/h$) is lower than in less disordered systems at the same density. Thus it is possible to resolve the small change in conductivity ($\Delta\sigma \approx e^2/h$, so $\Delta\sigma/\sigma \approx 1\%$) that identifies the second insulating regime, whereas in a less disordered system $\Delta\sigma/\sigma$ will be much smaller and might pass undetected. However, if the disorder is too large, then metallic behavior is never observed [4,9], leading to a delicate balance of having enough disorder to observe the insulator at high densities without destroying the metallic state.

To gain further insight into the nature of the metallic and insulating behaviors in regimes II and III we turn to the effects of a parallel magnetic field [13]. This couples only to the spin and not to the orbital motion [8,14]. In Figs. 3(a)–3(c) the change in differential conductivity $\Delta\sigma'(E)$ due to an applied electric field is plotted as a function of carrier density, for magnetic fields of $B_\parallel = 0$, 0.1, and 0.5 T. Once again we divide the data into three regimes, depending on the sign of $\Delta\sigma'$,

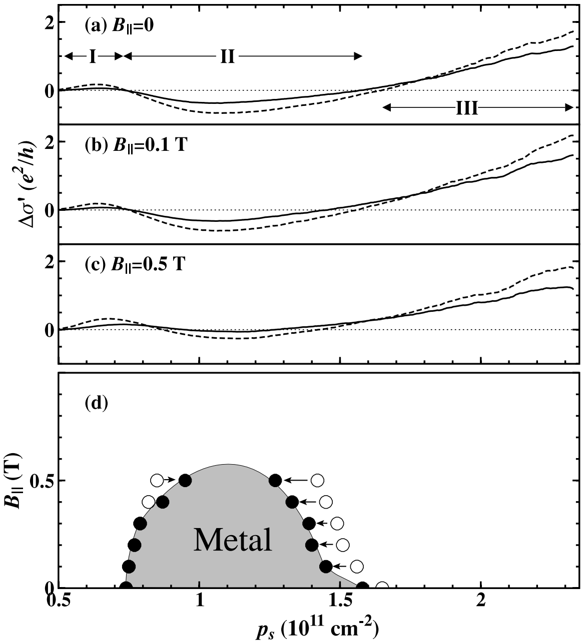

FIG. 3. Effect of a parallel magnetic field: [(a)–(c)] Change in the differential conductivity, $\Delta\sigma' = \sigma'(E) - \sigma'(E = 0)$, with applied electric field E, plotted as a function of carrier density for different magnetic fields. Solid and dashed lines show data for $E = 3$ and 7.5 mV/cm, respectively; $T =$ 30 mK. (d) Phase diagram for the observation of the 2D metal as a function of carrier density and magnetic field. The transitions are identified from the carrier densities at which $\Delta\sigma = 0$, using $E = 3$ and 7.5 mV/cm, respectively, for the closed and open symbols.

with the points at which $\Delta\sigma' = 0$ marking the transition between insulating and metallic behavior. Only two values of the electric field are shown, 3 and 7.5 mV/cm, so that the second transition can be more clearly seen. As noted previously the low density transition is independent of E, whereas the second transition moves to larger densities as E increases, consistent with the T-dependent data shown in Fig. 2(d). It can be seen that the magnetic field suppresses the metallic phase, reducing both the size of $\Delta\sigma'$ and the range of carrier densities over which metallic behavior is observed.

We are able to construct a phase diagram for the existence of the metal as a function of p_s and $B_{\|}$ at $T \simeq$ 30 mK from this data, which is plotted in Fig. 3(d). The solid and open symbols denote the transitions identified using electric fields of 3 and 7.5 mV/cm, respectively. Initially we consider the transitions marked by the open symbols: At low densities both p_s and σ (not shown) at the I → II transition increase as the magnetic field is applied. Conversely the II → III transition moves to lower densities and conductivities with increasing $B_{\|}$ and appears to be more strongly affected by the magnetic field than the I → II transition. Thus the overall effect of the magnetic field is to "squeeze" the metal from both sides, until at $B_{\|} \gtrsim 0.7$ T insulating behavior is observed for all p_s.

Considering now the transitions identified from the smaller electric field data ($E = 3$ mV/cm, closed symbols) we see that the effect of reducing the hole temperature is to shrink the range of densities over which the metallic behavior is observed. The first transition is sharp down to the lowest hole temperatures, but the figure provides a graphic illustration of how the metallic behavior is extinguished from the high density side as E (or T) tends to zero, and it again raises the question as to the ultimate low temperature nature of the metallic state.

In conclusion we have observed a reentrant insulator-metal-insulator transition at $B = 0$ in a two-dimensional system as the carrier density is increased. The reemergence of insulating behavior at high carrier densities thus bridges the gap between current data from strongly interacting systems and earlier theoretical and experimental studies which showed that all states in a weakly interacting 2D system are localized. Although the precise nature of the insulating state at high densities is not fully established, it is consistent with the interaction mechanism of Ref. [3] derived for weak electron-electron interactions. The evolution of this second insulating phase with carrier density does however raise the question as to whether the metallic behavior at lower densities persists to $T = 0$.

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