Metallic Behavior in Dilute Two-Dimensional Hole Systems

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We have studied the metallic behavior in low-density two-dimensional p-GaAs systems, close to the apparent metal-insulator transition. Two observations are made concerning the origins of the metallic-like behavior. Within a given sample the strength of the metallic behavior is almost independent of the asymmetry of the confining potential, and is predominantly determined by the low-temperature resistivity (i.e., by $k_F l$). In all our samples we find that at low densities, close to the transition from insulating to metallic behavior, the fractional decrease in conductivity with increasing temperature scales as T/T_F.

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The scaling theory of localization argues that there should be no metallic state in two dimensions (2D) for noninteracting electrons (or holes) [1]. Experimental studies of a wide variety of low disorder 2D semiconductor systems have, however, revealed an unexpectedly large decrease in the resistance as the temperature is lowered from $T \sim 1$ K, suggesting the existence of a 2D metal [2–6]. Although numerous theories have been put forward to explain this effect, the origin of this metallic behavior is still a subject of great debate. Is it a true quantum phase transition, where the resistivity continues to decrease, giving a finite resistance at $T = 0$, or is it a finite temperature phenomena that can be explained by existing semiclassical mechanisms?

Recent experimental studies have shown that a transition back to insulating behavior occurs at high carrier densities, in agreement with the early studies of weakly interacting systems [7,8]. Furthermore, even in the lower density "metallic" regime, where the resistance drops sharply with decreasing temperature, quantum corrections to the conductivity are still present as $T \rightarrow 0$ [9,10]. These localizing corrections, due *both* to weak carrier-carrier interaction effects, *and* to phase coherent weak localization, indicate that the system is still Fermi liquid-like [9], and question the existence of a true metallic phase even when interactions are strong.

If we consider the possibility that there is no true 2D metal in these systems, then what is the origin of the widely observed metallic-like drop in resistance? A number of semiclassical mechanisms have been proposed, including temperature dependent carrier-carrier scattering in a two-band system [11,12], and temperature dependent screening [13]. Using dilute 2D GaAs hole systems we investigate the relevance of these models, at low carrier densities, close to the transition from metallic-like to strongly localizing behavior. We find that the former model cannot describe the metallic behavior in extremely low density hole systems. However, we observe very similar behavior in several p-GaAs systems with different degrees of disorder, which suggests that a complex form of temperature dependent screening may be relevant to the metallic behavior observed in low density 2D systems.

A number of GaAs-AlGaAs modulation doped heterostructures were studied. Samples A and B were grown *simultaneously* on different (311)A GaAs substrates, with a layer structure similar to that described elsewhere [14]: Sample A was grown on an undoped substrate, whereas sample B had an *in situ* $n+$ back gate buried 1.2 μm below the 2D holes. The simultaneous growth ensures that the two samples have identical layer thicknesses, doping densities, and impurity densities. The hole density could be varied from $p_s = 0\text{–}10 \times 10^{10}$ cm^{-2}, with the transition from insulating to metallic behavior occurring at $p_s \sim 1 \times 10^{10}$ cm^{-2} ($r_s \sim 25$ if the hole effective mass is taken as $0.3m_e$, or $r_s \sim 31$ if $m^* = 0.38m_e$ [15]). The samples are of exceptionally high quality, with a peak mobility of 1.1×10^6 cm^2 V^{-1} s^{-1}. Sample C is a back-gated modulation doped quantum well, described in Ref. [6]. The peak mobility of 0.25×10^6 cm^2 V^{-1} s^{-1} is lower than samples A and B, with the transition occurring at a density of 5×10^{10} cm^{-2}. Similar data to that presented here were obtained both with other samples taken from the same wafers, and from other high quality wafers.

We begin by examining the relevance of the two-band model to the metallic behavior in dilute 2D hole systems. Figure 1(a) shows the characteristic drop in the resistivity ρ of sample B with decreasing temperature. At this low hole density of 2×10^{10} cm^{-2} (close to, but on the metallic side of, the "metal"-insulator transition) ρ decreases by 50% as the temperature is reduced from 700 to 30 mK.

A lack of inversion symmetry in a 2D system can lift the "spin" degeneracy of the electrons (or holes), creating two distinct bands. If the carriers in the two bands have different transport properties this can cause a metallic-like temperature dependence of ρ. Indeed, studies of the metallic phase in high density 2D hole systems, far from the metal-insulator transition, show a strongly temperature dependent positive magnetoresistance ($B_\perp$) that is characteristic of conduction in a two-band system [12,16]. Further evidence that interband scattering causes the metallic

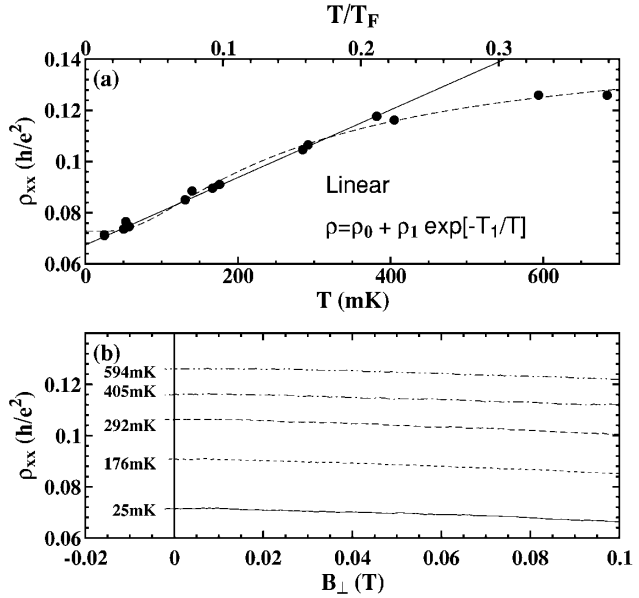

FIG. 1. (a) Temperature dependence of the zero field ($B = 0$) resistivity in the metallic regime for sample B. The carrier density is 2×10^{10} cm^{-2}, and the back-gate bias is 1.7 V. (b) Low field resistivity ρ_{xx} as a function of perpendicular magnetic field.

behavior comes from the fact that in Refs. [12,16] the magnitudes of the increase of the resistivity with temperature, $\rho(T = \infty) - \rho(T = 0)$, is comparable to the increases in resistivity with magnetic field $\rho(B = \infty) - \rho(B = 0)$ (ignoring Landau quantization). However, these experiments have been conducted at high carrier densities, $(2-4) \times 10^{11}$ cm^{-2}, far from the transition to strong localization, and it is not clear that the results can be related to the behavior observed at much lower densities.

In contrast, we investigate the metallic-like behavior immediately in the vicinity of the transition, where the metallic behavior is strongest. Here the carrier densities are an order of magnitude smaller than used in Refs. [12,16], and the interactions are strong: $r_s \simeq 17$ [15]. This low density has the additional advantage that complications due to the anisotropy and nonparabolicity of the valence band structure which occur at higher energies are avoided. Figure 1(b) shows the low field magnetoresistance for five different temperatures at $p_s = 2 \times 10^{10}$ cm^{-2}. Even though there is a factor of 2 drop in the zero field resistivity as T decreases from 700 to 30 mK, the absence of a positive magnetoresistance shows that the $B = 0$ "spin splitting" due to inversion asymmetry is extremely small. These results suggest that the two-band model of temperature dependent interband scattering is not appropriate at low densities, and cannot be solely responsible for the 2D metallic behavior.

We now consider what the effect of changing the asymmetry has on the metallic behavior close to the transition. The asymmetry of the potential confining the holes is determined by the electric field applied across the heterojunction. The combination of front and back gates makes it possible to tune the asymmetry and the strength of the interparticle interactions independently. It is therefore possible to separate these two effects and determine which is responsible for the metallic behavior observed in low density 2D systems. Sample A was grown without a back gate (i.e., $V_{\rm bg} = 0$) and represents the least asymmetric case, i.e., where the electric field across the sample is minimal. The asymmetry is increased in sample B by the incorporation of an $n+$ back gate, which creates a large electric field across the hole system. This built-in p-i-n structure gives rise to an effective back-gate bias equivalent to the low temperature GaAs band gap of 1.5 V [17]. The requirement that leakage currents should be below 1 pA limits the back-gate bias range to 1.25−1.7 V. It is not therefore possible to attain the flat-band condition $V_{\rm bg} = 0$ in sample B.

To quantify the effect of the back gate on the metallic behavior we fix the carrier density at $p_s = 2.1 \times 10^{10}$ cm^{-2}, just on the metallic side of the transition. The potential profile and hole wave function are calculated self-consistently following Ref. [18]. The net electric field across the hole system is the sum of the field due to the back gate and the field due to the accumulation of holes: $E = E_{\rm bg} + ep_s/\epsilon$. Here ϵ is the dielectric constant, and $E_{\rm bg} = V_{\rm bg}/d$, where d is the distance from the substrate to the heterointerface. The results are plotted in Figs. 2(a)–2(c), with the solid line showing the potential profile. This figure shows there is a large change in the electric field $E_{\rm bg}$ from 0 to

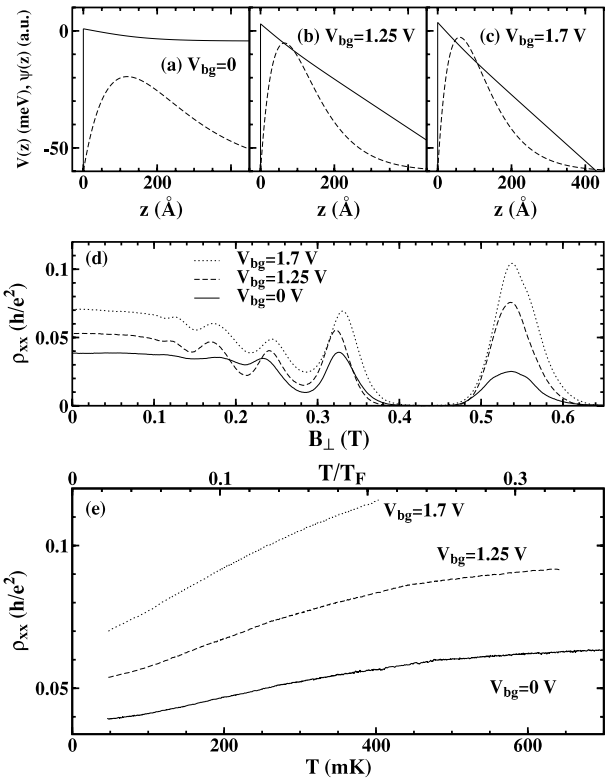

FIG. 2. Properties of the 2D holes at $p_s = 2.1 \times 10^{10}$ cm^{-2} for different back-gate biases. (a)–(c) Potential profiles $V(z)$ (solid lines) and hole wave functions $\psi(z)$ (dashed lines). (d) Perpendicular magnetoresistance ρ_{xx} ($T = 30$ mK). (e) Temperature dependence of the zero field resistivity.

14 kV/cm as the back-gate bias is altered from 0 to 1.7 V. In contrast the electric field due to the fixed carrier density is constant at only 3 kV/cm.

The effect of these changes in the asymmetry of the confining potential on the transport properties of the hole system are shown in Fig. 2(d), where the magnetoresistance is plotted for different V_{bg}. The three traces exhibit Shubnikov–de Haas oscillations with the same periodicity, confirming that the density is constant. In contrast to high density 2D hole systems the splitting of the heavy hole band is negligible at these low densities. As a result the oscillations show only a single frequency, with no sign of the beating that occurs when two bands are occupied.

To determine the influence of the electric field on the strength of the metallic behavior, defined by the decrease in ρ with decreasing temperature, we plot the temperature dependence of the $B = 0$ resistivity in Fig. 2(e). Although metallic behavior is observed in all three cases, it is not obvious how to quantify the strength of the metal because each trace starts from a different value of ρ at $T = 30$ mK. The change in resistance with T is clearly largest for the strongest electric field (top trace), where $\Delta\rho = 0.04h/e^2$, compared to $0.02h/e^2$ for $V_{bg} = 0$. However the comparison is complicated by the fact that the resistivity is larger for $V_{bg} = 1.7$ V than for $V_{bg} = 0$ V. This is because increasing the electric field due to the back gate pushes the holes closer to the heterointerface, enhancing the scattering from the remote ionized impurities in the AlGaAs. Thus even though the carrier density is constant, the effective disorder becomes larger with increasing V_{bg}. In these measurements the density p_s, Fermi wave vector k_F, and strength of interparticle interactions r_s are all fixed, with only the disorder related mean free path l and magnitude of the asymmetry varying. The metallic behavior is therefore sensitive either to the symmetry of the confining potential, or to the disorder, or both.

To distinguish between these possibilities, we now compare $\rho(T)$ traces that originate from the same point at $T = 30$ mK—i.e., we fix $k_F l$—and look for differences in the size of $\Delta\rho$ as T is increased. To fix $k_F l$ we increase the hole density from 1.8 to 2.3 $\times$ 10^{10} cm^{-2} as the back-gate bias is increased from 0 to 1.7 V. Although the carrier density and mean free path are now no longer constant in these measurements, they vary by only 30%, whereas the total electric field across the holes increases fivefold from 3 to 17 kV/cm. This can be seen in the plots of the potential profiles and hole wave functions in Figs. 3(a)–3(c). The corresponding temperature dependent resistivity traces are shown in Fig. 3(d). Despite the large change in the confining potential, the traces are almost indistinguishable. This confirms that the strength of the metallic behavior at low densities is not determined by the asymmetry of the confining potential, and is therefore not related to the degree of band splitting. Instead, the data indicate that metallic behavior is primarily affected by changes in the disorder.

As the data show that symmetry related phenomena cannot account for the large drop in resistivity in these

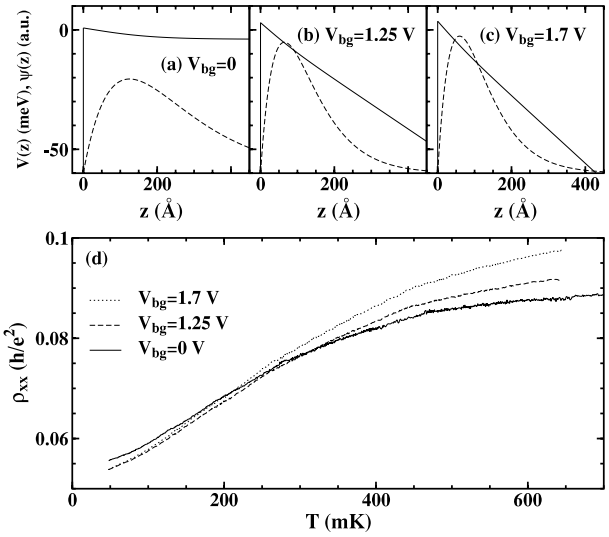

FIG. 3. Properties of the 2D holes with the $T = 30$ mK resistivity fixed at $0.055h/e^2$ ($k_F l = 18$), for three back-gate biases. (a)–(c) Potential profiles and hole wave functions. (d) Corresponding temperature dependence of the resistivity.

samples, we finally consider the effects of disorder and screening, looking in particular at the functional form of $\rho(T)$. Previous studies have shown it possible to fit the metallic-like $\rho(T)$ to the empirical formula $\rho(T) = \rho_0 + \rho_1 \exp[-T_1/T]$ [5,9,11]. Although this formula provides a reasonable fit to our data, as shown in Fig. 1(a), we note that the resistivity can also be seen to increase approximately linearly with increasing temperature for $T/T_F < 0.2$ [Figs. 1(a) and 3(d)]. This behavior is reminiscent of temperature dependent screening in the clean limit [19]. Indeed, previous experiments have shown that in the metallic-like regime the fractional decrease in conductivity with increasing T depends only upon T/T_F for temperatures down to 0.3 K [6]. We now re-examine this result, using higher quality systems and extending the measurements to lower temperatures. Figure 4(a) shows the temperature dependence of ρ at different carrier densities in the range 1.6–3.5 $\times$ 10^{10} cm^{-2} for sample B. These data are replotted in Fig. 4(b) to show the fractional change in conductivity $\Delta\sigma/\sigma$ against T/T_F. Here $\Delta\sigma$ is the change (decrease) in conductivity with increasing T, and T_F is the Fermi temperature. Remarkably, all the data for the different densities collapse onto a common curve, which is linear at low T/T_F, and saturate at higher T/T_F as the 2D system becomes nondegenerate.

The general applicability of this result is highlighted by a comparison with the metallic behavior observed in the quantum well of sample C [6]. The temperature dependence of the resistivity for this sample [Fig. 4(c)] shows metallic-like behavior for densities above 5 $\times$ 10^{10} cm^{-2}. This can be more clearly seen in Fig. 4(d), where we plot the corresponding fractional change in conductivity against T/T_F. Although the metallic-like drop in ρ is much smaller than in samples A and B, the $\Delta\sigma/\sigma$ data again collapse onto a common trace despite a threefold variation

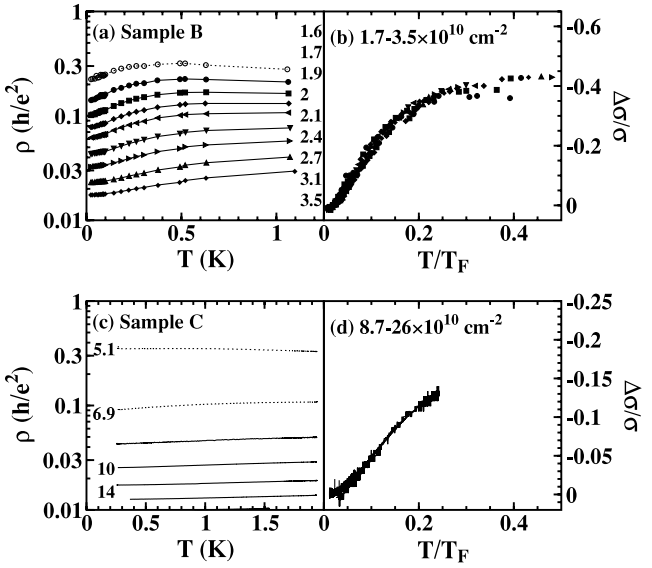

FIG. 4. Metallic behavior in different p-GaAs samples. (a) Temperature dependence of the zero field resistivity at different carrier densities in sample B. (b) Corresponding $\Delta\sigma/\sigma$ as a function of the dimensionless temperature T/T_F, for 14 equally spaced densities in the range $(1.7-3.5) \times 10^{10}$ cm^{-2}. (c),(d) Equivalent data for sample C.

in carrier density. As with sample B, $\Delta\sigma/\sigma$ is linear in T/T_F at low temperatures ($T/T_F < 0.2$), and flattens off at higher temperatures.

The observation that $\Delta\sigma/\sigma$ scales as T/T_F, for samples from different heterostructures, grown in different MBE systems, is an intriguing result. Although the metallic-like behavior takes a similar form, it is clearly stronger for the higher quality samples where lower carrier densities can be reached. Temperature dependent screening is an appealing mechanism for the metallic behavior as it does not depend on the details of the semiconductor system, and can cause an approximately linear decrease in conductivity with increasing temperature [19]: $\Delta\sigma/\sigma = -C(T/T_F) - D(T/T_F)^{3/2} + O(T/T_F)^2$. Furthermore, if C and D are density independent, the fractional change in conductivity will depend only on T/T_F. This would cause a collapse of the $\Delta\sigma/\sigma$ data onto a common trace, as seen in Fig. 4.

The analytical theory of Ref. [19] shows that C and D are density dependent, becoming larger as the carrier density decreases. This is consistent with the trend observed between samples: the magnitude of $\Delta\sigma/\sigma$ is larger for the low density data (sample B) than the data at higher densities (sample C). However, it cannot explain the observation that within a given sample all the $\Delta\sigma/\sigma$ data in the metallic regime collapse onto a single trace, with a deviation of less than 13% despite a twofold or threefold variation in carrier density. A more complex form of temperature dependent screening which takes into account self-consistent screening and multiple scattering effects, may therefore be necessary to fully explain the dependence of $\Delta\sigma/\sigma$ upon T/T_F, as well as the functional form of $\rho(T)$ [20]. Nevertheless, T-dependent screening is clearly important in dilute 2D systems, and can even qualitatively account for the experimentally observed suppression of the metallic behavior by an in-plane magnetic field [21].

The results presented here show that the two-band model of temperature dependent scattering does not describe the metallic behavior observed in low density 2D hole systems. Instead, we find that within a given sample the temperature dependence of the resistivity at low carrier densities is predominantly determined by the low-temperature resistivity (i.e., by $k_F l$), independent of the electric field across the heterojunction. Furthermore, we show that for a variety of single heterojunction and quantum well samples, the metallic behavior takes a similar form, with $\Delta\sigma/\sigma$ scaling as T/T_F. Surprisingly, these observations suggest that the metallic behavior is not due to the strong interactions, nor to the shape of the potential well, but is instead predominantly determined by the disorder. Although temperature dependent screening may account for some aspects of the data, further work will be needed to fully explain the cause of the metallic behavior in dilute 2D systems.

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