# Degenerate versus semidegenerate transport in a correlated two-dimensional hole system

Richard L. J. Qiu,[1] Xuan P. A. Gao,[1,*] Loren N. Pfeiffer,[2] and Ken W. West[2]
[1]*Department of Physics, Case Western Reserve University, Cleveland, Ohio 44106, USA*
[2]*Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, USA*
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It has been puzzling that the resistivity of high-mobility two-dimensional (2D) carrier systems in semiconductors with low carrier density often exhibits a large increase followed by a decrease when the temperature $T$ is raised above a characteristic temperature comparable with the Fermi temperature $T_F$. We find that the metallic 2D hole system in a GaAs quantum well has a linear density- ($p$-) dependent conductivity $\sigma \approx e\mu^*(p - p_0)$ in both the degenerate ($T \ll T_F$) and semidegenerate ($T \sim T_F$) regimes. The $T$ dependence of $\sigma(p)$ suggests that the metallic conduction $d\sigma/dT < 0$ at low $T$ is associated with the increase in $\mu^*$, the effective mobility of itinerant carriers. However, the resistivity decrease in the semidegenerate regime $T > T_F$ originates from the reduced $p_0$, the density of immobile carriers in a two-phase picture.

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Electron transport in two-dimensional (2D) electron systems has been the focus of research for a long time.[1] A pioneering work on the one-parameter scaling theory of localization[2] concluded that all noninteracting disordered 2D electronic systems have to be localized in a zero magnetic field ($B = 0$). The application of the celebrated scaling theory of localization and the Fermi-liquid model in strongly interacting 2D systems, however, was questioned by a number of experimental observations of an apparent metallic state and a metal-insulator transition (MIT) in various 2D electron or hole systems with low density and high mobility.[3] Although a low carrier density implies a large value of $r_s$ (the ratio between the Coulomb potential energy and kinetic energy) or strong correlation effects, different opinions exist on how the strong correlations affect the carrier transport in dilute 2D systems and what mechanism causes the metallic transport.[4–12]

After extensive experimental studies of transport in various dilute 2D carrier systems in semiconductors, one salient feature stands out in the 2D metallic transport phenomena. For densities above the critical density $p_c$, the temperature-dependent resistivity $\rho(T)$ is often nonmonotonic: $\rho$ first increases and then decreases as the temperature is raised above a characteristic temperature $T^* \sim T_F$. Such nonmonotonic behavior in $\rho(T)$ when a low-density 2D system becomes semidegenerate has been observed in all three of the most widely studied systems: $n$-Si,[13,14] $p$-GaAs,[15–17] and $n$-GaAs.[18] This sign change in $d\rho/dT$ at $T^*$ is generic for the 2D metallic state if the phonon-scattering contribution to resistivity does not overwhelm the impurity-scattering induced $\rho$ in the semidegenerate regime.[16,19] The existence of a nonmonotonic $\rho(T)$ is essential in many leading theoretical explanations for the 2D metallic state.[7–9,12] Therefore, to further distinguish the mechanisms of the 2D metallic state, it would be desirable to address experimentally the transport and scattering processes as the system crosses over from the degenerate ($T \ll T_F$) to the semidegenerate ($T \sim T_F$) regime. In addition, transport of 2D electron fluids with $r_s \gg 1$ in the semidegenerate regime is interesting in its own right. In this seldom-studied regime, non-Boltzmann-type transport such as hydrodynamics may play an important role.[9,20]

Here we compare the density dependence of conductivity in the degenerate and semidegenerate regimes for a low-density 2D hole system (2DHS) with strong interactions ($r_s > 18$ for the densities covered in this experiment[21]). In the metallic state, our 2DHS in 10-nm-wide GaAs quantum wells (QWs) exhibits a pronounced nonmonotonic $\rho(T)$ associated with the degenerate to semidegenerate crossover and a strong low-$T$ metallicity[17,22] due to the stronger confinement and smaller phonon-scattering contribution to the resistivity in narrow QWs.[16,17,19] The particular focus of this paper is on understanding the nonmonotonic $\rho(T)$ of the correlated 2DHS from the temperature dependence of $\sigma(p)$ in the high-conductivity regime ($\sigma \gg e^2/h$). In such a metallic regime away from the critical point of the MIT, we find that the conductivity has a Drude-like linear density dependence, $\sigma(p) \approx e\mu^*(p - p_0)$, consistent with a two-phase mixture picture where the total conductivity is dominated by mobile carriers with mobility $\mu^*$ and density $p - p_0$. The $\sigma(p)$ data at different $T$ further suggest that the resistivity changes on the two sides of the nonmonotonic $\rho(T)$ of low-density 2D systems have distinct origins: One comes from $\mu^*(T)$ and the other is a result of $p_0(T)$. The low-$T$ metallic conduction in the degenerate regime is accompanied by a sharply increasing $\mu^*(T)$ as $T$ decreases. In contrast, the resistivity change of the 2DHS in the nondegenerate regime is dominated by a $p_0$ that decreases rapidly as $T$ increases.

Transport measurements were performed on 2DHSs in two 10-nm-wide GaAs QW samples similar to the ones used in our previous studies.[19,22,23] The samples were grown on a (311)$A$ GaAs wafer using $Al_{0.1}Ga_{0.9}As$ barriers and symmetrically placed Si $\delta$-doping layers. The metal backgate used to tune the hole density was about 0.15 mm away from the QW such that the Coulomb interaction between holes was unscreened by the gate and remained long range. The samples were prepared in the form of a Hall bar, of approximately $2\times$ 9 $mm^2$ in dimension, with diffused In(1%Zn) contacts. The measurement current was applied along the high-mobility [$\bar{2}33$] direction and kept low such that the power delivered on the sample was less than 3 $fW/cm^2$ to avoid overheating.[19]

Before we go into the details of the density-dependent conductivity data and analysis, we use Fig. 1 to establish some basic transport and magnetotransport behavior of the

 

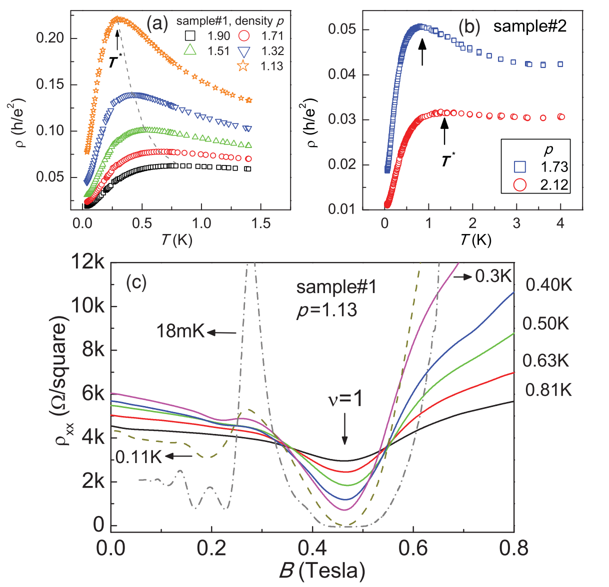


FIG. 1. (Color online) (a) Nonmonotonic $\rho(T)$ for the 2DHS with densities $p = 1.90, 1.71, 1.51, 1.32$, and 1.13 in the 10-nm-wide GaAs QW sample 1. The crossover temperature $T^*$ of the nonmonotonic $\rho(T)$ with different $p$ is connected by a dashed line to guide the eye. (b) $\rho$ vs $T$ for $p = 1.73$ and 2.12 in sample 2, showing that the nonmonotonic $\rho(T)$ exists even in the highly conductive regime with $\rho$ as low as $\sim 0.01h/e^2$. (c) Resistivity $\rho_{xx}$ vs the perpendicular magnetic field $B$ at different temperatures for $p = 1.13$ in sample 1. For $T > T^*$, the $\rho_{xx}(B)$ curves still exhibit a SdH dip at $\nu = 1$ whose position does not change with $T$.

low-density 2DHS. Figure 1(a) presents the temperature-dependent resistivity $\rho(T)$ at $B = 0$ for several densities ($p = 1.90, 1.71, 1.51, 1.32$, and 1.13) in sample 1 (the unit for $p$ is $10^{10}$ cm$^{-2}$ throughout this paper). For this sample, the MIT happens around $p_c \approx 0.8$ when the density is changed by the backgate voltage $V_g$.[23] It can be seen in Fig. 1(a) that $\rho(T)$ changes from metallic ($d\rho/dT > 0$) to insulatinglike ($d\rho/dT < 0$) above a characteristic temperature $T^*$, which becomes larger when $p$ increases, is consistent with previous findings in the literature.[15–18] Because of the suppressed phonon scattering in our narrow QWs compared to wider QWs or heterostructures,[16] here we are able to directly observe such nonmonotonic $\rho(T)$ in a much lower resistivity regime ($\rho \sim 0.01 \times h/e^2$) than found in the literature, as shown in Fig. 1(b) for $p = 2.12$ in sample 2.

The 2D hole density is determined by the positions of the Shubnikov–de Haas (SdH) oscillations as $p = \nu B_\nu e/h$, where $\nu$ is the Landau filling factor and $B_\nu$ is the perpendicular magnetic field at the corresponding $\nu$. Figure 1(c) plots the longitudinal magnetoresistivity $\rho_{xx}(B)$ for $p = 1.13$ of sample 1 at various temperatures ($T = 0.018$–$0.81$ K). Throughout this whole temperature range covering both $T < T^*$ and $T > T^*$, the SdH oscillation is well established at $\nu = 1$ and $B_{\nu=1}$ does not change with temperature, indicating a constant $p$. In addition, we note that the $\nu = 1$ SdH oscillation persists up to at least 0.81 K, a temperature comparable to $T_F$ [=1.0 K using effective hole mass $m^* = 0.3m_e$ (Ref. 21)] or the cyclotron energy $\Delta_c$ at $\nu = 1$. This is surprising since the SdH oscillation amplitude should decay strongly above $k_B T \sim 0.1\ \Delta_c$ according to the Lifshitz-Kosevich formula[24] $\delta\rho_{xx} \propto \frac{2\pi^2 k_B T/\Delta_c}{\sinh(2\pi^2 k_B T/\Delta_c)}$. The fact that the SdH observation is observed at $T > T^*$ points to the nonclassical nature of the dilute 2DHS with large $r_s$ at these semidegenerate temperatures.

While a decreasing $\rho$ with $T$ in the regime of $T > T^*$ is expected in several models, due either to interaction or correlation effects[7–9] or to classical scattering,[12] it has been difficult to identify the exact mechanism.[14] We studied the density dependence of the conductivity $\sigma$ to gain more insight into the transport mechanism of the metallic 2DHS when the temperature coefficient $d\rho/dT$ changes sign at $T^*$. Figures 2(a) and 2(b) present $\sigma(p)$ for samples 1 and 2 from 0.035 K ($T \ll T_F$) up to 4 K ($T > T_F$) over the density range $0.7 < p < 2$. A few features in $\sigma(p)$ are salient when the 2DHS crosses over from the low-$T$ degenerate regime (open symbols) to the high-$T$ semidegenerate regime (solid symbols). First, similar to a previous report,[25] at low $T$, $\sigma(p)$ turns up sharply around the MIT ($p = p_c$) and then follows a straight line with large slope at $p > p_c$. As $T$ increases, the slope of the linear dependence becomes smaller and at the same time the sharp upturn at $p \sim p_c$ straightens. Eventually, at high temperatures, $\sigma(p)$ becomes a linear function over the whole range of $p$. Yet the slope and intercept of the $\sigma(p)$ data at high $T$ are much smaller than the low-$T$ curves. A linear $\sigma(p)$ dependence is expected in the Drude model with

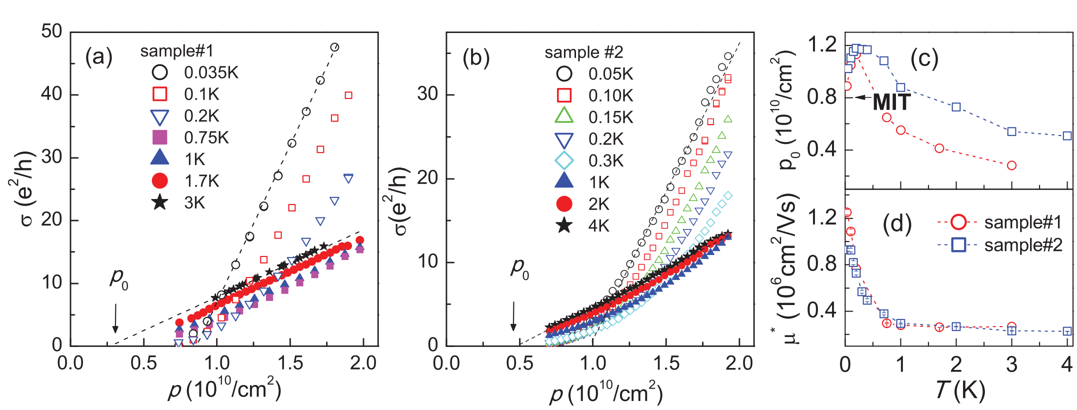


FIG. 2. (Color online) (a) 2D hole conductivity $\sigma$ plotted as a function of density $p$ at different temperatures for samples (a) 1 and (b) 2. A linear Drude-type function can be used to approximate the conductivity as $\sigma = e\mu^*(p - p_0)$, as denoted by the dashed lines. Fitting parameters (c) $p_0$ and (d) $\mu^*$ plotted against temperature.

the slope corresponding to the mobility of carriers. Therefore, the dramatic slope change in $\sigma(p)$ in our data suggests a dramatically enhanced mobility of free carriers at low $T$. In the Drude model, the finite intercept $p_0$ of $\sigma(p)$ would correspond to the density of localized carriers, which appears to change with $T$, as indicated by data in Figs. 2(a) and 2(b).

Previously, the low-$T$ behavior of $\sigma(p)$ near the critical regime ($p \sim p_c$) was analyzed in terms of the percolation model as $\sigma = A(p - p_c)^\delta$, with $\delta \approx 4/3$, where the MIT is driven by the percolation of itinerant carriers with density $p - p_c$ through localized carriers with density $p_c$.[14,26–28] A linear relation ($\delta = 1$) between $\sigma$ and $p - p_c$ at high $\sigma$ would reconcile the percolation model with the Drude formula when the overall conductivity is dominated by itinerant carriers (i.e., when $\sigma \gg e^2/h$). In that case, the coefficient $A$ in the percolation equation yields the effective mobility $\mu^*$ of itinerant carriers. Here we focus on the linear Drude part of $\sigma(p)$ in the high-conductivity limit ($\sigma \gg e^2/h$) to examine how the system evolves over a broad range of $T$. This analysis not only gives a physically meaningful parameter $\mu^*$, but also works in the high-temperature (semidegenerate) regime where the percolation fit is not applicable. We fit the data in Figs. 2(a) and 2(b) with $\sigma > 5e^2/h$ to $\sigma = e\mu^*(p - p_0)$ with $\mu^*$ and $p_0$ as the fitting parameters.[29] The fitted $\mu^*$ and $p_0$ are plotted as functions of $T$ in Figs. 2(c) and 2(d) for both samples. First of all, reflecting the metallic transport and rapidly increasing slope of $\sigma(p)$ at low $T$, $\mu^*$ exhibits a sharp upturn at $T$ lower than $\sim$0.5 K, in contrast to its nearly $T$-independent behavior at high $T$. In contrast, $p_0$ shows only a minor drop at $T < 0.5$ K but decreases greatly at high $T$ [a factor of 3 (2) for sample 1 (2)]. These effects, which are revealed through the density-dependent conductivity analysis, lead to an important insight into the nonmonotonic $\rho(T)$ or $\sigma(T)$ for the metallic 2DHS with a fixed density: While the metallic conduction in the degenerate regime could be attributed to an enhanced mobility of itinerant carriers, the increasing conductivity in the semidegenerate regime (i.e., $T > T^*$ in Fig. 1) is a consequence of decreased $p_0$, or the density of localized carriers, but not a mobility effect. This can actually be inferred directly from the raw data in Fig. 2(a): As $T$ is lowered from 3 to 0.75 K, the $\sigma(p)$ curves stay parallel to each other and shift toward a higher intercept $p_0$. Within this analysis, one obtains the following picture for the nonmonotonic $\rho(T)$ peak around $T^*$ in low-density 2D systems: The resistivity drop at $T < T^*$ is due to reduced scattering but the high-$T$ ($T > T^*$) resistivity drop comes from a different mechanism where some localized carriers become itinerant and contribute more and more to the overall conductivity when the temperature is increased.

To explain the nonmonotonic $\rho(T)$ of low-density 2D carrier systems, a few theories involving different mechanisms were proposed.[8,9,12] While it is natural that these theories have focused on the effect of temperature on the scattering, diffusion, or viscosity of the 2D carriers, our data supply two useful insights that are not contained specifically in the existing theories. First, in the high-$T$ semidegenerate regime, the effective mobility $\mu^*$ of itinerant carriers (essentially the slope of $d\sigma/dp$) is roughly $T$ independent and much smaller than the degenerate regime. This emphasizes a distinct transport property of the 2DHS between $T < T^*$ and $T > T^*$: Although the 2DHS can have the same resistivity value in the degenerate or the semidegenerate regime [Fig. 1(a)], carriers added to the system experience much stronger scatterings or collisions at $T > T^*$ than at $T < T^*$. Second, the decreasing $\rho$ in the $T > T^*$ regime is likely tied to the temperature dependence of $p_0$, the density of localized carriers, instead of a simple scattering rate effect. These features should be included in future theoretical considerations.

We studied the transverse magnetoresistance or Hall resistance $R_{xy}$ in the perpendicular magnetic field to obtain additional information on the nature of the two species of carriers inferred from the $\sigma(p)$ data. Figure 3(a) shows $R_{xy}$ vs $B$ for $p = 1.33$ of sample 2 over a broad temperature range ($T = 0.1$–4 K). The data have been symmetrized using both positive and negative field measurements to remove the slight mixing from longitudinal resistance. A dashed line is included to show the classical linear Hall resistance $B/ep$ according to the hole density $p$. It is interesting to see that the experimentally measured $R_{xy}$ is always smaller than $B/ep$, except in the fully developed $\nu = 1$ QH state. This significant difference between the measured $R_{xy}$ and $B/ep$ is quantified in Figs. 3(b) and 3(c). Figure 3(b) shows that $1/eR_H$ is significantly (40%–60%) higher than $p$. Here $R_H$ is the Hall coefficient obtained by fitting the slope of $R_{xy}(B)$ at low field ($|B| < 500$ G). It is tempting to relate the temperature dependence of $1/eR_H$ in Fig. 3(b) to a $T$-dependent carrier density effect similar to what we infer from $\sigma(p)$ data. However, two caveats are worth pointing out. First, the increase of $1/eR_H$ at $T < 1$ K reproduces previous results on the $T$-dependent $R_H$ in a similar 2DHS (Ref. 23) whose origin is not fully understood since multiple mechanisms can lead to temperature-dependent corrections to $R_H$.[30–32] The second caution or puzzle one needs to consider is the significant difference between $1/eR_H$ and $p$: It is as large as 40% even at the lowest temperature studied (80 mK). Figure 3(c) presents the $B$ dependence of the Hall slope $dR_{xy}/dB$ up to 0.8 T. It shows that although $dR_{xy}/dB$ exhibits some increase in $B$, it is still lower than $1/ep$, which is anticipated from the density. In the two-band transport model, the low-field Hall slope $dR_{xy}/dB$ is related to both the density and mobility of the two carrier species as $1/(edR_{xy}/dB) = (p_1\mu_1 + p_2\mu_2)^2/(p_1\mu_1^2 + p_2\mu_2^2)$, while $1/edR_{xy}dB$ at high fields ($\mu B \gg 1$) is equal to the total carrier density $p_1 + p_2$. Thus a smaller Hall slope at high field is always expected for the standard two-band model. We see that the opposite trend is exhibited in our 2DHS as $dR_{xy}/dB$ becomes larger at higher $B$ in Fig. 3(c). We speculate

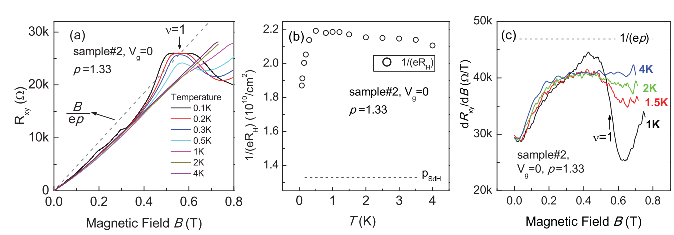


FIG. 3. (Color online) (a) Hall resistance $R_{xy}$ as a function of the perpendicular magnetic field $B$ for $p = 1.33$ in sample 2 at $T =$ 0.1–4 K. (b) $1/eR_H$ vs $T$ for $p = 1.33$ with $R_H$ as the low-field Hall coefficient. (c) Hall slope $dR_{xy}/dB$ vs the magnetic field at $T = 1$, 1.5, 2, and 4 K. At high $T$ when the $\nu = 1$ QH state weakens, the Hall slope shows a clear enhancement as $B$ increases.

that the increase in the Hall slope at high $B$ is caused by the localization or Wigner crystallization of carriers.[33] Because the two carrier species we consider can have both a temperature- and a magnetic-field-dependent density and mobility, we do not have a reliable model to fit $R_{xy}(B)$ data to compare with the zero-field conductivity analysis in Fig. 2. One possible implication of the small Hall slope in our experiments is that there exist carriers that contribute to the current but not the Hall voltage. Obviously, further study is required to understand the anomalous Hall slope and the nature of the two carrier species in the 2DHS with large $r_s$.

It is worth pointing out that our results may in fact be compatible with several theories that emphasize the coexistence of a conducting metallic phase and an insulating localized phase near the MIT.[6,9,12] A two-component and temperature dependent carrier freeze-out model for the 2D MIT was suggested by Das Sarma and Hwang in 1999.[12] In the more recently proposed microemulsion scenario of the 2D MIT, the 2D metallic phase consists of mobile Fermi liquids percolating through bubbles of Wigner crystals that have much lower conductivity.[9] The original microemulsion model suggested the $1/T$-dependent viscosity of the correlated electron fluid as the explanation for the decreasing $\rho$ in the high-$T$ regime of $T \sim T_F$. Our $\sigma(p)$ data suggest that the continuous melting of the Wigner crystal is perhaps more important in the experimentally accessed temperature range here since only $p_0$ has a strong temperature dependence at $T > T^*$. Thus theoretical calculations on the density-dependent conductivity and the Hall effect of microemulsion would be desirable to compare further with experiment. In other classical percolation models of the 2D MIT,[26–28] the nature and the high-temperature fate of the localized carriers have not been addressed theoretically so far. In those theories, more detailed calculations need be done to see if thermal activation of localized carriers can produce the effects reported here.

In summary, we have studied the density-dependent conductivity of a 2DHS in a GaAs QW as $T$ is raised from the low-$T$ degenerate regime ($T \ll T_F$) to the high-$T$ semidegenerate regime ($T > T_F$). In both regimes, the system's conductivity can be described by a Drude-like formula $\sigma(p) \approx e\mu^*(p - p_0)$ in the high-conductivity limit. The temperature dependence of $\sigma(p)$ reveals that the metallic transport at $T < T_F$ is associated with the dramatically enhanced $\mu^*$ at low $T$, while the system's resistivity decrease at $T \sim T_F$ is likely a result of some localized carriers becoming conductive. However, the temperature and magnetic-field dependence of the Hall resistance requires further understanding.

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*xuan.gao@case.edu


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