Temperature and Magnetic-Field-Enhanced Hall Slope of a Dilute 2D Hole System in the Ballistic Regime

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We report the temperature (T) and perpendicular magnetic-field (B) dependence of the Hall resistivity $\rho_{xy}(B)$ of dilute metallic 2D holes in GaAs over a broad range of temperature (0.02–1.25 K). The low B Hall coefficient, R_H, is found to be enhanced when T decreases. Strong magnetic fields further enhance the slope of $\rho_{xy}(B)$ at all temperatures studied. Coulomb interaction corrections of a Fermi liquid (FL) in the ballistic regime can not explain the enhancement of ρ_{xy} which occurs in the same regime as the anomalous metallic longitudinal conductivity. In particular, although the metallic conductivity in 2D systems has been attributed to electron interactions in a FL, these same interactions should reduce, *not enhance*, the slope of $\rho_{xy}(B)$ as T decreases and/or B increases.

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The interplay between single particle localization and electron-electron interactions in disordered electronic systems has been under much investigation for two decades [1]. Because of disorder induced localization, 2D noninteracting electron systems are predicted to be insulators at zero temperature in the presence of any disorder [1]. It was also widely accepted that adding electron interactions does not change this conclusion and, thus, there is no true metallic state in two dimensions at $T = 0$. It came as a surprise when a 2D metallic state and a metal-insulator transition (MIT) were observed in various high mobility low density 2D systems after the initial discovery of Kravchenko *et al.* [2]. The strong Coulomb interactions in these low density metallic systems revived interest in the role of Coulomb interactions in disordered 2D systems.

A comprehensive theoretical understanding of the Coulomb interaction effects on the 2D electron transport has emerged over the years [3–7]. For diffusive electrons at low T, Coulomb interactions are known to give a $\ln T$ conductivity correction, accompanying the similar $\ln T$ correction from single particle interference in the weakly disordered regime [3,4]. Recently, Zala, Narozhny, and Aleiner (ZNA) pointed out that the logarithmic Altshuler-Aronov interaction correction to σ originates from coherent scattering of Friedel oscillations. They extended the calculation to intermediate temperatures where transport is ballistic ($k_BT > \hbar/\tau$) instead of diffusive ($k_BT < \hbar/\tau$) [7]. For high mobility samples exhibiting 2D metallic conduction, the elastic scattering time τ is large and the sample is usually in the ballistic regime. In this regime, ZNA showed that $\delta\sigma(T)$, the interaction correction, could be positive (“metallic”) or negative (insulating), depending on the Fermi liquid (FL) parameter F_0^σ just as in the diffusive regime. The ZNA theory improves the previous screening theory of Coulomb interactions at intermediate temperatures [5,6(a),6(b)] and predicts a linear T-dependent $\delta\sigma(T)$ controlled by F_0^σ.

The interaction correction theory of FL systems in the ballistic regime [7] was applied by various experimental groups to explain the zero magnetic-field metallic conductivity [8–14]. In these analyses, negative F_0^σ's were obtained from fitting the metallic $\sigma(T)$ to a linear function of T, corresponding to ferromagnetic spin exchange interaction. While various scattering mechanisms besides the interaction correction can contribute to the longitudinal conductivity, the T-dependent Hall resistivity is a good probe for separating the Coulomb interaction effects [3,15–17]. In this Letter, we present an analysis of the temperature-dependent Hall resistivity together with the longitudinal conductivity of a metallic 2D hole system within the recent ballistic FL theory in both a weak [7] and a strong perpendicular magnetic field [18]. We found that for all the densities studied the slope of $\rho_{xy}(B)$ is enhanced by a decreasing temperature and/or increasing magnetic field. When the $B = 0$ metallic conductivity is used to fix the FL parameters, analysis shows that the enhanced slope of $\rho_{xy}(B)$ is qualitatively and quantitatively inconsistent with interaction corrections to FL.

We performed the experiments on two dilute 2D hole systems in two 10 nm wide GaAs quantum wells. The samples were made from the same wafer used in our previous study [19]. The hole density p was tuned by a gold backgate which is about 150 μm underneath the quantum well. The two samples were measured in two different top loading ^{3}He/^{4}He dilution refrigerators: sample A was mounted on the copper tail of the mixing chamber of the refrigerator at UC-Riverside, while sample B was immersed in the liquid ^{3}He/^{4}He mixture inside the mixing chamber of the refrigerator at LANL. The data collected from the two samples in the two refrigerators are consistent with each other even down to our lowest experimental temperature of 20 mK. During the measurements, the voltage applied to the sample was always kept low such that the power delivered to the sample was less than a few fW/cm^2 to avoid overheating the holes.

In Fig. 1(a), we present the T-dependent conductivity $\sigma(T)$ of sample A for various hole densities ($p = 0.74$–1.9×10^{10} cm^{-2}) at $B = 0$ (σ is in units of e^2/h throughout this Letter). The density is determined from the Shubnikov–de Haas (SdH) oscillations. For all the densities except 0.74×10^{10} cm^{-2}, $\sigma(T)$ turns from insulatinglike ($d\sigma/dT > 0$) to metalliclike ($d\sigma/dT < 0$) below a characteristic temperature T^*. The metallic $\sigma(T)$ for $p > p_c$ below T^* was recently attributed by some authors to the Coulomb interaction correction of a FL with $F_0^\sigma < 0$ at intermediate temperatures according to the ZNA theory [8–14]. Theoretically, interaction effects will also give a correction to the Hall resistivity. In the low T diffusive limit, interactions have a correction $\delta R_H(T) \sim \ln T$ to R_H, the Hall coefficient [the slope of $\rho_{xy}(B)$ in small B] [3]. In the ballistic regime, $\delta R_H(T)$ is expected to change to a $1/T$ dependence [7]. Thus, depending on the value of F_0^σ, R_H will increase or decrease towards the Drude-Hall coefficient as $R_H(T) \sim 1/T$ when T increases. Figure 1(b) presents the $R_H(T)$ data for four metallic densities in Fig. 1(a). R_H was obtained by linearly fitting $\rho_{xy}(B)$ between -0.05 and $+0.05$ T perpendicular fields. It can be seen that at temperatures above 0.1 K the measured $R_H(T)$ may be described as a const + $1/T$ function [Fig. 1(b)], although the fit fails at lower T where the theory should apply best.

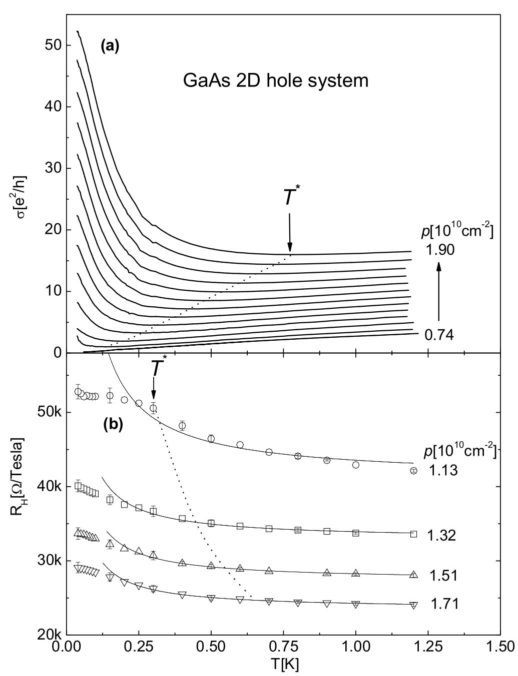

FIG. 1. (a) The $B = 0$ temperature-dependent conductivity $\sigma(T)$ of 2D holes with 13 different densities in a 10 nm wide GaAs quantum well (sample A). The hole density spans from $p = 0.74$ to 1.9×10^{10} cm^{-2} with 0.965×10^9 cm^{-2} step from the bottom curve to the top curve. The MIT of this sample happens around $p_c \sim 0.78 \times 10^{10}$ cm^{-2}. (b) The temperature-dependent Hall coefficients for four densities in (a). The black lines depict the functional behavior const + $1/T$. For $p > p_c$, a dotted line is plotted in both panels to indicate the temperature T^* where the sample turns metallic.

Now we quantitatively discuss the longitudinal transport together with the Hall resistivity within the interaction correction theory of FL, using a density ($p = 1.65 \times 10^{10}$ cm^{-2}) in sample B as an example. Figure 2(a) presents $\sigma(T)$ at $B = 0$. In the ballistic regime, the interaction correction to conductivity is [7]

$$\delta\sigma(T) = \sigma_D\left(1 + \frac{3F_0^\sigma}{1 + F_0^\sigma}\right)\frac{T}{T_F}. \tag{1}$$

Following the analyses of Refs. [8–14], we also can fit the conductivity data for $0.1 < T < 0.2$ K to the linear dependence of Eq. (1), obtaining a Drude conductivity $\sigma_D = 40$ and $F_0^\sigma = -0.6$. The hole mass was set to be $m^* = 0.38m_e$ in the fitting process, with m_e being the free electron mass. In Fig. 2(b), R_H data are plotted together with the predicted $R_H(T)$ (the gray line) according to ZNA theory with $\sigma_D = 40$ and $F_0^\sigma = -0.6$. In the ZNA theory, the interaction correction to R_H is the summation of the corrections from the singlet (charge) channel and the triplet (spin) channel, which are given as Eq. (17) and Eq. (18), respectively, in Ref. [7(c)].

The discrepancy between the data and theoretical expectation in the metallic regime of Fig. 2 is obvious. In fact, for $F_0^\sigma = -0.6$, the theory predicts a nearly flat but

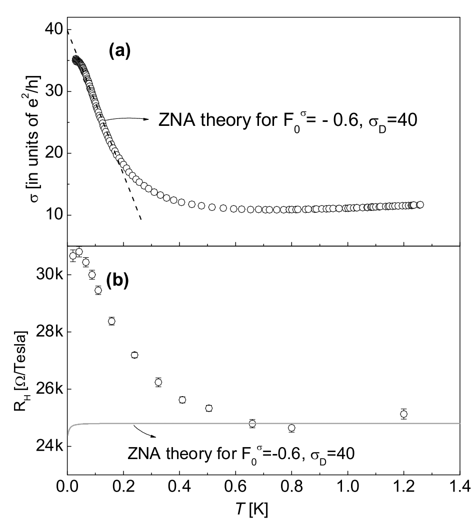

FIG. 2. (a) $\sigma(T)$ for 2D holes with $p = 1.65 \times 10^{10}$ cm^{-2} in sample B. The dashed black line is the linear fit of the metallic $\sigma(T)$ according to the FL interaction correction theory of ZNA, which yields $F_0^\sigma = -0.6$ and Drude conductivity $\sigma_D = 40$. (b) Comparison of the $R_H(T)$ data for 2D holes in (a) with the theoretical expectation assuming the $B = 0$ metallic conductivity is due to interaction correction of a FL. The gray line is the theoretical curve for $F_0^\sigma = -0.6$ and $\sigma_D = 40$.

decreasing R_H as temperature decreases in the experimental temperature range (0.02–1.2 K). Note that the FL theory predicts the interaction correction to R_H to be very small in the ballistic regime for large σ_D, consistent with the measurements for metallic 2D electrons in high mobility silicon–metal-oxide-semiconductor field-effect transistors (Si–MOSFET's) [20–22].

It is important to know if the temperature enhanced R_H is actually related to a varying carrier density effect. A standard way to measure carrier density is the SdH oscillations in the longitudinal magnetoresistivity $\rho_{xx}(B)$. From the positions of the SdH minima/maxima, one can extract the carrier density. At 20 mK we could observe SdH oscillation down to ~0.06 T. Figure 3(a) shows the index number vs $1/B$ for the positions of the SdH oscillations shown in the inset. We obtain the total hole density $p = 1.74 \times 10^{10}\ \mathrm{cm}^{-2}$ and the majority/minority spin subband densities $p_{+/-} = 1.15, 0.59 \times 10^{10}\ \mathrm{cm}^{-2}$, via linear fitting of the index number vs $1/B$ following Refs. [23,24]. The analysis of SdH beating is consistent with a B-independent density (with 30% net spin polarization at $B = 0$) in the regime of SdH oscillations and quantum Hall plateaus [25]. However, the low-field (≤ 0.05 T) Hall coefficient, $R_H(T)$, changes by more than 20% between 0.1 and 0.5 K, temperatures sufficiently high that most SdH oscillations at high filling factors are no longer observable. Nevertheless, the positions of the SdH dips at $\nu = 1, 2$ do not move with T, and hence strongly imply a fixed (T-independent) carrier density. The $T = 20$ mK SdH oscillations and Hall resistivity $\rho_{xy}(B)$ are presented in Fig. 3(b). The data are averaged from both positive and negative magnetic-field measurements to remove the admixture between ρ_{xx} and ρ_{xy}. We see that the SdH dips and quantized Hall plateaus occur at the same magnetic fields. Note, however, that the extrapolation of the low B ρ_{xy} intersects the Hall plateaus at magnetic fields higher than the plateau centers, indicating that the low-field R_H is smaller than that determined at high fields. While this 20% discrepancy could, in principle, be due to interaction corrections [3,15–17], we have already shown that the $\sigma(T)$ and $R_H(T)$ data are not explained consistently within the interaction theory of FL.

While the ZNA theory is only applicable in the low-field limit ($\omega_c\tau < 1$), Gornyi and Mirlin (GM) recently calculated the interaction correction to ρ_{xy} into the high magnetic-field regime ($\omega_c\tau \gg 1$), with $\omega_c = eB/m^*$ being the cyclotron frequency [18]. We also investigated the behavior of ρ_{xy} in strong magnetic fields to further test the FL interaction correction theory for our sample. In the GM strong magnetic-field theory, the interaction correction to ρ_{xy} is separated into two parts. One part is T dependent but B independent, and the other part is B dependent and T independent. In Fig. 4, we plot the Hall slope, ρ_{xy}/B vs B, at various temperatures. To remove the admixture of ρ_{xx} into ρ_{xy}, we antisymmetrized the ρ_{xy} data from both $B > 0$ and $B < 0$ measurements to obtain Fig. 4 . The low-field ($B \leq 0.05$ T) R_H data are also included. Figure 4 shows that the ρ_{xy}/B data indeed may be viewed as a T-independent magnetic-field enhancement on the background of a B-independent temperature enhancement [26]. The GM interaction correction to ρ_{xy} at strong B is also

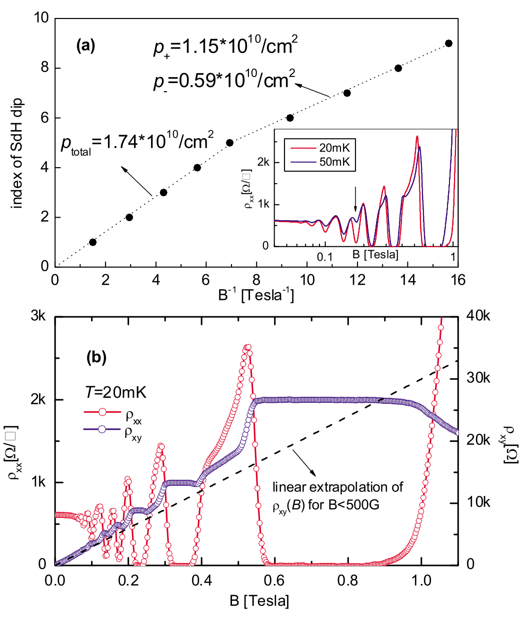

FIG. 3 (color online). (a) The index number i vs $1/B$ of SdH dips for sample B in Fig. 2. Linear fitting i vs $1/B$ in high B region yields a total hole density $p = 1.74 \times 10^{10}\ \mathrm{cm}^{-2}$. Linear fitting the low B part gives the densities for majority/minority spin subband $p_{+/-} = 1.15, 0.59 \times 10^{10}\ \mathrm{cm}^{-2}$. The inset shows the SdH oscillations at 20 and 50 mK, with an arrow marking the beating node around 0.15 T. (b) Longitudinal resistivity ρ_{xx} and Hall resistivity ρ_{xy} at 20 mK. The quantized Hall plateaus and SdH minima coincide, yielding a density that is ~20% smaller than deduced from the linear extrapolation (dashed line) of ρ_{xy} from low fields (< 0.05 T).

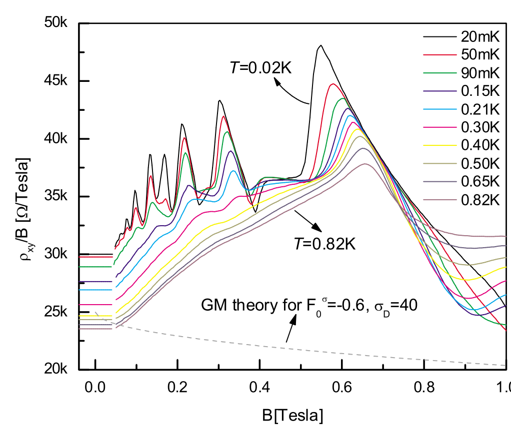

FIG. 4 (color online). ρ_{xy}/B, the slope of Hall resistivity vs magnetic field. When B is strong ($\omega_c\tau \gg 1$), a $\sqrt{B}$ dependent correction to ρ_{xy}/B is expected in the FL theory [18]. The dashed line is the theoretical curve for parameters $F_0^\sigma = -0.6$ and $\sigma_D = 40$ and a zero field value of $\rho_{xy}/B = 25\ \mathrm{k}\Omega/\mathrm{T}$.

quantitatively related to the FL parameter F_0^σ as in the ZNA theory [18]. The T-dependent part of the ρ_{xy} correction in the ballistic regime and strong B regime is given by Eqs. 3.53–3.56 in Ref. [18(b)], which also predicts a decreasing slope of $\rho_{xy}(B)$ with decreasing T for $F_0^\sigma = -0.6$. However, the opposite behavior, i.e., enhancement of ρ_{xy}/B, is observed when T decreases. The B-dependent part of the GM correction to ρ_{xy}, $\delta\rho_{xy}^B$, is also controlled by F_0^σ and has a $B^{3/2}$ dependence [18]. We also include the theoretically expected B-dependent ρ_{xy}/B in Fig. 4 as a dashed line according to Eq. 3.58 of Ref. [18(b)] for $F_0^\sigma = -0.6$, $\sigma_D = 40$, and $\rho_{xy}/B(B = 0) = 25\ \mathrm{k}\Omega/\mathrm{T}$. One can see that $\delta\rho_{xy}^B/\rho_{xy}$ is expected to be negative for $F_0^\sigma = -0.6$, but the data show a positive increase as B increases.

Figure 4 also suggests that ρ_{xy}/B is enhanced with decreasing T at both weak and strong magnetic fields in a similar fashion. It is reasonable to conclude that the T-dependent ρ_{xy}/B originates from the same mechanism for both magnetic-field regimes. Since our temperature-dependent SdH shows that the enhanced ρ_{xy}/B at high B is not related to a temperature-dependent density, we further conclude that the enhanced low magnetic-field Hall coefficient is not due to a density effect. In conclusion, for both the low magnetic-field (ZNA) and high magnetic-field (GM) regimes, our combined resistivity and Hall data are inconsistent with the electron interaction corrections interpretation in a Fermi liquid.

Finally, we briefly comment on the relevance between our data and several other FL-based models of the 2D metallic state, which do not invoke the FL parameters [6,27]. For our sample in the metallic state, σ is enhanced as large as 3 times as T is reduced, a result perhaps consistent with the screening theory of Das Sarma and Hwang [6]; however, the behavior of R_H has not yet been theoretically discussed within the screening theory. Alternatively, the enhanced R_H at low T could be interpreted as a carrier freeze-out [6(a)] or trapping effect [27]; however, the field ($B > 0.06$ T) and temperature independent density we observe in the SdH oscillations require these effects to disappear above 0.06 T and make these interpretations seem highly unlikely.

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