Interaction Correction to the Longitudinal Conductivity and Hall Resistivity in High Quality Two-Dimensional GaAs Electron and Hole Systems

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We present a systematic study of the corrections to both the longitudinal conductivity and Hall resistivity due to electron-electron interactions in high quality GaAs systems using the recent theory of Zala et al. [Phys. Rev. B 64, 214204 (2001)]. We demonstrate that the interaction corrections to the longitudinal conductivity and Hall resistivity predicted by the theory are consistent with each other. This suggests that the anomalous metallic drop in resistivity at B=0 is due to interaction effects and supports the theory of Zala et al.

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Despite much theoretical and experimental work, to date the origin of the anomalous metallic behavior in high quality 2D systems at zero magnetic field B remains a subject of controversy. The earliest results of Finkelstein2 and Castellani et al.2 suggested that in the presence of weak disorder and strong interactions it is possible to have a metallic ground state (where the conductivity \( \sigma_{xx} \) is a finite value at \( T=0 \) in 2D), even at \( B=0 \). It is well known that in the diffusive limit \( k_B T \tau/h \ll 1 \), electron-electron interactions give rise to a logarithmic correction to the conductivity. In the opposite ballistic limit \( k_B T \tau/h \gg 1 \), Stern, Gold & Dolgopolov and Das Sarma & Hwang have also shown that \( \sigma_{xx} \) can exhibit a metallic-like temperature dependence that is linear in temperature, and due to temperature-dependent screening of impurity and interface roughness scattering. While these previous theories were formulated in opposite limits of \( k_B T \tau/h \), most experimental data displaying \( B=0 \) metallic behavior falls in the intermediate region between these limits.

Recently, quantum conductivity corrections have received renewed interest following the development of a theory by Zala et al. that is valid for the entire range of \( k_B T \tau/h \). This theory shows that the previous results in the two opposite limits are due to the same physical process – elastic scattering of electrons by the self-consistent potential created by all the other electrons (i.e., scattering from the screened impurity potential). As the temperature is reduced, Ref. predicts a correction to the conductivity that is either localizing or delocalizing depending on the value of the Fermi liquid parameter \( F_0^0 \). The parameter \( F_0^0 \) is a measure of the interaction strength in the triplet channel and is related to the spin susceptibility \( \chi \propto 1/(1+F_0^0) \). Several recent experimental studies following Ref. have shown that the \( B=0 \) metallic behavior in a variety of material systems is consistent with the theory of Zala et al.

In addition to producing a correction to the longitudinal conductivity \( \sigma_{xx} \), interaction effects also lead to a correction to the Hall resistivity \( \rho_{xy} \). Whilst many of these authors have examined the \( \sigma_{xx} \) interaction correction, both at \( B=0 \) and in parallel magnetic fields, \( ^9,10,11,12,14 \) studies of the \( \rho_{xy} \) correction are less common. In particular there has been no experimental confirmation that the observed correction to \( \rho_{xy} \) is consistent with the correction to \( \sigma_{xx} \) or with the theoretical predictions of Ref. Since the magnitude of the corrections to \( \sigma_{xx} \) and \( \rho_{xy} \) both depend on \( F_0^0 \), then if \( B=0 \) metallic behavior is due to electron-electron interactions, the two values of \( F_0^0 \) extracted separately from measurements of \( \sigma_{xx} \) and \( \rho_{xy} \) should be consistent.

In this paper we report a systematic study of the interaction corrections to both the longitudinal conductivity \( \sigma_{xx} \) and Hall resistivity \( \rho_{xy} \), and extracted values for the Fermi liquid parameter, \( F_0^0 \). We show that the values of \( F_0^0 \) obtained from these two independent measurements are consistent. Our results support the theory of Zala et al. and suggest that the \( B=0 \) metallic behavior is due to interaction effects.

The experiments were performed on both n- and p-GaAs samples. The measured mobilities were \( 8.0 \times 10^5 \) cm\(^2\)V\(^-1\)s\(^{-1}\) at a carrier density of \( n_s = 2.0 \times 10^{10} \) cm\(^{-2}\) for the n-GaAs sample, and \( 2.0 \times 10^5 \) cm\(^2\)V\(^-1\)s\(^{-1}\) at \( n_s = 2.0 \times 10^{11} \) cm\(^{-2}\) for the p-GaAs sample. The temperature dependence of \( \sigma_{xx} \) shows a transition from insulating to metallic behavior at \( n_s = 5.17 \times 10^9 \) cm\(^{-2}\) (n-GaAs) and \( 4.50 \times 10^{10} \) cm\(^{-2}\) (p-GaAs). Firstly, we will outline the procedures used to extract the interaction correction and \( F_0^0 \) from the experimental measurements of \( \sigma_{xx} \) and \( \rho_{xy} \) for the n-GaAs sample. After extracting the interaction correction and \( F_0^0 \) for the p-GaAs data, we will present a comparative analysis of \( F_0^0 \) for the two samples, and discuss the ramifications of our measurements with respect to the theory of Ref. D

We begin by discussing the interaction correction to \( \sigma_{xx} \) and \( \rho_{xy} \) in n-GaAs because it is close to the ideal system considered in Ref. – electrons in n-GaAs have spin \( 1/2 \), no valley degeneracy, and well defined effective
mass \( m^* = 0.067m_e \). Furthermore additional corrections from phonon scattering and weak localization are negligible for the range of experimental parameters that we have explored.

The Fermi energy \( \sigma \) involves fitting Eqn. 1 to the data.

Commencing with the longitudinal conductivity correction, the temperature dependence of \( \sigma_{xx} \) at \( B=0 \) can be written as:

\[
\sigma_{xx}(T) = \sigma_D + \delta\sigma_S(T) + \delta\sigma_T(T)
\]

where \( \sigma_D \) is the Drude conductivity. The terms \( \delta\sigma_S(T) \) and \( \delta\sigma_T(T) \) are the singlet and triplet channel interaction corrections given by Zila et al. as:

\[
\delta\sigma_S = \frac{\epsilon^2}{\pi h} \left[ f(k_BT\tau) \frac{k_BT\tau}{h} - \ln \left( \frac{E_F}{T} \right) \right]
\]

\[
\delta\sigma_T = \frac{\epsilon^2}{\pi h} \left[ g(k_BT\tau; F_0) \frac{k_BT\tau}{h} - h(F_0) \ln \left( \frac{E_F}{T} \right) \right]
\]

where \( f(x) \), \( g(x; F_0) \) and \( h(x) \) are detailed in Ref. 8. The procedure for extracting \( F_0^\sigma \) involves fitting Eqn. 1 to the graph of \( \sigma_{xx} \) vs. \( T \) in the degenerate limit \( T \ll T_F \). The Fermi energy \( E_F \) and momentum scattering time \( \tau \) are given by \( E_F = \pi h^2 n_s / m^* \) and \( \sigma_D = n_s e^2 / m^* \) respectively using measured values of \( n_s \) and \( \sigma_D \). This leaves \( F_0^\sigma \) as the only fitting parameter in Eqn. 1.

Figure 1 (a-c) shows plots of \( \sigma_{xx}(T) \) vs. \( T \) at several temperatures in the range 150 mK < \( T < 600 \) mK, for \( n_s \) values corresponding to those in Fig. 1. In each case the slope of \( \sigma_{xx}(T) \) vs. \( B \) decreases by \( \approx 1.5\% \) as the temperature is raised from 150 mK to 600 mK. This temperature-induced slope change is more clearly shown in Fig. 2 (c) (inset) where we plot the difference between the straight line fits to the Hall resistivity at \( T = 600 \) mK, \( \Delta \rho_{xy}(T) = \rho_{xy}(T) - \rho_{xy}(600mK) \) vs. \( B \) as a function of \( T \). We have confirmed that this slope change is not due to variations in \( n_s \) by tracking the Shubnikov-de Haas (SdH) oscillations as a function of \( T \) – we find that the SdH minima occur at constant \( B \) to within 0.1 % as \( T \) is varied.

FIG. 1: (a-c) Longitudinal conductivity \( \sigma_{xx} \) vs temperature \( T \) from the n-GaAs sample at the indicated carrier densities. The solid lines are fits of Eqn. 1 to the data.
Figure 2 (d-f) shows the extracted Hall slope $d\rho_{xy}(T)/dB$ as a function of $k_B T \tau/\hbar$. Since it is difficult to reliably cool 2D systems to temperatures below 100 mK\cite{19}, we only present experimental data where we have confirmed that the electron temperature matches the lattice temperature using Arrhenius plots of the SdH have confirmed that the electron temperature matches the lattice temperature using Arrhenius plots of the SdH minima.

**FIG. 2:** Left panel (a-c) shows the Hall resistivity $\rho_{xy}$ at the indicated carrier densities (in $\times 10^9$ cm$^{-2}$) for the n-GaAs sample at temperatures ranging from 150 mK to 900 mK. Inset shows the difference between the straight line fits at $T$ and 600 mK, $\Delta \rho_{xy} = \rho_{xy}(T) - \rho_{xy}(600\text{mK})$, the arrow indicates decreasing $T$. Values of the Hall slope are presented in the right panel (d-f) along with the fit. The shaded region indicates the error in the fitting.

Fits of Eqn. 3 to the $d\rho_{xy}(T)/dB$ vs. $k_B T \tau/\hbar$ data are shown as solid lines in Fig. 2(d-f), the shaded region indicates one standard deviation of error for the fit. Before we discuss the values of $F_0^x$ extracted from the n-GaAs data, we will first repeat this analysis to extract interaction corrections for the p-GaAs sample, which also shows metallic behavior at $B=0$. Commencing with obtaining $F_0^x$ from the $\sigma_{xx}$ correction, weak localization effects are not negligible and hence we need to subtract the weak localization correction from the $B=0\ \sigma_{xx}$ data before fitting with Eqn. 3 to extract values for $F_0^x$. The weak localization correction to the conductivity was obtained by fitting the low field magnetoconductivity using the theory of Dmitriev et al.\cite{20} which is valid over a wider range of $B$ than the simpler theory of Hikami et al.\cite{21,22}.

**FIG. 3:** (a) Longitudinal conductivity $\sigma_{xx}$ of the p-GaAs sample after subtracting the weak localization correction $\Delta \sigma_{WL}$ at the indicated carrier densities (in $\times 10^{10}$ cm$^{-2}$). (b) The Hall resistivity $\rho_{xy}$ at $n_s = 4.97 \times 10^{10}$ cm$^{-2}$ for different temperatures from 150 mK to 900 mK, and (c) the corresponding Hall slope along with the fit to Eqn. 3. The shaded region indicates the error in the fitting.

The resulting values of $\sigma_{xx} - \Delta \sigma_{WL}$ for several different carrier densities are presented in Fig. 3(a) along with the fits of Eqn. 3. At each $n_s$, the theory fits the experimental data well. The phonon contribution is again small compared to $\delta \sigma_{xx}(T)$ and fitting with or without the phonon term gives similar values of $F_0^x$ (within 5%), this will be discussed later.

To obtain an independent measurement of $F_0^x$ in the p-GaAs sample, we again study the $T$-dependent corrections to $\rho_{xy}$. Fig. 3(b) presents a typical $\rho_{xy}$ trace at several different temperatures, showing a decrease in the slope of $\rho_{xy}$ as $T$ is increased from 150 mK to 900 mK. Again we have confirmed that changes in the Hall slope
are not due to changes in carrier density. The Hall slope \( d\rho_{xy}(T)/dB \) vs. \( k_B T \tau/\hbar \) is presented in Fig. 3(c) along with a fit of Eqn. which describes the experimental data reasonably well. The fit quality for the p-GaAs data is poorer than that of the n-GaAs and is likely due to the fact that p-GaAs is a more complex experimental system (e.g. \( m^* \) not well known, holes are spin 3/2 particles).

![Graph](image)

**Fig. 4:** Values of the Fermi liquid parameter \( F_0^\sigma \) extracted from \( \sigma_{xx}(T) \) at \( T=0 \) (solid) and \( \rho_{xy}(T) \) (open) as a function of \( n_s \) for the (a) n-GaAs and (b) p-GaAs samples.

Fig. 4 contains the key result of our study. Firstly in Fig. 4(a) we plot the values of \( F_0^\sigma \) for the n-GaAs sample. The error bars correspond to the fit errors discussed earlier (for the \( \sigma_{xx} \) data in Fig. 4(a), these are too small to show). As the carrier density is increased, \( F_0^\sigma \) increases in agreement with both theoretical expectations and previous studies. Most significantly at all carrier densities, the \( F_0^\sigma \) values extracted using the two different methods agree to within 9%. The excellent agreement can only occur if the corrections to \( \sigma_{xx} \) and \( \rho_{xy} \) originate from the same mechanism, thereby supporting the theory of Zala et al. that these corrections both derive from electron-electron screening of scattering processes.

Secondly, we plot the data for \( F_0^\sigma \) extracted from \( \sigma_{xx} \) (solid circles) and \( \rho_{xy} \) (open squares) as a function of \( n_s \) in Fig. 4(b) for the p-GaAs sample. A number of features stand out in this data. For both methods of extracting \( F_0^\sigma \) we see qualitatively similar behavior - in general \( F_0^\sigma \) decreases with decreasing \( n_s \) - to that observed in the n-GaAs data. However, in contrast to the n-GaAs data, there is a marked quantitative discrepancy between the \( F_0^\sigma \) values extracted from the two methods, with the values differing by 30%. This discrepancy suggests that additional corrections may be involved in the p-GaAs data, which is not entirely unexpected. Although the interaction effects are easier to measure due to the significantly larger \( r_s \) in p-GaAs, the holes are spin 3/2 particles and the effective mass is not well known (we have taken it as \( m^* = 0.3m_e \) here), making comparisons between experimental data and the theory of Zala et al. a more complicated prospect. However, despite the quantitative discrepancy, the qualitative trends in the p-GaAs data still support Ref. and suggest that the anomalous \( B=0 \) metallic behavior is due to electron-electron or hole-hole interactions, in agreement with previous studies in p-GaAs, n-Si, p-SiGe, and n-GaAs.

In summary, we present a study of the interaction correction in both 2D GaAs electron and hole systems using the theory of Zala et al. We find that independent measurements of the interaction correction from the \( B=0 \) \( T \)-dependence of \( \sigma_{xx} \) and the low-\( B \) \( \rho_{xy} \) are in excellent agreement for the n-GaAs system, and are quantitatively consistent to within 30%, and in good qualitative agreement in p-GaAs. This supports the theory of Zala et al. in explaining the anomalous \( B=0 \) metallic behavior as due to electron-electron interactions screening the impurity potential.

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