Suppression of weak localization effects in low-density metallic 2D holes

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We have measured the resistivity $R$ in a gated high-mobility GaAs two dimensional hole sample with densities in the range $(7-17) \times 10^9$ cm$^{-2}$ and at hole temperatures down to $5 \times 10^{-5} E_F$. We measure the weak localization corrections to the conductivity $\sigma = R^{-1} e^2/h$ as a function of magnetic field ($\Delta g = 0.019 \pm 0.006$ at $g=1.5$ and $T=9$ mK) and temperature ($\partial \ln g / \partial T < 0.0058$ and 0.0084 at $g=1.56$ and 2.8). These values are less than a few percent of the value $1/\pi$ predicted by standard weak localization theory for a disordered 2D Fermi liquid.

Established theory predicts that all two-dimensional systems of non-interacting fermions in zero magnetic field and with finite disorder become insulating as they approach zero temperature [1-5]. Experiments, on the other hand, have shown a range of 2D carrier densities for which the resistivity $R(T)$ decreases with decreasing temperature $T$ at the lowest temperatures measured [6]. At lower densities $R(T)$ increases with decreasing $T$ and at a particular density $R(T)$ is found to be nearly temperature independent [7]. While the experiments could indicate the existence of a new metallic state at $T=0$ separated from the insulating state by a $T=0$ (quantum) phase transition, the data could also be explained within conventional theory by including the effects of $T$ dependent impurity scattering [8]. Exploring this phenomenon in a high mobility hole doped GaAs sample, we have reached temperatures low enough to show that the temperature dependence of $R(T)$ extends over a wide range of densities. The difficulty of explaining, within a conventional theory, a temperature independent $R(T)$ over a range of densities leaves open the possibility of the new metallic state of matter suggested by the original experiments [6].

The essential idea of weak localization theory is that constructive interference of time reversed paths (coherent backscattering) for current carrying particles moving in the presence of random impurities reinforces the probability amplitude of the particles staying near their initial positions, and thus reduces the conductivity. The set of constructively interfering paths is confined by the rate of loss of phase coherence $\tau_{\phi}^{-1}$ to paths of length $(D \tau_{\phi})^{1/2}$, and is further restricted by the phase accumulated due to the vector potential if a magnetic field is present. For a single band of noninteracting fermions in 2D with a 2-fold spin degeneracy, the predicted change in electrical conductivity $g$ (expressed throughout this paper in units of $e^2/h$), assuming $g \gg 1$, is [9-12],

$$
\Delta g \approx -{(1/\pi)}[\psi(1/2 + \beta/x) - \psi(1/2 + y/x)].
$$

(1)

Here $\psi(z) \approx \ln z - (2z)^{-1} - (12z^2)^{-1}$ is the digamma function; $x = g^2H/H_1$; $H$ is the magnetic field; $H_1 = \hbar c/e$; and $\rho$ is the hole density. The momentum scattering rate is $\tau^{-1} = 4\pi E_F/\rho g$, where $E_F = kT_F$ is the Fermi energy; and the ratio of the coherence loss and momentum scattering rates is $y = \tau/\tau_{\phi}$. The total elastic scattering rate is $\tau_0^{-1}$, with $\beta = (\tau/\tau_0) \approx 1$ for short ranged potential scattering and $\beta > 1$ otherwise.

The largely geometrical effect which is the basis for Eq 1 makes contact with a real physical system when we attempt to insert the temperature dependence of the coherence loss rate, $\tau_{\phi}^{-1}(T)$. If we assume, as is usually done, that $\tau_{\phi}^{-1} \propto T^\beta$, Eq 1 exhibits the well known logarithmic dependence on temperature at low values of the magnetic field, with $\Delta g \approx -(g/\pi)\ln(T)$. In the simplest model, in which electron-electron interactions cause dephasing, $\tau_{\phi} = \tau_{\phi}^ee(T) \equiv h g/\{4\pi^2kT\ln(g/2)\}$, and $y = \pi\ln(g/2)(kT/E_F) \equiv T/T_{\phi}$. For $x \ll 1$ we then have

$$
\Delta g \approx (1/\pi)[\ln(T/T_{\phi}) - \ln(\beta) + f_2(H/H_{\phi}) + \ldots]
$$

(2)

where $H_{\phi} = H_1 g^2 T/T_{\phi}$ and the function $f_2(x) = \ln(x) + \psi(1/2 + 1/x) = x^2/24 + \ldots$. Since $H_{\phi}$ is a function of temperature, the $\ln T$ dependence of $\Delta g$ in Eq 2 ceases for $T < T_{min} = g^2T_{\phi}H/H_1$. At constant $H \ll H_1/g^2$ we may write [12]

$$
\Delta g(T) - \Delta g(T_{\phi}) \approx \frac{1}{\pi}[\psi(1/2 + T/T_{min}) + \ln(g^2H/H_1)]
$$

Perturbation theory shows that the effect of interactions tends to make a 2D system more metallic, but the perturbation expansion is only valid for interaction strengths characterized by $r_s < 1$ [13], where $r_s$ is the Wigner-Seitz radius, the mean spacing between particles in units of the effective Bohr radius. Thus at present there are no clear predictions of what interaction effects there might be in our low density system for which $r_s \approx 15 \times m^*/0.18 \times [10^{10}cm^{-2}/\rho]^{1/2} > 11$, $m^*$ being the hole effective mass.

In this paper we will interpret our measurements as follows: First, the magnetic field dependence of the conductivity allows us to deduce $H_{\phi}$ and hence $\tau_{\phi}$, with the latter being consistent with $\tau_{\phi} = \tau_{\phi}^ee(T)$, as expected in the simple model of electron-electron dephasing. Second, we find that the magnetic field dependent weak localization correction, while definitely present, is suppressed by a factor of $\sim 30$. Third, we find that the weak localization temperature dependence of the conductivity, expected based on the measured value of $\tau_{\phi}$, is suppressed by at least the same amount.

Our measurements were performed on a back-gated hole-doped GaAs sample made from one of the wafers
used in our previous study [14], a (311)A GaAs wafer using AlxGa_{1-x}As barriers (typical x = 0.10) and symmetrically placed Si delta-doping layers above and below a pure GaAs quantum well of width 30 nm. The sample was thinned to \( \approx 150 \mu m \) and prepared in the form of a Hall bar, of approximate dimensions \((2.5 \times 9) \text{ mm}^2\), with diffused In(5%Zn) contacts. The hole-density was varied from \( 3.8 \) to \( 17 \times 10^9 \text{ cm}^{-2} \) by means of a gate at the back of the sample. The zero gate bias density was \( 1.2 \times 10^{10} \text{ cm}^{-2} \) and the density at which we observe the zero magnetic field \((H = 0)\) metal-to-insulator (MI) transition is roughly \( 6 \times 10^9 \text{ cm}^{-2} \). The measurement current \((\sim 100 \text{ pA, } 2 \text{ Hz})\) was applied along the \( [233] \) direction. Independent measurements of the longitudinal resistance per square, \( R_{xx} \), from contacts on both sides of the sample were made simultaneously as the temperature or applied magnetic field was varied. The sample has a low temperature hole mobility for zero gate bias \( \mu = 2 \times 10^5 \text{ cm}^2\text{V}^{-1}\text{s}^{-1} \). The sample was mounted in a top-loading dilution refrigerator.

The most critical part of our experiment is the determination of the temperature \( T_L \) of the 2D holes for a given sample lattice temperature \( T_R \). The refrigerator temperature \( T_R \) was measured by a germanium resistance thermometer calibrated from the 4 mK base temperature to 320 mK by in situ He-3 capacitance thermometry, the primary standard at such temperatures [15]. With commercial electronics, we were unable to obtain measurements on the sample at such temperatures. We used instead, spatially compact, well-shielded low power custom instrumentation. With this instrumentation we observed that at low carrier densities, for which the sample exhibits insulating behavior, the sample resistivity \( R(T) \) keeps increasing as \( T_R \) is decreased to the base temperature [see Fig. 1]. From this we infer that \( T_L = 2 \times 10^{-4} \text{ K} \) is not significantly different from \( T_R \) at sufficiently low measurement power levels. According to the calculation of Chow et al. [16], the power radiated by the 2D hole gas at temperature \( T_H \) and zero lattice temperature is \( P = (T_H/g) \times 6.75 \times 10^{-6} \text{ W cm}^{-2} \text{ K}^{-4} \). From this we would infer that at our base temperature \( T_L = 4 \text{ mK} \), the hole gas temperatures for \( g = 1 \) and \( g = 10 \) are 5.6 and 9.4 mK respectively at our measurement power level of less than \( 5 \times 10^{-15} \text{ W cm}^{-2} \). Our measurements [17] suggest that the Chow et al. estimate is about a factor of two too large for our sample, but that there is an additional cooling rate proportional to \( T^2 \) [16]. This revises the estimated minimum hole temperatures to 5.0 and 7.5 mK at \( g = 1 \) and 10 respectively.

The noise power delivered to the sample due to its being connected to the measuring apparatus is calculated as follows. The Johnson noise power from each of the six measurement leads attached to the sample is \( P_j = 4kT_{\text{lead}} f R_{\text{lead}} / R_{\text{samp}} = [R_{\text{lead}} / R_0] \times 6.4 \times 10^{-14} \text{ W} \), where \( R_{\text{lead}} = 3.2 \Omega \) per lead, \( T_{\text{lead}} \approx 200 \text{K} \), \( f = 8 \text{MHz} \) and where the sample resistance is about twice the sample resistivity \( R_0 \) given in ohms per square. Normaliz-

![FIG. 1. Resistance per square as a function of temperature for 2D hole sample at various gate biases. The temperature is read from the Ge resistance thermometer attached to the refrigerator mixing chamber.](image1)

![FIG. 2. Variation of longitudinal resistance with perpendicular magnetic field for 2D hole sample at various gate biases. The solid grey lines are the fit described in the text. The width of the zero field resistance peak is a measure of the dephasing rate.](image2)
We model the data using the function 

\[ p_{\text{gradual}} = \frac{1}{1 + (t/12)^2} \times 1.1 \times 10^{-15} \text{ W/cm}^2. \]

This is the only significant source of Johnson noise and raises the temperature of the holes in the quantum well of our sample by less than 2 mK for all values of \( R \) encountered in this study.

We determined our carrier density from Shubnikov-de Haas (SdH) magnetoresistance measurements obtained by averaging the longitudinal resistances per square \( R_{xx1} \) and \( R_{xx2} \) obtained from both sides of the sample. We plot the SdH minima vs. gate bias and fit the data using a straight line \( P(V_{\text{gate}}) = p_0 - \alpha V_{\text{gate}} \) and the relation \( P(V_{\text{gate}}) = (2.418 \times 10^{10} \text{ cm}^{-2}) \times H_{\text{res}}(V_{\text{gate}}) \). The measured slope is \( \alpha = (0.420 \pm 0.005) \times 10^9 \text{ cm}^{-2} \text{V}^{-1} \) independent of sample history and the gate capacitance is \( \epsilon C_o = (67.3 \pm 0.7) \text{ pF cm}^{-2} \). The zero gate bias density is \( \rho_0 = (12.0 \pm 0.5) \times 10^9 \text{ cm}^{-2} \), where the variation reflects a gradual increase over the course of six months time.

We exhibit in Fig 2 the low field magnetoresistance of our sample at hole temperatures of \( \sim 9 \text{ mK} \) and for gate biases of 0, +6, +9 and +12V. The data were obtained over 14 sweeps of the magnetic field over the range \( \pm 400 \text{ G} \) and averaged into \( 10 \text{ G} \) bins [18]. At the lowest density \( p = 7 \times 10^9 \text{ cm}^{-2} \) there is a clear peak near zero field. We model the data using the function

\[ R(H) = R_0 - R_c \left[ \frac{(H/H_c)^2}{1 + (H/H_c)^2} \right] + \Delta R f_2(H/H_c) + \eta H \]

shown as the solid grey lines in Fig 2. The second term on the right hand side is a Lorentzian representing the classical magnetoresistance [19]. The third term has the form expected from weak localization according to Eq 2. The last term is included to account for the drift associated with temporal fluctuations of \( R_0 \) [18]. The field \( H \) is measured relative to the residual field \( H_0 \). The data for \( V_{\text{gate}} = +12 \text{V} \) was fitted to obtain the following values of the free parameters: \( R_0 = (17365 \pm 14) \Omega/\square; \)

\[ H_0 = (24.8 \pm 2.9) \text{ G}; \]

\[ R_c = (4995 \pm 1270) \Omega/\square; \]

\[ H_c = (777 \pm 155) \text{ G}; \]

\[ \eta = (0.36 \pm 0.03) \Omega/\square \text{G}^{-1}; \]

\[ H_\varphi = (7.8 \pm 3.2) \text{ G}; \]

\[ \Delta R = (215 \pm 68) \Omega/\square. \]

The data in the remaining panels of Fig 1 were fitted with the thus determined value of \( H_0 = (24.8 \text{ G}) \) and with \( H_\varphi \) scaled from \( H_\varphi = 7.8 \text{ G} \) as \( H_\varphi \propto p/g^2 \). The fitted values of \( \Delta g \) are consistent with a constant \( \Delta g = 0.01 \), much less than the minimum hole temperature is less than 6 mK for the highest resistivity curve. Likewise, the minimum temperature for which we fit the superconducting field of the superconducting solenoid to within the \( \pm 2.5 \text{ G} \) precision of our fitted value of \( H_0 \). The excitation levels were in all cases \( 5 \text{ fW/cm}^2 \) or less, thus ensuring that the exciton temperature is less than 8 mK for the 3 k\text{\Omega} \text{ measurement}. The dashed lines, calculated by simply adding \( (1/\pi) \log(T/20 \text{ mK}) \) to the low temperature conductivity \( g(20 \text{ mK}) \), are clearly at variance with the measurements. Rather, at temperatures well below the characteristic temperature \( 0.2T_F \) associated with the activated resistance bump, the resistance becomes nearly constant. Fitting an expression \( g(T) = e^2/(HR_0) + b\log(T/T_0) \) to

\[ \text{FIG. 3. Temperature dependence of the longitudinal resistance of a 2D hole gas for various gate biases. The dashed lines are approximate weak localization predictions according to Eq 2.} \]

Fig 3 shows a measurement of \( R(T) \) over the range 5 to 100 mK for gate biases of 0, +6, +9, and +12V. The data were obtained with the 25G residual field of the superconducting solenoid cancelled to within the \( \pm 2.5 \text{ G} \) precision of our fitted value of \( H_0 \). The excitation levels were in all cases \( 5 \text{ fW/cm}^2 \) or less, thus ensuring that the exciton temperature is less than 8 mK for the 3 k\text{\Omega} \text{ measurement}. The dashed lines, calculated by simply adding \( (1/\pi) \log(T/20 \text{ mK}) \) to the low temperature conductivity \( g(20 \text{ mK}) \), are clearly at variance with the measurements. Rather, at temperatures well below the characteristic temperature \( 0.2T_F \) associated with the activated resistance bump, the resistance becomes nearly constant. Fitting an expression \( g(T) = e^2/(HR_0) + b\log(T/T_0) \) to
the data for \( T < T_0 = 20 \) mK, we find 99% confidence upper limits of \( b < 0.0058, 0.0084, 0.018, 0.015, \) and 0.033 for densities \( p = 7.0, 8.2, 9.5, 12, \) and \( 14.5 \times 10^9 \) cm\(^{-2}\), and corresponding \( R(T_0) = 16500, 9290, 6000, 3100, \) and 1950 \( \Omega \). These upper limits for \( b \) are one to nearly two orders of magnitude smaller than the \( b = 1/\pi \) expected according to Eq 2.

At this time there is no satisfactory explanation for a suppression of weak localization effects in a 2D electron gas. Weak localization effects in \( R(T) \) of the expected magnitude have been observed in a Si MOSFET sample at electron densities of order 3 \( \times 10^{12} \) cm\(^{-2}\) by Pudalov et al. \[20\], and in a GaAs sample at hole densities of order 10\(^{11} \) cm\(^{-2}\) by Hamilton et al. \[21\]. This suggests that interaction effects associated with the large value of \( r_s \) in our experiment may be playing an important role \[13\].

The first author is grateful to C. M. Varma for encouraging him to pursue these experiments and for useful conversations. The authors benefited greatly from the assistance of D. S. Greywall in calibrating the Ge resistance temperature scale using He-3 melting curve thermometry.

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