Dephasing Time in a Two-Dimensional Electron Fermi Liquid

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The observation of coherent quantum transport phenomena in metals and semiconductors is limited by the eventual loss of phase coherence of the conducting electrons on the time scale \(\tau_\varphi\). We use the weak localization effect to measure the low-temperature dephasing time in a two-dimensional electron Fermi liquid in GaAs/AlGaAs heterostructures. We use a novel temperature calibration method based on the integer quantum Hall effect in order to directly measure the electrons’ temperature. The data are in excellent agreement with recent theoretical results, including contributions from the triplet channel, for a broad temperature range. We see no evidence for saturation of the dephasing time down to \(\sim 100mK\). Moreover, the zero-temperature dephasing time is extrapolated to be higher than 4ns.

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The electron dephasing time, \(\tau_\varphi\), is a quantity of great importance for the analysis of transport in semiconductor and metal mesoscopic samples. Essentially, \(\tau_\varphi\) sets the scale at which the quantum-mechanical properties of the microscopic system crossover to the familiar classical behavior seen in macroscopic objects. The study of quantum coherence has attracted much attention, motivated both by questions of fundamental scientific interest concerning sources of decoherence in materials, and by the possibility of using solid-state electronic devices to store quantum information. The investigation of electron dephasing has advanced significantly thanks to the observation of a variety of prominent quantum interference phenomena. Weak localization [1, 2], universal conductance fluctuations [3, 4], the Aharonov-Bohm effect [5], and persistent currents [6] exhibited in mesoscopic electronic systems make these systems suitable for studying decoherence. The most prominent interference effect is weak-localization, the quantum-mechanical enhancement of coherent backscattering. This coherent interference is destroyed by the break of time-reversal symmetry, resulting in a noticeable “anomalous” magnetoresistance of disordered conductors at low temperatures and low magnetic fields. Analysis of the magnetoresistance curves may provide quantitative information on the various electron dephasing mechanisms.

A number of basic microscopic dephasing processes may coexist in real systems at low temperatures, with one or two mechanisms typically dominating, depending on system dimensionality, level of disorder and temperature. For two-dimensional semiconducting samples at low temperatures, the dominating dephasing process is quasi-elastic e-e interactions. These give rise to \(1/\tau_\varphi \sim T^2 \ln(T)\) at relatively high temperatures, due to large energy transfer processes (or, using the terminology of Ref. [6], the ballistic term) and \(1/\tau_\varphi \sim T\) at lower temperatures, where small energy transfer processes dominate the dephasing (diffusive term in [2]). Accordingly, the zero temperature dephasing time, \(\tau_\varphi^0 \equiv \tau_\varphi(T \to 0)\), is expected to diverge. Contrary to this prediction, a number of experimental groups have shown indications for a finite saturated dephasing time at low temperatures [8]. Recently, this contradiction has been the focus of considerable attention. Among the current opinions on the matter, it has been suggested that the saturated value should depend on the specific sample geometry [9], the level of disorder in the sample [10], the microscopic qualities of the defects [11, 12], or e-e scattering mediated by the magnetic exchange interaction [13]. Others argue that the saturation is caused by extrinsic mechanisms, such as magnetic spin-spin scattering [14], hot electron effects [15], electromagnetic noise sources [16] or non-equilibrium effects [17]. The possible extrinsic mechanisms urge caution when determining the actual temperature of the two-dimensional electron system and ensuring outside radiation is small.

Most of the above-mentioned experiments were compared with theoretical results for the two-dimensional electron gas, focusing on the universal contribution of the singlet channel interaction, both in the energetically diffusive [17] and ballistic regimes [18]. Recently, the effect of Fermi liquid renormalization of the triplet channel of the Coulomb interaction on the dephasing time has been studied theoretically for arbitrary relation between inverse temperature and elastic mean free time [7]. The prefactors of these dependencies are not universal, but are determined by the Fermi liquid constant characterizing the spin-exchange interaction. It is expected that taking into account the Fermi liquid normalization would facilitate better quantitative understanding of the experimental data.

In this work, weak-localization magnetoresistance measurements were performed in two-dimensional Fermi liquid fabricated in GaAs/Al0.3Ga0.7As heterostructures with high conductance, in order to extract the dephasing time at various temperatures down to \(\sim 100mK\). We com-
pare our results to the theoretical prediction that includes contributions from both the singlet and triplet channels. Our measurements are in the intermediate temperature range, where both small and large energy transfer scattering contribute to phase braking. The measurements were accompanied by integer quantum Hall measurements showing variable-range-hopping behavior in the diagonal resistivity minima at very low temperatures. This predicted, exponential behavior was used to calibrate the electrons’ temperature as a means to quantify hot electrons effects. We observe good quantitative agreement with theory over all the temperature range, in both energetically ballistic and diffusive regimes. No indications for saturation of the dephasing time are detected down to the lowest temperature measured.

It has been shown in [7] that at low temperatures, where small energy transfer scattering processes dominate \((k_B T \tau / h \ll 1)\), the temperature dependence of the dephasing time is:

\[
1/\tau_\varphi = \left\{ 1 + \frac{3\left(F_0^s\right)^2}{\left(1 + F_0^s\right)^2(2 + F_0^s)} \right\} \frac{k_B T}{g^2} \ln\left[g^2(1 + F_0^s)\right] + \frac{\pi}{4} \left\{ 1 + \frac{3\left(F_0^s\right)^2}{\left(1 + F_0^s\right)^2} \right\} \frac{(k_B T)^2}{E_F} \ln\left(E_F^2 \tau / h\right),
\]

where \(F_0^s\) is the interaction constant in the triplet channel which depends on interaction strength \([20, 21]\), \(g \equiv 2\pi\hbar/e^2R_\Box\) and \(E_F\) is the Fermi energy. At higher temperatures where large energy transfer scattering processes contribute \((k_B T \tau / h \gg 1)\),

\[
1/\tau_\varphi = \frac{\pi}{4} \left( \frac{k_B T}{B E_F} \right) \left\{ \ln \left[ \frac{2E_F}{k_B T} \right] \right\} + \frac{3\left(F_0^s\right)^2}{\left(1 + F_0^s\right)^2} \ln \left( \frac{E_F}{k_B T \sqrt{b(F_0^s)}} \right),
\]

where \(b(x) \approx (1 + x^2)/(1 + x)^2\), and \(B\) is a numerical factor that varies between 0.84 for weak magnetic fields \((\Omega_H \tau_\varphi \gg 1)\) where \(\Omega_H = 4DE^2H/hc\) and 0.79 in the opposite limit \([7]\). These results were recently compared by Minkov et al. [22] to measurements of magnetoresistance and dephasing times for samples of intermediate conductances, where higher orders in \(1/g\) contribute. Taking into account high orders corrections, good agreement between theory and experiment has been observed.

The samples are fabricated from single-well AlGaAs/GaAs heterostructures in order to avoid complications from inter-valley scattering magnetic impurities, and due to the negligible spin-orbit coupling in these heterostructures. The samples are mesa-etched into standard Hall-bar configuration using standard lithography. The sample dimensions are 200\(\mu\)m long and 10\(\mu\)m wide. The electron density was \(2.8 \times 10^{11}\)\(cm^{-2}\) with a mobility of \(87000cm^2/Vsec\). The corresponding electron diffusion constant(D) and mean free time (\(\tau\)) are \(D = 0.085nm^2/sec\) and \(\tau = 3.3 \times 10^{-12}sec\). The magnetoresistance measurements are carried out using a four-probe configuration, using a lock-in amplifier by applying a magnetic field perpendicularly to the sample. \(V_L\), the applied bias on the whole sample of length \(L\), is kept below the temperature \([10]\), \(eV_L/k_B < T\), rather than the conventional \(eV_\phi/k_B < T\) criterion, where \(V_\phi\) is the bias applied to the phase-coherent length, \(L_\phi\), in order to prevent any non-equilibrium effects from causing dephasing. In addition, we explicitly verified that the magnetoresistance
curve was insensitive to further reduction in the voltage bias.

At very low temperatures, lack of good thermal contact between the lattice and the electrons might occur. This might lead to a difference between the actual electron temperature and that measured by the thermometer. This hot electrons effect, requires careful temperature measurement. We employ longitudinal resistance measurements in the integer quantum Hall effect regime in order to directly measure the temperature of the electron gas using an effect independent of the weak localization phenomenon. It is well established \cite{29} that the longitudinal conductance in the plateau area in the quantum Hall regime is due to thermal activation over the mobility edge at relatively high temperatures, and to variable-range-hopping at lower temperatures. These effects predict exponentially strong temperature dependence of the conductivity/resistivity, \( \rho_{xx} \propto 1/T \exp(-(T/T_0)^{1/2}) \). This dependence was measured and shown in AlGaAs/GaAs heterostructures very similar to ours in Ebert et al. \cite{22}, at least down to 30mK. We use these theory and experimental findings to calibrate our temperature by comparing our data (Fig. 1(a)) with the theoretical prediction they established. By taking the minima resistivity measured by us and comparing it to a value from the equation given in Ebert et al., we measure the electrons’ temperature and indeed find that it is higher than the thermometer temperature, indicating hot electron effects. In order to minimize small lock-in amplifier deviations, we calibrated it by setting the resistivity values at the minima corresponding to plateau \( i=4 \) to zero, where the value is already at the saturated value for the entire temperature range. In addition, we normalized the measured and calculated resistivity values at the high temperatures where we expect the temperature deviation between the gas and thermometer to be absent in order to fix the prefactors. The difference between the measured and calculated values is shown in Fig. 1(b). By comparing the measured data with the theoretical predictions, we can measure the actual electron gas temperature (Fig 1(c)).

According to theory of weak localization, the magnetoconductance in the 2D limit is given by the following combination of digamma functions \cite{23}:

\[
\Delta \sigma = \frac{\epsilon^2}{2\pi^2h} \left\{ \frac{3}{2} \Psi \left[ \frac{1}{2} + \frac{B_2}{B} \right] - \Psi \left[ \frac{1}{2} + \frac{B_1}{B} \right] \right\} \\
- \frac{1}{2} \Psi \left[ \frac{1}{2} + \frac{B_3}{B} \right] - \ln \left[ \frac{B_2^{3/2}}{B_1 B_3^{1/2}} \right] \right\}, \tag{3}
\]

where \( \Psi \) is the digamma function and

\[
B_1 = B_0 + B_{so} + B_s \\
B_2 = B_\phi + 4/3B_{so} + 2/3B_s \\
B_3 = B_\phi + 2B_s. \tag{4}
\]

In Eq. 4, \( B_s \equiv \hbar/4eD\tau_s \) are the characteristic fields of elastic scattering \( (B_0) \), spin-orbit \( (B_{so}) \), phase loss \( (B_\phi) \) and magnetic impurities \( (B_s) \) related to the corresponding times \( \tau, \tau_{so}, \tau_\phi \) and \( \tau_s \). B is the applied perpendicular field. The Magnetoresistance data are shown in Fig. 2, for temperatures between 4.2K and ~130mK. The solid lines are best fits using Eq. 3. In our MBE grown samples there are no magnetic impurities and \( B_{so} \ll B_\phi \), making \( \tau_\phi \) the only fitting parameter. The values of the extracted dephasing time from Eq. 3 are plotted in Fig. 3 as a function of temperature. The green solid line is the theoretical value from Eq. 1, applicable where the small-energy transfer term dominates, and the blue dashed line is the theoretical value from Eq. 2, applicable where the
large-energy transfer term dominates. The red dotted line is the combination of the theoretical value from Eq. 2 and the linear term from Eq. 1, which represents the ballistic limit with some contribution from the small-energy transfer linear term. These curves are plotted with no fitting parameter. The value used for the Fermi-liquid constant is $F_0 = -0.4$, consistent with the known value for GaAs for our electron concentration. This value was used for all theoretical values described in Fig. 3.

The measured dephasing times agree well with Eq. 1, up to $T \sim 1K$. This is in agreement with the estimated transition temperature $T = \hbar/k_B \tau \approx 1.4K$ describing the transition to the ballistic limit where large energy transfer processes dominate. At higher temperatures, comparison to the ballistic term (Eq. 2) shows agreement at least asymptotically. Combining the high energy transfer term from the high temperature limit together with the linear term from Eq. 1, we can observe even better agreement, albeit with a small deviation at the highest temperatures which might be the result of the proximity to the limit where $L_0 \approx l$, making the application of Eqs. 1,2 somewhat problematic.

The excellent agreement at the low temperature range allows us to use this equation to extrapolate the dephasing times to lower temperatures. We estimate our experimental error to be no more than 10 percent. Using this estimate and attributing the deviations at the lowest temperature achieved to a constant value, we can calculate the minimum saturated dephasing time value and estimate the saturation temperature. The dephasing rate we measure at the lowest temperature is $1.54 \text{ns}^{-1}$, while the theoretical prediction from Eq. 1 is $1.46 \text{ns}^{-1}$. Taking into account a possible measurement error of 10%, and attributing all the deviation from the predicted theoretical value to an unknown temperature-independent dephasing mechanism yields a rate of $0.23 \text{ns}^{-1}$ for this zero-temperature dephasing mechanism. The minimal saturated dephasing time is thus estimated to be $\tau_{\varphi \text{sat}} > 4 \text{ns}$ and the maximal corresponding saturation temperature is $\sim 25mK$. To the best of our knowledge, this saturated dephasing time value is higher than the saturation dephasing times reported in previous experiments.

To conclude, we have measured the dephasing time using weak localization magnetoresistance measurement, demonstrating very good quantitative agreement with recent theoretical results for a Fermi liquid (given in Eqs. 1 and 2), with no fitting parameters. Our data are at a range where both large and small energy transfer scattering contribute to dephasing. We demonstrate the agreement on a relatively broad temperature scale. We see no evidence for saturation down to the lowest temperature measured. Comparing our data to the theoretical results, we limit the possible temperature independent dephasing rate to $0.23 \text{ns}^{-1}$ at most, resulting in zero-temperature dephasing time of at least 4ns, which cannot be observed in our samples at electron temperatures above 25mK.

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