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 τ_φ. 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 temperature calibration method based on the integer quantum Hall effect in order to directly measure the electrons' temperature. The data are in good 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 ~100 mK.

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I. INTRODUCTION

The electron dephasing time, τ_φ, is a quantity of great importance for the analysis of transport in semiconductor and metal mesoscopic samples. Essentially, τ_φ 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 considerable 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 breakup 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 (2D) semiconducting samples at low temperatures, the dominating dephasing process is quasielastic *e-e* interactions. These give rise to $1/\tau_\varphi \simeq T^2 \ln(T)$ at relatively high temperatures, due to large energy transfer processes (or, using the terminology of Ref. 7, the ballistic term) and $1/\tau_\varphi \simeq T$ at lower temperatures, where small energy transfer processes dominate the dephasing (diffusive term in Ref. 7). Accordingly, the zero temperature dephasing time, $\tau_\varphi^0 \equiv \tau_\varphi(T \to 0)$, is expected to diverge. Contrary to this prediction, however, a number of experimental groups have shown indications of 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 impurities[14] and magnetic spin-spin scattering,[15] hot electron effects,[16] electromagnetic noise sources,[3] or non-equilibrium effects.[17] The possible extrinsic mechanisms urge caution when determining the actual temperature of the two-dimensional electron system and ensuring low external 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[18,19] and in the ballistic regimes.[19,20] 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 a two-dimensional Fermi liquid fabricated in $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructures with high conductance, in order to extract the dephasing time at various temperatures down to ~100 mK. We compare 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 scatterings contribute to phase breaking. 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 in order to quantify hot electrons effects. We observe good quantitative agreement with theory over the whole 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 Ref. 7, that at low temperatures, where small-energy transfer scattering processes dominate ($k_BT\tau/\hbar \ll 1$), the temperature dependence of the dephasing time is

$$1/\tau_\varphi = \left\{1 + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)(2+F_0^\sigma)}\right\}\frac{k_BT}{g\hbar}\ln[g(1+F_0^\sigma)] + \frac{\pi}{4}\left\{1 + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)^2}\right\}\frac{(k_BT)^2}{\hbar E_F}\ln(E_F\tau/\hbar), \quad (1)$$

where F_0^σ is the interaction constant in the triplet channel which depends on interaction strength,[21,22] $g \equiv 2\pi\hbar/e^2R_\square$ and E_F is the Fermi energy. At higher temperatures where large energy transfer scattering processes contribute to the dephasing ($k_BT\tau/\hbar \gg 1$)

$$1/\tau_\varphi = \frac{\pi}{4}\frac{(k_BT)^2}{BE_F}\left\{\ln\left(\frac{2E_F}{k_BT}\right) + \frac{3(F_0^\sigma)^2}{(1+F_0^\sigma)^2}\ln\left(\frac{E_F}{k_BT\sqrt{b(F_0^\sigma)}}\right)\right\}, \quad (2)$$

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 $\Omega_H = 4DeH/\hbar c$) and 0.79 in the opposite limit.[7] These results were recently compared by Minkov *et al.*[23] to measurements of magnetoresistance and dephasing times for samples of intermediate conductances, where higher orders in $1/g$ contribute. Taking into account high order corrections, good agreement between theory and experiment has been observed. Recent measurements done on one dimensional samples also show no sign of saturation.[24]

II. EXPERIMENT

The samples are fabricated from single-well AlGaAs/GaAs heterostructures in order to avoid complications from intervalley scattering magnetic impurities, and due to the negligible spin-orbit coupling in these heterostructures. The samples are mesa etched into a standard Hall-bar configuration using standard lithography. The samples dimensions are 200 μm long and 10 μm wide. The electron density is 2.8×10^{15} m^{-2}, with a mobility of 8.7 m^2/V sec (determined by Hall and resistivity measurements). The corresponding electron diffusion constant (D) and mean free time (τ) are $D=0.085$ m^2/sec and $\tau=3.3\times10^{-12}$ sec, respectively. The Fermi energy is $E_F=9.9$ meV (calculated from the electron density). The magnetoresistance measurements are carried out employing a four-probe configuration, using a lock-in amplifier by applying a magnetic field perpendicularly to the sample. The applied bias $V_L=5$ μV, corresponding to $eV_L/k_B \sim 58$ mK on the whole sample of length L, is kept below the bath temperature at the low temperature range.[17] The criterion $eV_L/k_BT<1$ is more stringent than the conventional $eV_\varphi/k_B<T$ criterion, where V_φ is the bias applied to the phase-coherent length, L_φ, in order to prevent any nonequilibrium effects from causing dephasing. In addition, we explicitly verify that the magnetoresistance curve is 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 electron gas temperature using an effect independent of the weak localization phenomenon. It is well established[25] 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, $\rho_{xx} \propto 1/T\exp[-(T_0/T)^{1/2}]$. This dependence was measured and shown in AlGaAs/GaAs heterostructures very similar to ours in Ebert *et al.*,[26] at least down to 30 mK. We use these theory and experimental findings to calibrate our temperature by comparing our data [Fig. 1(a)] to the theoretical prediction they verified experimentally. We used $T_0=38$ K, which is different from the value ($T_0=41$ K) used in Ref. 24 for the same Landau level only due to renormaliztion factor 1.08 arising from the different magnetic fields at the which the data were taken in both experiments. 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 calibrate 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 normalize 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)]. Our calibration procedure is valid as long as the electronic temperature is not altered by the application of a high magnetic field, which is a reasonable assumption.

III. RESULTS AND DISCUSSION

According to the theory of weak localization, the magnetoconductance in the 2D limit is given by the following combination of digamma functions:[27]

$$\Delta\sigma = \frac{e^2}{2\pi^2\hbar}\left\{\frac{3}{2}\Psi\left[\frac{1}{2}+\frac{B_2}{B}\right] - \Psi\left[\frac{1}{2}+\frac{B_1}{B}\right] - \frac{1}{2}\Psi\left[\frac{1}{2}+\frac{B_3}{B}\right] - \ln\left[\frac{B_2^{3/2}}{B_1B_3^{1/2}}\right]\right\}, \quad (3)$$

where Ψ is the digamma function and

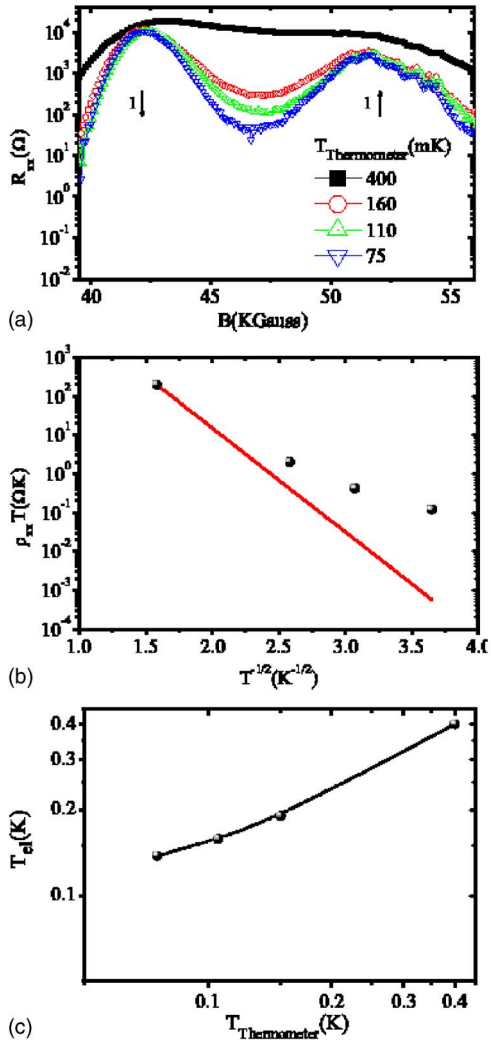

FIG. 1. (Color online) The temperature calibration process: (a) Magnetoresitance measurements. The longitudinal resistance is presented as a function of the magnetic field for several different temperatures. The magnetic field is in the range 3.9–5 T ($1\downarrow -1\uparrow$). The temperature ranges from 400 mK (top) to around 75 mK (bottom), as measured by the thermometer. (b) The measured resistance minima multiplied by temperature (in logarithmic scale) as function of $T^{-1/2}$ (black circles), compared to the variable-range-hopping result $\varrho_{xx} \propto 1/T \exp -(T_0/T)^{1/2}$ (red solid line). Clearly, the measured resistance surpasses the variable-range-hopping results, reflecting the hot electrons effect. (c) The actual electron temperature as a function of thermometer temperature.

$$B_1 = B_0 + B_{so} + B_s,$$

$$B_2 = B_\varphi + 4/3B_{so} + 2/3B_s,$$

$$B_3 = B_\varphi + 2B_s. \tag{4}$$

In Eq. (4), $B_x \equiv \hbar/4eD\tau_x$ are the characteristic fields of elastic scattering (B_0), spin orbit (B_{so}), dephasing (B_φ), and magnetic impurities (B_s) related to the respective times τ, τ_{so}, τ_φ, and τ_s. B is the applied perpendicular field. The magnetoresistance data are shown in Fig. 2, for temperatures between

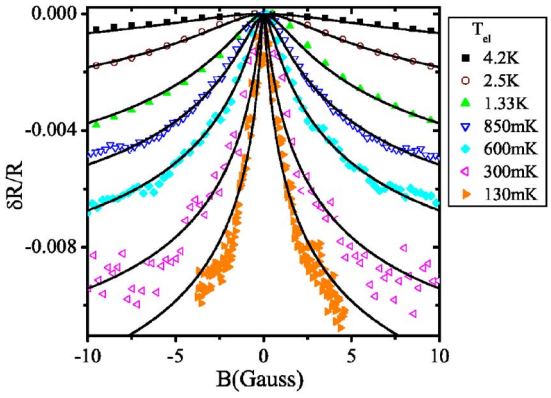

FIG. 2. (Color online) Weak localization magnetoresistance measurements at different temperatures. The temperature range is from 4.2 K (top) down to 130 mK (bottom). The black solid lines are the best fits to Eq. (3).

4.2 K and ~130 mK. The solid lines are best fits using Eq. (3). In our samples there are no magnetic impurities and the well is symmetric B_{so}, $B_s \ll B_\varphi$, making τ_φ the only fitting parameter. The values of the extracted dephasing time from Eq. (3) are plotted in Fig. 3 as a function of temperature, and compared with the theoretical predictions given by Eqs. (1) and (2). F_0^σ is used as a restricted fitting parameter, and we use the value $F_0^\sigma = -0.4$ throughout the calculations. This value is comparable with the estimate given in Ref. 20, of $F_0^\sigma = -0.28$ for GaAs samples at our electron concentration $r_s \approx 1.05$. 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. The cyan dashed-dotted line presents the prediction for a[28] 2DEG ig-

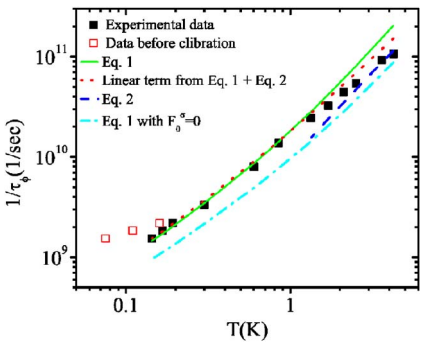

FIG. 3. (Color online) The temperature dependence of the dephasing rate τ_φ^{-1} extracted from the weak-localization measurements (black squares). The green solid line is the theoretical value from Eq. (1). The blue dashed line is the theoretical value from Eq. (2). The red dotted line is the theoretical value from the combination of the linear term in Eq. (1) and Eq. (2). The cyan dashed-dotted line represents the data for $F_0^\sigma = 0$. The red empty squares represent the data for low temperatures without temperature calibration.

noring the Fermi liquid renormalization, i.e., setting $F_0^\sigma=0$. The measured dephasing times agree well with Eq. (1), up to $T\sim 1$ K. This is in agreement with the estimated transition temperature $T=(1+F_0^\sigma)\hbar/k_B\tau\approx 1.4$ K, describing the transition to the ballistic limit where large energy transfer processes dominate. Above this transition temperature, the deviations from the ballistic term [Eq. (2)] decrease with temperature. Combining the high-energy transfer term from the high temperature limit with the linear term from Eq. (1), one observes even better agreement, albeit with a small deviation at the highest temperatures which might result from the proximity to the limit where $L_\varphi\approx l$, making the application of Eqs. (1) and (2) somewhat problematic.

It should be noted that there could be higher-order corrections to the prefactor of the linear term in Eq. (1).[29] However, the temperature dependence of these is still linear. Had we taken them into account, we would have gotten a lower value of F_0^σ, maybe closer to the analytical estimate[21] (which, by itself, is subject to higher order corrections), but the main observation—a linear temperature dependence at low temperature—would have remained intact.

IV. SUMMARY

To conclude, we have measured the dephasing time using weak localization magnetoresistance measurement, demonstrating good quantitative agreement with recent theoretical results for a Fermi liquid [given in Eqs. (1) and (2)]. Our data is at a range where both large and small energy transfer scatterings 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.

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