Interference and Dephasing by Electron-Electron Interaction on Length Scales Shorter than the Elastic Mean Free Path

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A modified Young's double-slit experiment is realized for electrons in a high-mobility two-dimensional electron gas (2DEG). The observed quantum interference is employed to study dephasing by electron-electron interaction on length scales shorter than the elastic mean free path. It is found that the measured phase-breaking length agrees very well with theoretical calculations of the e-e mean free path in an ideal 2DEG. In contrast to the diffusive regime, dephasing occurs via e-e scattering events with an energy exchange on the order of the carrier excess energy.

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Electronic interference phenomena in solid-state systems and their destruction by electron-electron interaction have been extensively studied both theoretically and experimentally in recent years. Examples include weak localization, Aharonov-Bohm oscillations in small rings, universal conductance fluctuations in mesoscopic conductors, and the magnetoresistance of narrow wires. All these studies, however, were concerned with diffusive electronic motion where the elastic mean free path l_e was the shortest relevant length in the system. In particular, in all of these experiments and corresponding theories, the e-e mean free path $l_{e\text{-}e}$, as well as the phase-breaking length l_ϕ, has been much longer than l_e. Here we are concerned with the opposite limit, the ballistic one (as far as phase breaking is concerned), where $l_e \gtrsim l_\phi$. Macroscopic transport in this case is expected to be purely classical and the experiment presented below was therefore carried out on length scales smaller than or comparable to both l_e and l_ϕ.

In Fermi-liquid theory, the dephasing time is a key parameter that determines the quasiparticle lifetime. An experimental determination of this quantity, and its dependence on different parameters in the various regimes, is therefore of great importance in testing our theoretical understanding of an interacting two-dimensional electron gas (2DEG). A more practical motivation originates from the need to predict the constraints on operation of electronic devices based on quantum interference phenomena. For the diffusive case, $l_\phi \gg l_e$, it was shown by Altshuler, Aronov, and Khmelnitzkii[1] that for dimensionality equal to or lower than 2, and low enough temperatures, phase is lost due to e-e scattering events characterized self-consistently by an energy exchange on the order of $\hbar/\tau_\phi$ (τ_ϕ is the phase-breaking time). For 2D conductors, this energy is smaller than the temperature k_BT by a factor $k_Fl_e/\ln(k_Fl_e) \gg 1$ (k_F is the Fermi wave vector). The quasiparticle energy is therefore a well-defined quantity as required for a quasiparticle description of a Fermi liquid. The resulting phase-breaking time is considerably shorter than the energy relaxation time, which is governed by scattering events with an energy exchange on the order of k_BT. The importance of small-energy scattering events for dephasing in 1D wires was confirmed experimentally by Wind *et al.*[2]

For the ballistic case, we are not aware of any detailed discussion of phase-breaking processes. The e-e scattering time due to electron-hole pair excitation was, however, calculated for an ideal 2DEG by Chaplik[3] and by Giuliani and Quinn[4] and was found to be given for $k_BT = 0$ and $\Delta \ll \hbar^2 k_F Q_{\mathrm{TF}}/m$ by

$$\frac{1}{\tau_{e\text{-}e}} = \frac{E_F}{4\pi\hbar}\left(\frac{\Delta}{E_F}\right)^2\left[\ln\left(\frac{E_F}{\Delta}\right)+\ln\left(\frac{2Q_{\mathrm{TF}}}{k_F}\right)+\frac{1}{2}\right]. \quad (1)$$

Here, $Q_{\mathrm{TF}} = 2me^2/\epsilon\hbar^2$ is the 2D Thomas-Fermi screening wave vector, Δ is the quasiparticle energy relative to E_F, m is the effective electronic mass, and ϵ is the dielectric constant (12.7 for GaAs). The calculated e-e scattering rate is dominated by processes with momentum exchange much smaller than k_F and an energy exchange on the order of the excess energy Δ.

In the present Letter we report on a realization of an interference experiment in a high-mobility 2DEG, analogous to Young's double-slit experiment in optics. The observed quantum interference is then employed to directly probe dephasing of the injected carriers by interaction with electrons in the Fermi sea. The measured phase-breaking length agrees very well with the e-e mean free path for electron-hole excitation in an ideal 2DEG calculated using Eq. (1). It then follows, in contrast with the case of diffusive motion, that dephasing in the ballistic regime occurs via single e-e scattering event with an energy transfer on the order of the carrier excess energy. The phase-breaking length, measured here for the first time on length scales shorter than l_e, differs from the corresponding quantity in the diffusive regime in both magnitude and its dependence on excess energy.

The experiment was carried out employing a modulation-doped 2DEG formed in the interface between GaAs and AlGaAs. The carrier concentration and mobility, measured at 1.4 K by a standard van der Pauw procedure, were found to be $n = 3.85\times10^{11}$ cm^{-2} and $\mu = 1.4\times10^{6}$ cm^{2}V^{-1}sec^{-1}, respectively, leading to $E_F = 13.7$ meV and $l_e = 14$ μm. A top-view micrograph of one of the devices is presented in Fig. 1. Two pairs of metallic gates were deposited on top of the heterostructure and were biased negatively with respect to the 2DEG to define an emitter and a voltage probe (E and P in Fig. 1). The remaining pair of gates, G_1 and G_2, were used to modulate the wavelength, and hence the accumulated phase, of electrons passing underneath them. A similar idea was previously employed to fabricate an electrostatic electron lens.[5,6] Electrons and holes (in the conduction band) were injected by applying a dc bias V_E to the emitter relative to the base (B in Fig. 1) with a small ac modulation voltage v_{ac} superimposed on it for phase-locked-detection purposes. The probe voltage was measured in a four-terminal configuration relative to one of the base contacts (Fig. 1) using standard lock-in technique. The various regions, namely, E, P, and several base terminals, were contacted, 50 μm away, using NiGeAu-alloyed Ohmic contacts. All measurements were done at 1.4 K.

Using the Büttiker-Landauer multiprobe formula,[7] it can be shown that the measured voltage is given by $v_P = v_{ac}T_{PE}/T_P$, with T_{PE} and T_P being the transmission coefficient from the emitter to the voltage probe and the total transmission of the voltage probe, respectively. The total probe transmission is simply related to its conductance g_P via the Landauer formula $T_P = (h/2e^2)g_P$. For constant emitter voltage and voltage-probe conductance, measurement of v_P amounts, therefore, to a direct probing of T_{PE}. The transmission probability T_{PE} can be expressed as a coherent sum over all paths i leading from E to P with corresponding amplitudes a_i. In the case discussed here, where the separation L between E and P is smaller than l_e, those paths are approximately directed along the line connecting E and P and can hence be divided into two groups. Group A consists of all paths passing underneath, say, G_1 and a second group B contains all other paths. An application of a small, negative gate voltage V_G to G_1 results in a partial depletion of the 2DEG underneath the gate and, hence, in a phase change ϕ in all paths pertaining to A. The transmission coefficient $T_{PE} = |\sum_{i\in A} a_i \exp(i\phi) + \sum_{i\in B} a_i|^2$ is then expected to oscillate as a function of V_G with a period corresponding to the optical path of group A by one wavelength. Assuming a constant capacitance between the gate and the 2DEG, it can be shown that the oscillation should be periodic in $(1 - V_G/V_d)^{1/2}$ with a period given by $2\pi/k_F W$. Here, W is the electrical gate width and V_d is the gate voltage needed to exactly deplete the 2DEG underneath the gate. For our structure, $V_d = 0.29$ V was measured by monitoring the emitter resistance as a function of the voltage applied to the gates defining it. The depletion voltage agrees well with the capacitance expected from the separation between the gates and the 2DEG.

The measured probe voltage as a function of $(1 - V_G/0.29)^{1/2}$ for $V_E = 0$ is depicted in Fig. 2 for two gate widths. For clarity, the upper curve is offset up by one division. The oscillation resulting from the interference between paths pertaining to groups A and B is pronounced. Its magnitude relative to the background varied in different devices between 20% and 50%. The periodicity is evident both from the main figure and from its inset, where $(1 - V_G/0.29)^{1/2}$ is plotted versus peak number. The slopes of the resulting straight lines can be used to determine the electrical widths of the two gates.

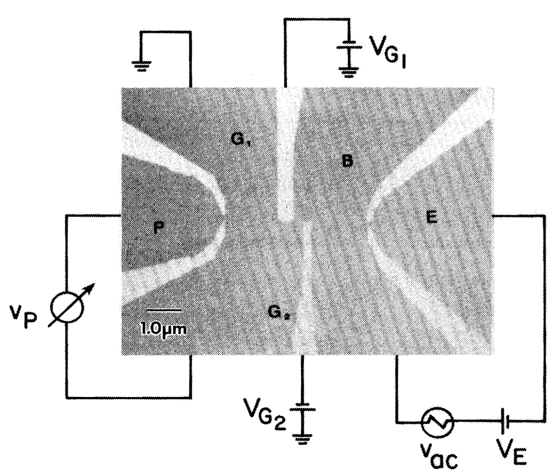

FIG. 1. A top view of one of the devices used in the experiment ($L = 4.30$ μm). The light areas are the metallic gates deposited on top of the the GaAs/AlGaAs heterostructure.

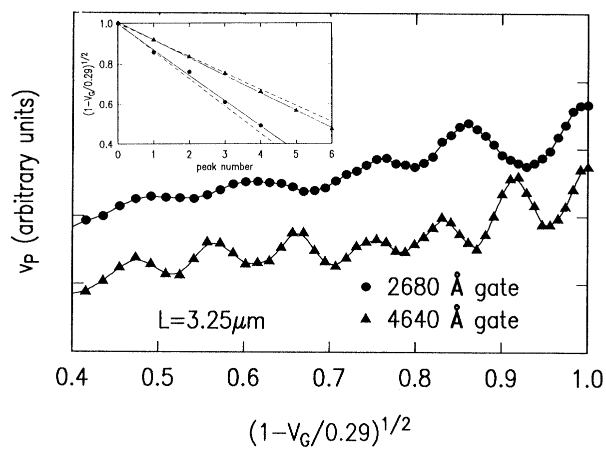

FIG. 2. The measured probe voltage v_P vs $(1 - V_G/0.29)^{1/2}$ for two different gate widths. $T = 1.4$ K and $V_E = 0$. The upper curve is offset by one division. Inset: $(1 - V_G/0.29)^{1/2}$ vs peak number. The dashed lines correspond to the theoretically expected slopes.

For the wider gate we find $W = 4640$ Å, while for the narrower one $W = 3170$ Å. The measured widths should be compared with the capacitive ones including fringing fields. Numerical solutions[8] of the corresponding 2D Poisson equation yield 4930 and 2940 Å for the wider and narrower gates, respectively. The theoretically calculated slopes are depicted in the inset of Fig. 2 by dashed lines. An application of a small, constant bias to the other gate results in a phase shift in the oscillations presented in Fig. 2. A similar phase shift is also produced by a very weak magnetic field applied perpendicularly to the 2DEG. These two effects result from the relative phase change between paths pertaining to the two groups, A and B, when either a gate voltage or magnetic field is applied. Further verification of our interpretation of the observed oscillation was obtained using a device with two identical gates. While a scan of each gate bias separately yielded the expected oscillation, a simultaneous scan of both gate voltages resulted in a similar phase change for all paths and hence produced no oscillation.

The observed quantum interference can be employed to directly probe the dependence of l_ϕ upon carrier excess energy relative to E_F. One possibility is to monitor the oscillation amplitude as a function of temperature. However, in the ballistic regime, a more detailed measurement can be carried out by applying a dc bias V_E to the emitter with a small ac voltage v_{ac} superimposed on it. A simple analysis shows that such an experiment is equivalent to injecting an energetically narrow electron beam with an energy width determined by the larger between k_BT and ev_{ac} (in our experiment $k_BT \geq ev_{\mathrm{ac}}$). Either electron or hole transport can be studied in this fashion by applying a negative or positive V_E, respectively. The measured oscillation amplitude as a function of injection voltage is presented in Fig. 3 for three different device lengths L. The three curves are again vertically offset by one division for clarity. Each point in the graph represents a scan, similar to that in Fig. 2, with a given injection voltage. The relative oscillation amplitude is defined as the peak-to-peak amplitude divided by the average probe voltage for a given oscillation (i.e., relative magnitude of the quantum effect). Each point in the graph was obtained as an average over three periods corresponding to the smaller gate voltages in plots similar to Fig. 2. All results are normalized to the oscillation amplitude at an injection voltage comparable to the temperature ($k_BT = 0.1$ meV). The solid line passing through each set of data is of the form $\exp(-L/l_{e\text{-}e})$, with $l_{e\text{-}e} = \tau_{e\text{-}e}v$, $\tau_{e\text{-}e}$ given by Eq. (1), and $v = [2(E_F - eV_E)/m]^{1/2}$ [since $\hbar^2 k_F Q_{\mathrm{TF}}/m = 36$ meV, Eq. (1) is valid for all injection energies used in the experiment]. Note that the expression $\exp(-L/l_{e\text{-}e})$ describes the probability of traversing a length L with no e-e scattering event. The agreement between the experimental data and the theoretical curve therefore indicates that in the ballistic regime $l_\phi = l_{e\text{-}e}$, namely, that dephasing occurs via a single scattering event with an energy exchange on the order of the carrier excess energy. An exponential dependence of the oscillation amplitude on L implies a universal (independent of L) curve for $-[\ln(\text{amplitude})]/L = l_\phi^{-1}$. The result of such an analysis is presented in Fig. 4. As can clearly be seen, the data corresponding to various device lengths scale onto a single curve. The solid line depicts $l_{e\text{-}e}^{-1}$ calculated from Eq. (1). No adjustable parameters have been used throughout the analysis. The scattering of the data at small injection voltages results from the long dephasing length compared with L.

In the analysis presented in Figs. 3 and 4 it was assumed that the carrier excess energy is identical to the externally applied voltage. While such an estimate certainly sets an upper limit, the actual excess energy relative to the Fermi energy in the base might be smaller. In the Ohmic regime, a linear dependence on injection energy is expected. In fact, magnetic-focusing experiments[9,10] with electrons injected to a high-mobility 2DEG at similar energies reveal a linear relation between the applied injection voltage and the measured ki-

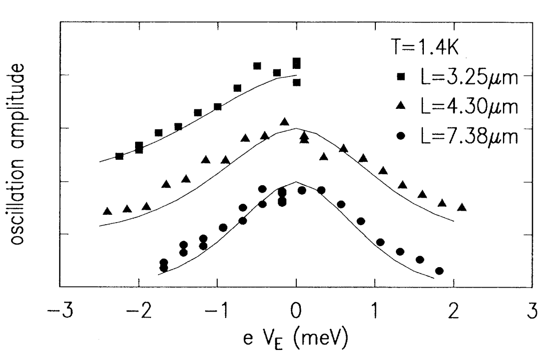

FIG. 3. Oscillation amplitude (see text) vs injection voltage for three different devices. The curves are vertically offset, each with respect to the other, by one division. The solid lines correspond to $\exp(-L/l_{e\text{-}e})$ calculated from Eq. (1).

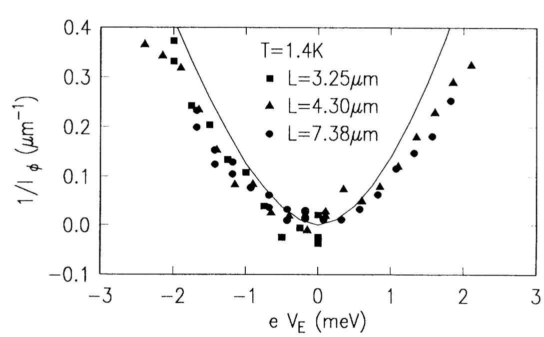

FIG. 4. Measured l_ϕ^{-1} vs injection voltage for three different devices. The similarity between the results corresponding to devices of different lengths supports the exponential dependence assumed in the analysis. The solid line is calculated from Eq. (1).

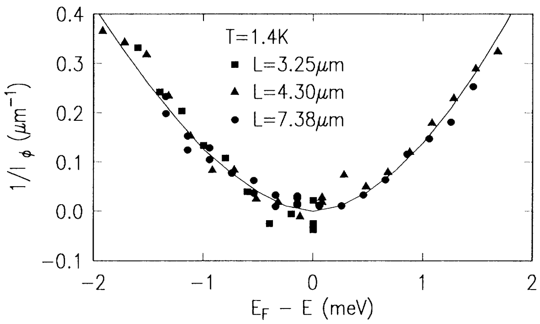

FIG. 5. Same as Fig. 4 but assuming that the actual excess energy is smaller than the applied voltage, $E_F - E = 0.82eV_E$. The remarkable agreement with theory and previous experimental results supports this assumption.

netic energy, $E = E_F - \alpha eV_E$, with $\alpha = 0.67$ and 0.82 in Refs. 9 and 10, respectively. The origin of the difference between the applied voltage and the measured kinetic energy is not clear but might be related to relaxation processes on the emitter side of the constriction. The results of such calibration, with $\alpha = 0.82$, as measured by our group[10] on a rather similar 2DEG, are shown in Fig. 5. The remarkable agreement between theory and experiment strongly supports such an assumption. At any rate, l_ϕ is bounded between the experimental results presented in Figs. 4 and 5, namely, it agrees within 20% with the theoretical $l_{e\text{-}e}$ calculated using Eq. (1). The main uncertainty resulting from the unknown injection energy can probably be resolved in a temperature-dependence study.

An additional possible source for dephasing might, in principle, be due to electron–acoustical-phonon scattering. However, both theoretical calculations[11] and mobility measurements in an ultrapure GaAs/AlGaAs heterostructure[12] find, for temperatures equivalent to the injection energies used in the present experiment, an electron-phonon mean free path on the order of 20 μm. The low lattice temperature used here excludes phonon absorption and stimulated emission, leading to an even longer mean free path. It hence follows that in our experiment phonon scattering is negligibly weak compared with e-e scattering.

In summary, dephasing due to electron-electron interaction was studied in a regime where the phase-breaking length was shorter than the elastic mean free path. It was found, in contrast with the diffusive regime, that dephasing occurs via a single scattering event with an energy exchange on the order of the carrier excess energy. The experimentally measured dephasing length agrees very well with the calculated e-e scattering length in an ideal 2DEG.

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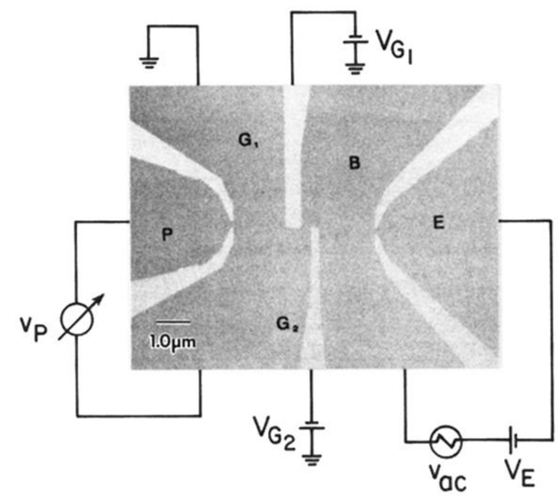

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