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INVITED PAPER

Dephasing of ballistic electrons as a function of temperature and carrier density

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Abstract. Dephasing of ballistic electrons is measured as a function of both temperature and Fermi energy in a high-mobility two-dimensional electron gas. We find a *qualitative* agreement between the measured phase-breaking length and the theoretical prediction for the electron–electron scattering length using the value of E_F measured with large-area Hall bars. A good *quantitative* agreement is obtained when a local value of E_F, measured via on-chip magnetic focusing, is used. The good agreement between the measured phase-breaking length and the theoretical electron–electron scattering length strongly suggests that these two quantities are the same in the ballistic regime.

Interference effects of electrons in semiconductors and metallic systems and their destruction by various scattering mechanisms are of great importance in the understanding of the crossover between quantum and classical behaviour of electronic systems. Moreover, in any foreseeable practical application, external voltages that are applied cause electrons to gain energy, heat up and hence dephase (mostly due to electron–electron (e–e) scattering) over distances that are typically shorter than the elastic mean free path, l_{el}. In this transport regime, l_{el} is not a relevant quantity and dephasing is studied as in the ballistic regime.

In recent years, e–e interactions have been studied extensively, mainly in the diffusive transport regime, both theoretically [1] and experimentally [2]. In this regime, at low enough temperatures, the e–e scattering time (τ_{e-e}) is larger than the elastic scattering time (τ_{el}) and electrons' momentum is not conserved throughout collisions. Altshuler *et al* [3] showed that in this regime dephasing due to e–e scattering is dominated by scattering events involving small energy exchange between the injected electrons and the Fermi sea electrons (with amount much smaller than the electrons' excess energy or temperature). This is to be contrasted with the much larger energy relaxation times due to e–e interactions involving energy exchange of the order of the excess energy of the electrons or the temperature. Experimentally, in the diffusive regime, the energy dependence of the dephasing time of the electrons is studied via the dependence of weak localization (WL) on temperature. In the low-temperature range, good qualitative agreement between theory and experiment is observed [2]. As the temperature rises, e–e scattering times get shorter, eventually reaching the elastic scattering time. Above this temperature, momentum conservation is restored and a new temperature dependence of the WL is evident [4]. However, since the WL effect relies on the diffusive nature of the electrons, its analysis in the range where the phase coherence length, l_ϕ, is smaller than l_{el} (in the higher temperature range) is no longer valid.

Recently, the dependence of the phase coherence length, l_ϕ, on excess energy was deduced directly in the ballistic (momentum conserving) regime, $l_{e-e} < l_{el}$, using an interference-type experiment [5]. In this so-called ballistic regime, there are no theoretical discussions on phase-breaking processes, and it is assumed, implicitly that the dominant dephasing mechanism is e–e interactions. In turn, the e–e scattering time in an ideal two-dimensional electron gas (2DEG) was calculated by Chaplik [6] and by Giuliani and Quinn [7] and was found to be

$$\frac{1}{\tau_{e-e}(T)} \approx \frac{-E_F}{2\pi\hbar}\left(\frac{k_B T}{E_F}\right)^2\left[\ln\left(\frac{k_B T}{E_F}\right) - \ln\left(\frac{Q_{TF}}{k_F}\right) - \ln 2 - 1\right] \tag{1}$$

where $Q_{TF} = 2me^2/\varepsilon\hbar^2$ is the 2D Thomas–Fermi screening wavevector, m is the effective electronic mass and ε is the dielectric constant (12.9 for GaAs). Since the scattering rate is dominated by scattering events with large energy exchange, of the order of the temperature $k_B T$, its dependence on temperature and Fermi energy, E_F, seen in equation (1), is mostly dependent on the phase space available for scattering and only weakly on the matrix elements resulting from the Coulombic interaction.

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Fukuyama and Abrahams [8] have also calculated the e–e scattering rate while treating disorder perturbatively. Their zero-order perturbation, describing the ballistic regime, reveals the same temperature dependence as in [1]; however, the numerical prefactor differs from that of Giuliani and Quinn resulting in a predicted scattering rate greater by an order of magnitude. In addition, Fasol [9] and ourselves performed more exact numerical calculations of the e–e scattering rate and found it to have the same temperature dependence aside from a prefactor twice that given in equation (1).

In a previous publication [5] we presented measurements of l_ϕ at low temperatures, as a function of the excess energy of the electrons relative to the Fermi energy. We showed that the measured value of l_ϕ agrees qualitatively with [7], lacking, however, a good quantitative agreement. In the present work we present results of detailed measurements of l_ϕ of ballistic electrons in a 2DEG, as a function of temperature and Fermi energy, measured using a modified version of Young's double-slit experiment. The measured l_ϕ agrees only qualitatively with equation (1) using a Fermi energy extracted from Shubnikov–de Haas (SdH) measurements on large macroscopic Hall bars. Measuring E_F locally, using on-clip magnetic focusing measurements, we find E_F always to be higher by as much as 50% than the value deduced from SdH measurements. Using this local density we find good quantitative agreement (within 15%) between the measured l_ϕ and our numerical calculations of the e–e scattering length.

The experiments were carried out on a few selectively doped AlGaAs–GaAs heterojunctions supporting a 2DEG. In a typical structure described here the carrier concentration and mobility measured by SdH and Hall measurements were 4.3×10^{11} cm^{-2} and 1.5×10^6 cm^2 V^{-1} s^{-1}, respectively, corresponding to a Fermi energy of 15.5 meV and l_{el} of 16 μm. The overall distance between the surface and the interface, where the 2DEG resides, is 70 nm and the corresponding depletion (or pinch-off) voltage is $V_d = -0.57$ V. A top-view SEM micrograph of a typical device is shown in figure 1. The bright areas are Ti–Au gates fabricated by standard electron beam lithography techniques. A large negative voltage (more negative than the depletion voltage) was applied to all narrow gates, thus forming, all together, three point contacts. The 2DEG was contacted, using standard Au–Ge–Ni alloyed ohmic contacts, at several points such as in the base (B), emitters (E_1 and E_2) and collector (C) of the device. The voltage of the central gate (G) was scanned continuously up to the depletion voltage, thereby modulating the wavelength and hence the phase of the electrons traversing underneath it. The large gate (D) was used to change the Fermi energy in most of the transport region. The device length, L, (the distance from E1 to C) is 5 μm and the length of the modulating gate, G, is $W = 0.5$ μm (the dependence on device and gate lengths has been studied elsewhere [5]). The open circuit collector voltage was measured in a four-terminal configuration relative to one of the base contacts using a standard lock-in technique in a variable-temperature pumped He_4 station.

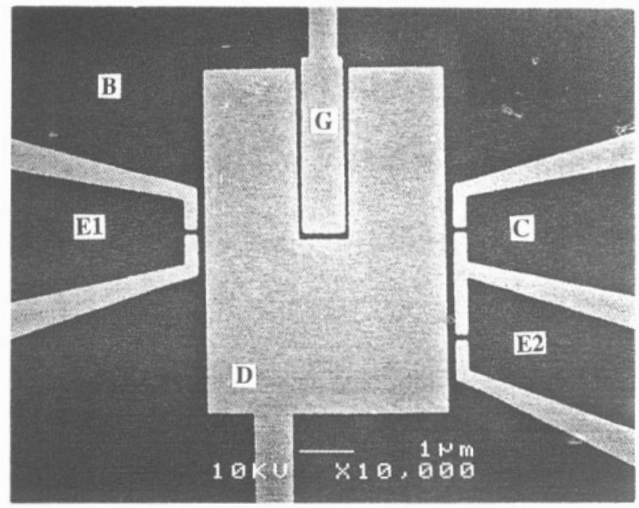

Figure 1. A top-view micrograph of the device used in the experiment. The light areas are the metallic gates deposited on top of the GaAs/AlGaAs heterostructure.

Assuming there are three terminals participating in the measurement (say E_1, C and B), it can be shown [10] that the measured collector voltage is given by $V_C = v_{AC} T_{CE_1}/T_C$, T_{CE_1} and T_C being the transmission probabilities from E_1 to C and the total transmittance of the collector respectively, and v_{AC} is the amplitude of the AC voltage applied between E_1 and B. T_C is simply related to its conductance g_c via the Landauer formula $T_C = (h/2e^2)g_c$. For constant emitter voltage and constant collector conductance, measurement of V_C indicates directly T_{CE_1}. Theoretically, the transmission probability T_{CE_1} can be expressed as a coherent sum over all path amplitudes a_i leading from E_1 to C. In the case discussed here, where the separation between E_1 and C is shorter than l_{el}, these paths are approximately directed along the line connecting E_1 and C and hence can be divided into two groups, group A consisting of all paths passing underneath gate G, and group B containing all other paths. Applying a small negative voltage V_G to G results in a partial depletion of the 2DEG underneath the gate, hence leading to a phase change $\Delta\phi$ for all paths pertaining to A. The transmission probability

$$T_{CE_1} = \left| \sum_{i \in A} a_i e^{i\Delta\phi} + \sum_{i \in B} a_i \right|^2$$

is then expected to oscillate as a function of V_G with a period corresponding to a change of 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 oscillations should be periodic in

$$N = \frac{\Delta\phi}{2\pi} = \frac{W k_F}{2\pi}\left(1 - \sqrt{1 - \frac{V_G}{V_d}}\right)$$

N being the period number.

The measured collector voltage as a function of the normalized phase difference $\Delta\phi$ or the period number, N, for three different temperatures is shown in figure 2. The temperature dependence of the strength of the

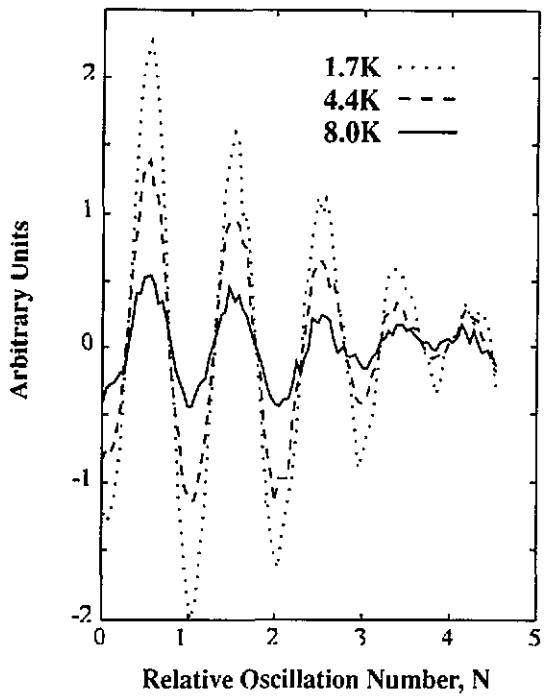

Figure 2. The measured collector voltage V_C versus the period number, N, for three different temperatures.

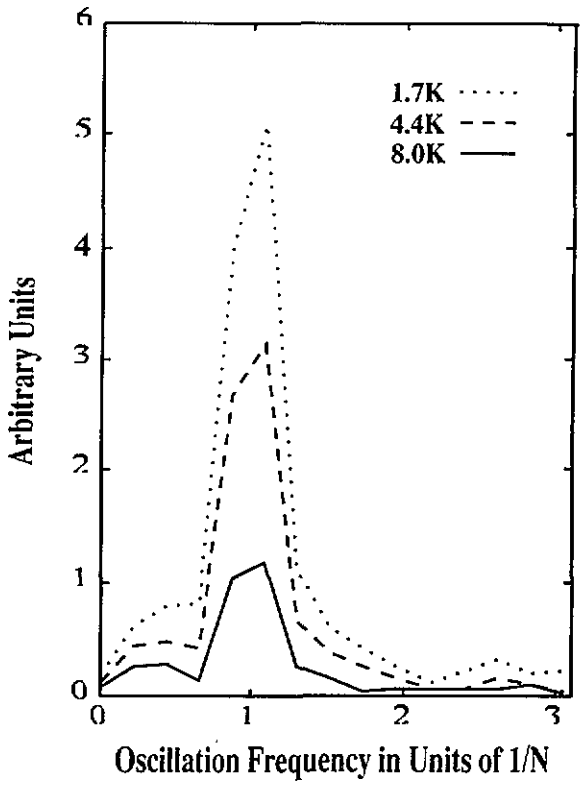

Figure 3. Fourier transform of the data shown in figure 2 versus the oscillation frequency $1/N$.

oscillations can be now used to probe the dependence of l_ϕ on temperature. The oscillation amplitude is a measure of the number of electrons that traverse a distance L without undergoing any phase randomizing events, and is therefore proportional to $\exp(-L/l_\phi)$. The average oscillation amplitude, $A(T)$, is obtained from the peak height or peak area of the Fourier transform spectrum which exhibits a dominant peak (figure 3). In some of our structures, the spectra of the data revealed an *additional* peak corresponding to a period twice the expected one; however, the origin of this period isn't clear at the moment. Since the absolute value of the oscillation amplitude is dominated by geometrical factors (like the acceptance angle of the collector), we normalize it to the amplitude measured at our lowest temperature (1.4 K), obtaining

$$A(T)/A(1.4\text{ K}) = \exp[-L(1/l_\phi(T) - 1/l_\phi(1.4\text{ K}))].$$

This expression may now be used to express l_ϕ as function of the oscillation amplitude in the following way

$$\frac{1}{l_\phi(T)} = \frac{1}{l_\phi(1.4\text{ K})} - \frac{1}{L}\ln\left(\frac{A(T)}{A(1.4\text{ K})}\right). \qquad (2)$$

It should be noted that as the temperature rises the electrons are injected with an energy spread of the order of k_BT, thus leading to a superposition of all the contributions within k_BT, each with a slightly different phase, and hence to some thermal smearing and to a reduction in the oscillation amplitude. However, in the ballistic regime, one can show that the temperature needed in order to smear the interference pattern is given by $k_BT = 2E_F/N$. Since N in our experiment can be as high as 10, the minimum temperature needed to smear the interference is approximately 30 K, much larger than the maximum temperature used in the experiment ($\sim$10 K).

The measured phase-breaking length extracted from the oscillation amplitude according to equation (2) is plotted in figure 4(a) for two different voltages applied to the large gate D (affecting E_F). The full curves passing through the data are the results of our numerical calculations (greater by a prefactor of 2 than equation (1)) with E_F taken from SdH measurements. A discrepancy between experiment and theory is observed. We choose also to measure E_F locally, namely in the local area of the device. This was done by injecting carriers via the point contact E_2 and directing them into the collector point contact (C) via an application of a magnetic field (a magnetic focusing experiment). The value of the field needed for focusing is $B = \sqrt{8mE_F}/ed$ (d being the distance from the emitter point contact E_2 to the collector point contact C, and e being the electronic charge). Using this E_F, as seen in figure 4(b), we get a much better agreement with theory. Extracting typical values for l_ϕ from figure 4(b) we find it to reduce from 50 μm to 5 μm as the temperature rises from 1.4 K to 8 K (with $E_F = 17.5$ meV).

In a spherically isotropic semiconductor, magnetic focusing and SdH measurements give the same value of E_F. The reasons for the large difference we measure are not clear at the moment. Moreover, we looked for density variations across the chip via a few local magnetic focusing measurements; however, all measurements led to similar Fermi energies, quite different from the more global SdH measurements.

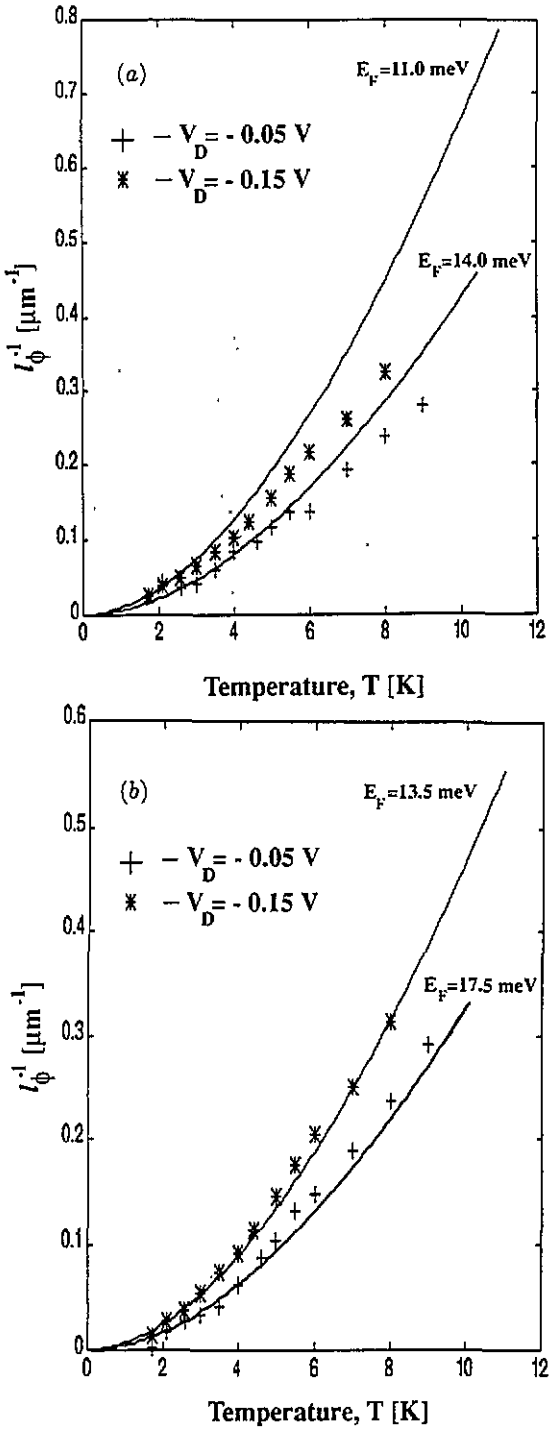

Figure 4. (*a*) The measured phase-breaking length versus temperature for two different voltages applied to the large gate *D*. The full curves passing through the data represent the numerical calculations with E_F measured by SdH on large gated Hall bars. (*b*) The same results as in (*a*). This time the numerical calculations are done with E_F measured locally by magnetic focusing.

In summary, dephasing of ballistic electrons due to e–e interactions has been studied both as function of temperature and Fermi energy. It was found that the phase-breaking length agrees *qualitatively* well with the e–e scattering length calculated by Giuliani and Quinn [7]. A good *quantitative* agreement requires an additional prefactor of 2 in equation (1) and the use of a Fermi energy measured locally. This local Fermi energy differs by as much as 50% from the globally measured Fermi energy. Typical values of l_ϕ are 50 μm at 1.4 K and 5 μm at 8 K (with $E_F = 17.5$ meV). The strong dependence of the phase-breaking length on E_F and the good agreement between theory and experiments suggests that dephasing measurements in the ballistic regime may be used as an accurate measurement of the local Fermi energy void of geometry dependence.

Acknowledgments

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