Conductance Fluctuations in a Ballistic Metallic Point Contact

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(Received 28 May 1991)

The magnetoconductance of a 3D ballistic Ag point contact is found to show reproducible fluctuations with rms amplitude 2 orders of magnitude lower than usually observed in diffusive systems and insensitive to temperature up to $T=5$ K. This is explained by quantum interference of electrons, the length scale of the trajectories of interfering waves being the elastic mean free path. For an applied voltage across the constriction, the observed magnetofingerprint changes asymmetrically under bias reversal with a roughly constant rms amplitude. At higher voltages ($V \geq 10$ mV), electron-phonon coupling destroys the phase coherence and a strong decrease in fluctuation amplitude is observed.

PACS numbers: 73.40.Jn, 72.15.Gd, 72.15.Rn

Magnetoconductance fluctuations with a reproducible aperiodic structure have been studied in various mesoscopic systems. In samples with diffuse electron transport, these so-called universal conductance fluctuations (UCF) originate from quantum interference of multiply scattered electrons. UCF have the property that at $T=0$ their rms amplitude is of the order e^2/h, independent of sample size or degree of disorder [1]. A change in applied magnetic field shifts the phases of the electron waves, giving the fluctuations a typical field scale $B_c \simeq \Phi_0/A$, corresponding to a flux quantum $\Phi_0=h/e$ through a phase-coherent area A of the sample. So far, UCF have been observed at low temperatures in small metal wires and rings [2] and in semiconductor devices [3]. For systems smaller than the phase-coherent area, it has been shown that the geometry of the measuring contacts influences the quantum interference effects in the electronic transport via the size and dimensionality of the contacting regions [4]. In these systems the elastic electron mean free path l_e is much smaller than the size of the sample, indicating diffusive transport. Fluctuations of similar appearance have recently been observed in laterally confined two-dimensional electron gases with essentially no disorder [5]. In this ballistic transport regime chaotic scattering of electrons from geometrical features occurs, resulting in the trapping of electrons in the confinement and leading to conductance fluctuations as a function of magnetic field [6,7].

In this Letter we report the first observation of magnetoconductance fluctuations in a ballistic metallic point contact, a constriction in a three-dimensional system with a mean free path l_e larger than the size (radius a) of the contact. An applied voltage V across the constriction drops off within a distance of order a and accelerates electrons passing the contact to an excess energy eV. After an elastic- (energy change $\Delta\epsilon \simeq 0$) or an inelastic- ($\Delta\epsilon \simeq eV \simeq \hbar\omega_{\text{phonon}}$) scattering event there is the possibility for electrons to flow back through the contact, thus increasing the resistance [8]. The second derivative d^2I/dV^2 of the current I with respect to the voltage V measures directly the point-contact variant $\alpha^2F_p(eV)$ of the Eliashberg function for the electron-phonon interaction, a technique known as point-contact spectroscopy [8]. The ballistic transport of electrons in a point contact offers the unique possibility to study conductance fluctuations as a function of the well-defined excess energy eV of the electrons.

The point contacts used in our experiments were fabricated using nanofabrication techniques [9]. A single hole is patterned in a 20-nm-thick silicon nitride membrane by e-beam lithography and dry etching. The device is formed by evaporating under UHV conditions a 200-nm metal layer onto both sides of the membrane. The hole is filled with metal and a nanobridge is formed between the two metal layers. For the investigated Ag nanobridges the elastic mean free path l_e at liquid He temperatures is determined from the ratio $R_{300\,\text{K}}/R_{4.2\,\text{K}}$ of a metal layer and of the point contact itself, yielding in both cases $l_e \simeq 240$ nm, comparable to the thickness of the evaporated film. The samples were investigated in a dilution refrigerator in magnetic fields up to 7 T parallel to the constriction axis of the point contacts. The differential resistance dV/dI and point-contact spectrum d^2V/dI^2 were measured using phase-sensitive techniques with excitation voltages never exceeding 0.3 mV rms.

Figure 1 shows magnetoresistance traces for a typical Ag device with a resistance $R=11\ \Omega$, for differential applied voltages, measured at a temperature $T=400$ mK. Reproducible resistance fluctuations, superimposed on a bias-dependent background, are clearly visible. As the bias voltage is changed in small steps, the typical fluctuation pattern (magnetofingerprint) evolves gradually. When the change in voltage exceeds about 2 mV (Fig. 1), a completely different magnetofingerprint results. With increasing bias (Fig. 1), the typical "period" B_c of the fluctuations in the magnetoresistance traces increases

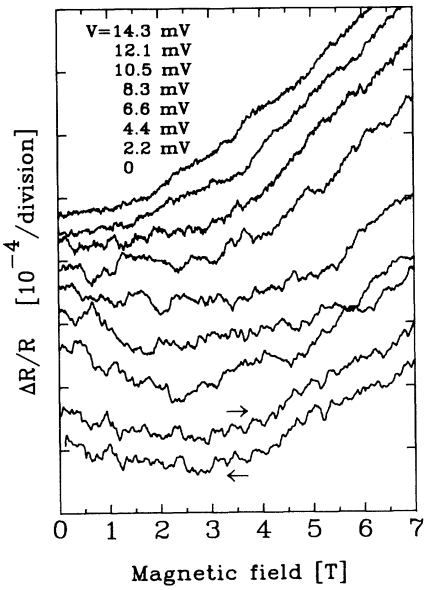

FIG. 1. The relative resistance change $\Delta R/R$ of a Ag point contact with resistance $R_0=11\ \Omega$ at temperature $T=400$ mK as a function of magnetic field for different applied voltages across the contact. For clarity, the curves have been shifted with respect to each other. The zero-bias resistance trace is shown for magnetic-field sweep up (→) and down (←) to demonstrate the reproducibility of the fluctuations.

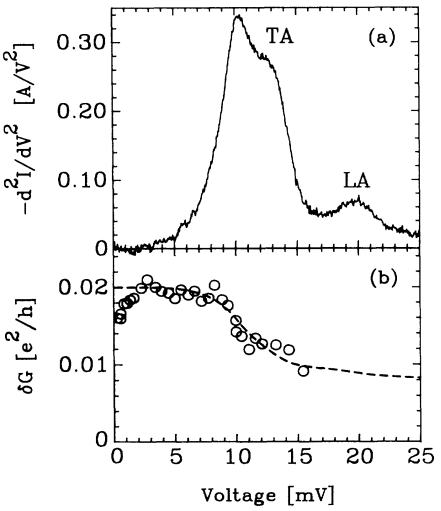

FIG. 2. (a) Point-contact spectrum and (b) the rms amplitude δG of the conductance fluctuations in units of e^2/h, again for the 11-Ω Ag point contact. The dashed line is the calculated voltage dependence $\exp[-l_e/L_{in}(eV)]$ of the fluctuation amplitude.

while their amplitude decreases. At zero bias the rms amplitude of the conductance fluctuations is $\delta G\simeq 1.8\times 10^{-2}e^2/h$, insensitive to temperature up to $T=5$ K. In Fig. 2 we have plotted the rms amplitude of the fluctuations of the same device as a function of the applied voltage, together with the point-contact spectrum $d^2I/dV^2(V)$. After an initial increase, the amplitude of the fluctuations is roughly constant, whereafter at $V\simeq 10$ mV [the transverse-acoustic (TA) phonon peak] a clear decrease starts. The characteristic field scale B_c, obtained from the half-width of the autocorrelation function $F(\Delta B)=\langle\Delta G(B)\Delta G(B+\Delta B)\rangle$ [1], and corresponding size $L\simeq(\Phi_0/B_c)^{1/2}$ of the interference loops are found to change from $B_c\simeq 0.07$ T and $L\simeq 245$ nm at zero bias to $B_c\simeq 1$ T and $L\simeq 65$ nm at $V\simeq 12$ meV and higher. From the contact resistance $R_p=(4\rho l_e/3\pi a^2)(1+0.82a/l_e)$ [8], we obtain a constriction radius $a\simeq 5$ nm for our 11-Ω device. Since the thickness of the membrane ($\simeq 20$ nm) is comparable with the diameter of the constriction ($\simeq 10$ nm), but much smaller than the elastic mean free path, we will consider the point contact as being an orifice in a thin impermeable screen. The length scale determining the fluctuation phenomena is much larger than the constriction size. Therefore, it seems unlikely that a quantum chaos model, where essentially the constriction is important, can explain the observed fluctuations. The influence of flux cancellation due to boundary scattering [10] can be excluded, since for interference inside the contact it would even reduce the effective loop size (contrary to the observed values), while for interference extending away from the contact the geometry of the sample boundaries makes this effect less important. We propose a simple model in terms of the quantum interference of electrons near the contact, over loop sizes of the order of the elastic mean free path l_e.

To estimate the amplitude of the fluctuations we used the generalized Landauer formula for the conductance [11,12],

$$G=\frac{2e^2}{h}\sum_{\alpha,\beta}^{N}|t_{\alpha\beta}|^2. \tag{1}$$

Here $|t_{\alpha\beta}|^2$ is the transmission probability from incoming channel α to outgoing channel β and N is the number of channels. In the presence of impurities around the constriction the transmission probabilities are not equal to $\delta_{\alpha\beta}$, and depend on the probability for injected electrons to return through the contact. This backflow probability is given in first order by $0.82a/l_e$ [8], yielding the ensemble-averaged transmission probabilities $\langle|t_{\alpha\beta}|^2\rangle=(1-0.82a/l_e)/N$. Evaluation of Eq. (1) with these transmission probabilities and the number of channels $N=a^2k_F^2/4$ in a circular constriction with radius a gives the mean conductance $\langle G\rangle\simeq R_p^{-1}$. Calculating the $\mathrm{var}(G)=(G-\langle G\rangle)^2$ using Eq. (1) and the transformation from transmission to reflection probabilities to include the influence of correlations in the transmission [11,13], we find for the rms amplitude of the fluctuations,

$$\delta G=\sqrt{\mathrm{var}(G)}\simeq 1.6(e^2/h)a/l_e. \tag{2}$$

In contrast to the $T=0$ UCF magnitude e^2/h, Eq. (2) *depends on effective sample size and degree of disorder*

to take account for the efficiency of scattering contributions to the resistance. With $a \simeq 5$ nm and $l_e \simeq 240$ nm, Eq. (2) gives a fluctuation amplitude $\delta G \simeq 3.3 \times 10^{-2} e^2/h$ for our 11-Ω device, in reasonable agreement with the observed $\delta G \simeq 1.8 \times 10^{-2} e^2/h$. In diffusive point contacts ($l_e \leq a$) larger fluctuations [$(0.2\text{-}1) e^2/h$] were observed [14], in support of Eq. (2).

The decrease of δG starting at 10 mV can be understood from phonon emission by electrons with excess energy eV, resulting in a reduced inelastic mean free path L_{in}. This reduction of L_{in} destroys phase coherence of the larger interference loops. To account for inelastic processes we multiplied Eq. (2) by a factor $\exp[-l_e/L_{\text{in}}(eV)]$, the probability that an electron with excess energy is inelastically scattered due to phonon emission on a length scale l_e. The energy-dependent inelastic mean free path $L_{\text{in}}(eV)$ is calculated from the normalized spectrum in Fig. 2(a) using [8] $1/L_{\text{in}}(eV) = (2\pi/\hbar v_F) \int_0^{eV} \alpha^2 \times F_p(\epsilon) d\epsilon$ and the electron-phonon-interaction parameter $\lambda_p = 2\int [\alpha^2 F_p(\epsilon)/\epsilon] d\epsilon = 0.1$ for Ag (v_F is the Fermi velocity). After adjusting the amplitude at low voltages to the roughly constant level of δG between 3 and 9 mV [Fig. 2(b)], good agreement with the measured voltage dependence of the rms amplitude is found.

In our point contact the impurity scattering takes place far away from the region where the applied voltage drops ($l_e \gg a$). The excess energy, acquired by an electron passing the constriction, determines the electronic wavelength. When the voltage is changed, the wavelengths, and, therefore, the interference conditions are changed [15,16]. A significant change in the magnetofingerprint is expected when the electron energy exceeds $E_c = \hbar/t_c$, with E_c the correlation energy and t_c the time to traverse a coherent electron trajectory. From the effective length $L \simeq 240$ nm at zero bias, calculated via $L \simeq (\Phi_0/B_c)^{1/2}$, and $t_c \simeq L/v_F$, we find a correlation energy $E_c \simeq 4$ meV, 2 orders of magnitude larger than observed in metallic rings [17].

Because of the random distribution of scatterers around the constriction, the point contact lacks inversion-center symmetry. Changing the sign of the excess energy of the electrons influences the interference conditions for the different impurity configurations on each side of the contact. Therefore, the conductance will be asymmetric with respect to bias reversal. In Fig. 3 we have plotted the fluctuating component of R^S and of R^A, the symmetric and antisymmetric parts of the magnetoresistance, for a number of positive and negative applied voltages. The decomposition in Fig. 3 demonstrates a new magnetofingerprint in the antisymmetric component R^A with increasing amplitude for $eV < E_c$. The magnetofingerprints of R^S and R^A change again within the correlation voltage E_c/e. We plotted the rms amplitudes of the conductance deduced from the magnetoresistance traces in Fig. 3 as a function of the voltage in Fig. 4. At low voltages, the rms amplitude of the antisymmetric component increases linearly. Comparing this result with theoretical predictions and former experiments on diffusive systems [15,16], we find good agreement if we include the reduction factor a/l_e in the expressions for the fluctuation amplitude in the antisymmetric part of the conductance.

In diffusive systems, for voltages $V \geq E_c/e$ a decrease of the fluctuation amplitude is expected because of classical averaging over eV/E_c coherent subsystems [15]. However, in our experiment the electrons scattered by

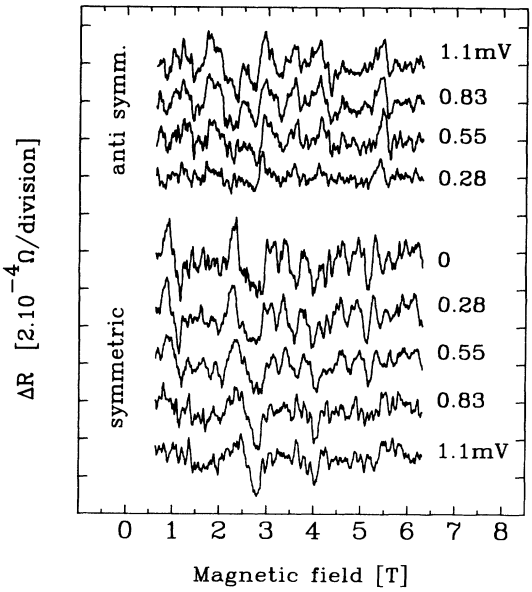

FIG. 3. The fluctuating component of $R^S = [R(V,B) + R(-V,B)]/2$ and of $R^A = [R(V,B) - R(-V,B)]/2$, the symmetric and antisymmetric resistances, as a function of magnetic field for different applied voltages (for clarity, the curves have been shifted with respect to each other).

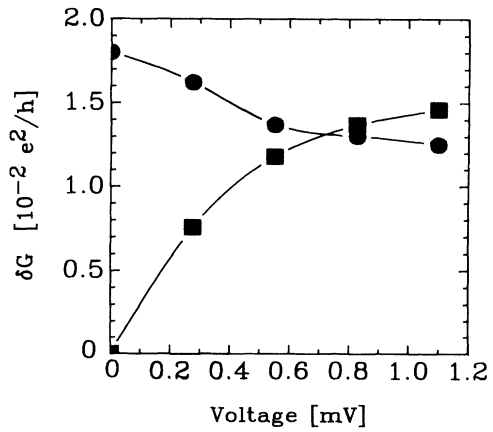

FIG. 4. The rms amplitude of the symmetric component $\delta G^S = \langle [G(V,B) + G(-V,B)]^2 \rangle^{1/2}/2$ (●) and the antisymmetric component $\delta G^A = \langle [G(V,B) - G(-V,B)]^2 \rangle^{1/2}/2$ (■) of the conductance as a function of the applied voltage in units e^2/h.

impurities around the constriction have a constant excess energy eV and the resistance is measured *differentially* around the applied voltage V. Apart from the small increase of δG for voltages $V < E_c/e$, increasing the voltage above E_c/e does not affect the rms amplitude (Fig. 2) of the fluctuations, but will only give access to different coherent subsystems with energy width $\delta E \simeq E_c$. Each time the voltage is changed by $\Delta V \simeq E_c/e$ a new subsystem is entered and hence the magnetofingerprint is completely changed. This is clearly visible in Fig. 1. Inelastic processes influence the fluctuation amplitude at higher voltage.

In conclusion, this work reports the first observations of reproducible magnetoconductance fluctuations in a three-dimensional ballistic metallic point contact. The characteristic field scale B_c, the correlation energy E_c, and the amplitude reduction (a/l_e) of the fluctuations are in agreement with the model that the elastic mean free path determines the size of interfering paths. Using the possibility to tune the nonequilibrium energy of the electrons by the applied voltage, the ballistic transport in a point contact yields energy-resolved information about the influence of electron-phonon scattering and voltage polarity on the electron interference effects.

We wish to thank H. Appelboom of the Solid State Physics Group of the Delft University of Technology for assistance with the UHV evaporation. One of the authors (J.A.K.) expresses his gratitude for the hospitality of the Delft Institute of Microelectronics and Submicron Technology during the experiments, and would like to thank G. Maret for stimulating discussions. R. Rammal took great interest in this work. This work is part of the research program of the Stichting Fundamenteel Onderzoek der Materie (FOM), which is financially supported by the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

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