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Nyquist phase relaxation in one-dimensional metal films

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We have measured the magnetoresistance of narrow (600–1000 Å) and thin (150–200 Å) gold films, one dimensional with respect to weak localization and electron-electron interaction effects. It is shown that electron-electron collisions with small energy transfer (Nyquist phase-breaking mechanism) govern the phase relaxation in such films over a wide temperature range. The Nyquist time τ_N was estimated from the magnetoresistance data on the basis of the theoretical dependence $\Delta R_{\rm loc}(H)$ that is applicable to the case when Nyquist phase relaxation dominates other phase-breaking proceses. The temperature dependence $\tau_N(T) \propto T^{-2/3}$ obtained in this way is in good agreement with the theoretical prediction for one-dimensional conductors.

In the past decade the processes of inelastic electron scattering in disordered conductors have been investigated intensively at low temperatures by means of the study of weak localization (WL) effects.[1,2] Inelastic scattering governs the phase-breaking time τ_φ of the electron wave function, and the length $L_\varphi = \sqrt{D\tau_\varphi}$ (D is the electron diffusion constant), in turn, determines the magnitude of the WL effects and the size of the conductance fluctuations in mesoscopic systems. The effective dimensionality of a sample with respect to WL effects is also determined by the magnitude of L_φ relative to the sample dimensions. At low temperatures the main contribution to the phase-breaking time comes from electron-electron scattering.[1,3] It was shown by Altshuler, Aronov, and Khmelnitskii[3] that electron-electron collisions with small energy transfer ($\Delta E \sim \hbar/\tau_N \ll k_B T$, where τ_N is the phase relaxation time due to such quasielastic collisions) is the dominant mechanism of phase relaxation in low-dimensional disordered systems. For this process the length scale is given by $L_N = (D\tau_N)^{1/2}$ in contrast to electron-electron scattering with large energy transfer, which is characterized by the thermal diffusion length $L_T = \sqrt{\hbar D/k_B T}$. Electron-electron interaction (EEI) with small energy transfer is equivalent to the scattering of electrons by the fluctuating electric field created by all other electrons (Nyquist noise). The Nyquist phase-breaking mechanism should be especially important in one-dimensional (1D) conductors.[3]

Nyquist phase relaxation has been extensively studied in 2D conductors.[2] There are also a few experimental studies of phase relaxation in 1D metal films[4–6] and semiconductor structures.[7–9] In spite of a narrow temperature range where τ_φ was governed by the Nyquist mechanism, these authors claimed that they have managed to separate the Nyquist relaxation rate $(\tau_N)^{-1}$ from all other contributions with large energy transfer $(\tau_{\varphi 0})^{-1}$, and that the experimental values of τ_N were in reasonable agreement with the theory.[3] In all those papers the total phase-breaking rate was considered as the sum of the contributions related to the different phase-breaking mechanisms. Unfortunately, this approach is not applicable to the situation when electron-electron collisions with small energy transfer becomes the dominant phase-breaking mechanism in 1D conductors. In this case, as was emphasized in Ref. 3, the characteristic collision times are of the order of the phase-relaxation time, and the problem cannot be solved in the framework of the kinetic equation. The process of phase relaxation becomes nonexponential, and it cannot be described with a single relaxation time. The Nyquist time τ_N, which has been introduced in Ref. 3, is just a typical time scale rather than the relaxation time. As a result, the magnetic-field dependence of the WL correction to the resistivity $\Delta R_{\rm loc}(H)$, obtained from the cooperon averaged over the electromagnetic field fluctuations,[3] differs from the opposite limiting case ($\tau_N \gg \tau_{\varphi 0}$) of the WL magnetoresistance of 1D conductors,[10] which has been used to fit the experimental data in all previous experimental works.[4–9]

The main purpose of the work reported in this paper was to study in detail the Nyquist phase relaxation in 1D samples. In our experiment we have tried to avoid two drawbacks of previous experiments: the usable temperature interval was too narrow to separate different contributions to τ_φ unambiguously, and the procedure of comparison with the theory was applicable only to the case $\tau_N \gg \tau_{\varphi 0}$. The magnetoresistance of gold films clean enough to avoid any complications due to spin-spin scattering has been measured at temperatures between 0.1 and 10 K. The samples were sufficiently narrow to be considered one dimensional with respect to WL and EEI in that temperature range. We have used a procedure of extraction of τ_N from the magnetoresistance data, applicable for any relation between the Nyquist rate and the rates of the other phase-breaking mechanisms. As a re-

sult, the temperature dependence of τ_N was obtained in a wide temperature range (0.1–5 K). This temperature dependence $\tau_N(T)$ is in good agreement with the theory,[3] although the absolute values of τ_N turned out to be smaller than the theoretical estimate.

Our samples consisted of 21 narrow Au strips, 100 μm long, connected in parallel between contact pads. The width W of the strips was the same in each sample and varied between 0.06 and 0.1 μm from sample to sample. The distances between strips varied from sample to sample between 0.06 and 0.7 μm, and were large enough to avoid any interference between strips.[11] The samples were fabricated on top of oxidized Si substrates using a standard bilayer electron beam lithography process followed by thermal evaporation of thin films and liftoff. The gold films had thickness $d=150$–200 Å, and were evaporated at a residual pressure of 4×10^{-6} mbar at a rate of 4 Å/s. The resistance per square $R_\square$ was 2–3 Ω, depending on the film thickness. The values of the electron mean free path l were estimated from the relation $\rho l=8.7\times10^{-12}$ Ω cm^2 ($\rho=R_\square d$ is the resistivity of a film).[12] The values of l for these films were very close to d, indicating that the main electron scattering mechanism is diffuse surface scattering and the diffusion process is two dimensional ($l\sim d\ll W$) with a diffusion constant $D=lv_F/2$ [the Fermi velocity for gold is $v_F=1.4\times10^8$ cm/s (Ref. 12)]. The experimental data were very similar for all the samples investigated. We have studied the magnetic-field dependence of the resistivity of such samples between 100 mK and 10 K in magnetic fields 0–600 Oe perpendicular to the plane of the field. The magnetoresistance data were collected using a computer-controlled acquisition system allowing data averaging to improve the signal-to-noise ratio. The measuring current of 1 nA per strip was small enough to avoid electron heating for $T\geq0.1$ K. The results shown in detail in this paper were obtained for a sample with the following parameters: $R_\square=3.0$ Ω, $W=0.09$ μm, interstrip distance 0.1μm, $d=150$ Å, $l=190$ Å, and $D=135$ cm^2/s (referred to as sample 1).

The magnetoresistance $\Delta R(H)/R(H=0)=[R(H)-R(H=0)]/R(H=0)$ of sample 1 at different temperatures is shown in Fig. 1. The magnetoresistance due to suppression of WL effects is positive because in gold films WL effects are affected by a strong spin-orbit scattering (SOS).[2] Our samples, as will be shown below, were one dimensional with respect to WL effects for $T\leq10$ K and $H\leq400$ Oe. The WL correction to the resistivity of 1D samples, calculated for an arbitrary value of $\tau_N/\tau_{\varphi0}$ ($\tau_{\varphi0}$ is the phase-relaxation time due to all phase-breaking mechanisms other than the Nyquist one) in the limit of strong SOS can be represented as follows:[1,3]

$$\Delta R_{\rm loc}/R_0=-(1/\pi\sqrt{2})(e^2R_\square/\hbar)(L_N/W)\times f[2(L_N/L_{\varphi0})^2]\ ,$$
$$f(x)={\rm Ai}(x)/{\rm Ai}'(x)\ , \qquad (1)$$

where Ai(x) is the Airy function. Note that Eq. (1) differs from $\Delta R_{\rm loc}(T,H)$ obtained in Ref. 3 by a factor $-\frac{1}{2}$, because the results of Ref. 3 were calculated for

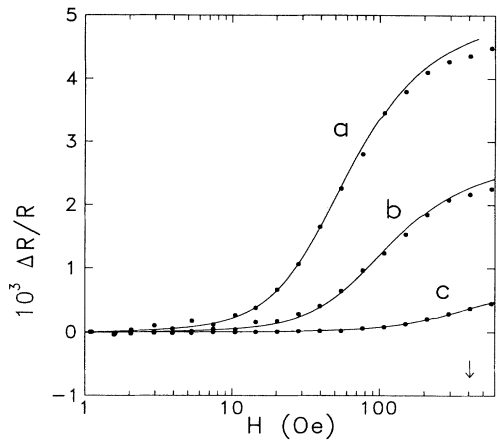

FIG. 1. Magnetoresistances obtained for sample 1 at 0.12 K (a), 1.03 K (b), and 7.05 K (c). The solid curves are the theoretical fits based on Eq. (1). The magnetic field at which $L_H=W$ is shown by an arrow.

weak SOS ($\tau_{so}\gg\tau_N,\tau_{\varphi0}$, where τ_{so} is the spin-orbit scattering term).

The theoretical prediction for the 1D Nyquist time is[3]

$$\tau_N({\rm 1D})=(\hbar^2W/e^2k_BT\sqrt{2D}R_\square)^{2/3}\propto T^{-2/3}\ . \qquad (2)$$

For 1D samples, the phase-breaking rates due to an external magnetic field and to collisions with large energy transfer are additive:[13]

$$1/\tau_{\varphi0}=1/\tau_{\varphi0}(H=0)+1/\tau_H\ . \qquad (3)$$

Note that for two-dimensional systems the situation is more intricate because the phase relaxation induced by a magnetic field is nonexponential in this case.[13,14] For a magnetic field perpendicular to the plane of the 1D film of width W,[10]

$$\tau_H=12L_H^4/DW^2\ , \qquad (4)$$

where $L_H=\sqrt{\hbar C/2eH}$ is the magnetic length.

If the Nyquist phase relaxation is the dominant mechanism [$\tau_N\ll\tau_\varphi(H=0)$], then

$$\frac{\Delta R_{\rm loc}(T,H)}{R_0}\cong-0.31\frac{e^2R_\square}{\hbar W}[1/L_N^2+1/D\tau_H]^{-1/2}\ . \qquad (5)$$

In the opposite case [$\tau_N\gg\tau_{\varphi0}(H=0)$], Eq. (1) could be rewritten as

$$\frac{\Delta R_{\rm loc}(T,H)}{R_0}\cong-\frac{e^2R_\square}{2\pi\hbar W}[1/L_{\varphi0}^2+1/D\tau_H]^{-1/2}\ . \qquad (6)$$

The last equation has been used previously to fit all the experimental data.[4–9] Note that the application of Eq. (6) instead of Eq. (5) to the limit $\tau_N\ll\tau_{\varphi0}$ would result in an overestimation of $\tau_{\varphi0}$ (roughly by a factor of 4).

Equation (1) contains two unknown parameters, τ_N and $\tau_{\varphi0}(H=0)$. Although both electron-electron with large energy transfer and electron-phonon scattering contribute to $\tau_{\varphi0}$, for our films, the only mechanism that we need to consider is electron-phonon scattering. In our

previous work we obtained $\tau_{e\text{-ph}} \simeq (7.4\times10^{-9}\ \mathrm{s\,K^3})\ \mathrm{T}^{-3}$ for 2D gold films with similar values of l and d.[15] This estimate is applicable to the present case because the width of our samples is not small enough to produce any change in the phonon spectrum for $T > 0.1$ K. By comparison, we estimate (see Eq. 4.12 in Ref. 1) $\tau_{e\text{-}e} \sim (2\times10^{-9}\ \mathrm{s\,K^{1/2}})\ \mathrm{T}^{-1/2}$. Electron-electron scattering with large energy transfer only becomes important below 2K where we are already in the limit $\tau_N \ll \tau_{\varphi 0}(H=0)$. As a consequence [see Eq. (5)], the estimation of τ_N in the lower temperatures no longer depends on $\tau_{\varphi 0}$.

The solid curves in Fig. 1 are theoretical fits based on Eq. (1). The magnetic-field dependences of the resistance measured experimentally and calculated from Eq. (1) are in very good agreement in the field range $H=0$–200 Oe. The deviation of the experimental magnetoresistance from the theoretical fits for larger H is accounted for by the crossover to a two-dimensional WL behavior when the magnetic length becomes smaller than the width of the sample. The value of H corresponding to $L_H = W$ is shown by an arrow in Fig. 1. The values of the fit parameter τ_N are plotted in Fig. 2. The uncertainty in τ_N becomes larger at higher temperatures, where τ_N and $\tau_{e\text{-ph}}$ are of the same order of magnitude.

Sample 1 can be considered as one dimensional with respect to EEI effects below 10 K. The best single power-law fit to the temperature dependence gives $\tau_N = 7.7\times10^{-11}\ \mathrm{s(T/K)}^{-0.64\pm0.02}$, in good agreement with the theoretical prediction for the 1D Nyquist time [see Eq. (2)].[3] This is the first time, to our knowledge, that the temperature dependence of τ_N for a 1D sample has been obtained in a wide temperature range—this is important to get an accurate estimate of the weak temperature dependence of τ_N. While the temperature dependence of τ_N is in excellent agreement with the theory, the numerical prefactor is smaller than the estimate from Eq. (2) by a factor ~ 4. This discrepancy cannot be ascribed to the uncertainty in the film parameters, which are known to an accuracy of $\sim 10\%$.

We note that it is possible to fit the experimental magnetoresistance using Eq. (6) (which is not applicable when $\tau_N \ll \tau_{\varphi 0}$) over the whole temperature range. In fact, that has been done in all preceding papers on the study of phase-relaxation processes in 1D conductors. In this approach $(\tau_{\varphi 0})^{-1}$ should be substituted for by a phase-breaking rate $(\tau_\varphi)^{-1} = (\tau_{e\text{-ph}})^{-1} + (\tau_N)^{-1}$. We have used this (incorrect) procedure to demonstrate the difference in the results. The resulting values of τ_φ are shown in Fig. 3. For $T \geq 3$ K the dominant phase-breaking mechanism is electron-phonon scattering and this approach is valid $(\tau_N > \tau_{e\text{-ph}})$. Correspondingly, the values of τ_φ are very close to the values of $\tau_{e\text{-ph}}$ obtained for 2D films (dashed line in Fig. 3). At lower temperatures, where $\tau_N \ll \tau_{e\text{-ph}}$, the experimental values of τ_φ can also be approximated by $\tau_\varphi(T) \propto T^{-2/3}$, but the absolute values of τ_φ are larger than the actual values of τ_N due to the difference in coefficients between Eqs. (6) and (5). The values of τ_φ obtained with this procedure are in good quantitative agreement with the values of τ_N predicted by Eq. (2). Unfortunately, this agreement is fortuitous, because Eq. (6) cannot be applied for $T \leq 5$ K, where $\tau_N \ll \tau_{e\text{-ph}}$. Taking into account the difference between Eqs. (5) and (6) we conclude that $\tau_N(T)$ data obtained previously for metal films and semiconductor structures[4–9] were also considerably smaller than the theoretical prediction of Eq. (2). It is worth noting that the values of τ_N obtained for 2D samples were also smaller than the corresponding theoretical estimate of τ_N(2D) by a factor of 2–3.[2] The reason for this discrepancy is still unclear.

The dependence $\tau_N(T)$ of Fig. 2 can be used to calculate the temperature dependence of the weak localization correction $\Delta R_{\mathrm{loc}}(T, H=0)$ in zero magnetic field [see Eq. (1)]. In contrast to the magnetoresistance, the temperature dependence of the resistivity is the sum of several contributions due to different quantum interference effects (EEI, WL, and quantum interference between

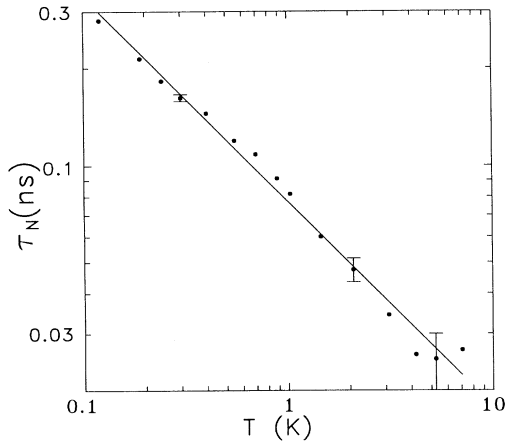

FIG. 2. Temperature dependence of τ_N. The solid line is the best power-law fit $\tau_N = 7.7\times10^{-11}\ \mathrm{(T/K)}^{-0.64}$.

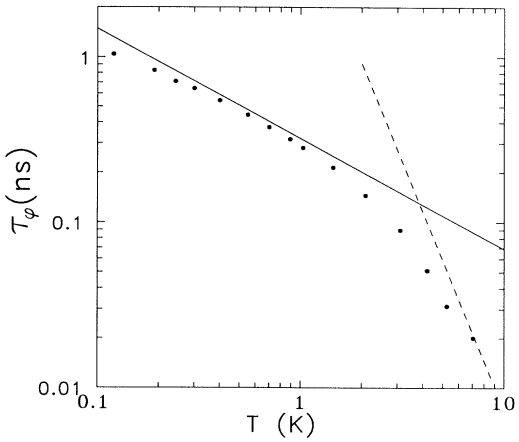

FIG. 3. The temperature dependence of τ_φ obtained from fitting the experimental magnetoresistance to Eq. (6) (not applicable below ~ 5 K, where $\tau_N \ll \tau_{e\text{-ph}}$). The solid line is the estimate of τ_N from Eq. (2), and the dashed line is the temperature dependence $\tau_{e\text{-ph}} = (7.4\times10^{-9}\ \mathrm{s\ K^3})\ \mathrm{T}^{-3}$, obtained for 2D gold films (Ref. 15), which has been used as $\tau_{\varphi 0}(H=0)$ for the calculation of τ_N from Eq. (1).

electron-phonon and electron-impurity scattering).[15] Using the values of τ_N obtained in a proper way we have managed to fit *quantitatively* the experimental dependences $\Delta R(T,H=0)$ by the sum of all quantum corrections. These results will be discussed elsewhere in a more detailed paper.[11]

In conclusion, the magnetoresistance of narrow gold films, one dimensional with respect to WL and EEI effects, has been measured in a wide temperature range. This magnetoresistance is caused by the suppression of the WL correction to the resistivity by a magnetic field and is in good agreement with the theoretical predictions for the weak localization magnetoresistance of 1D conductors. At low temperatures electron-electron scattering with small energy transfer is the dominant phase-breaking mechanism for the samples studied. The experimental data were compared with the complete theory,[3] applicable for any relation between the Nyquist rate $(\tau_N)^{-1}$ and the rate of the phase relaxation $(\tau_{\varphi 0})^{-1}$ due to other phase-breaking mechanisms with large energy transfer. The values of the Nyquist phase-breaking time τ_N were extracted over a range spanning nearly two decades of temperature, which enables us to provide a detailed comparison with the theoretical prediction for $\tau_N(1D)$. The temperature dependence $\tau_N(T) \propto T^{-2/3}$ is in agreement with the results of EEI theory for 1D samples,[1] but the absolute values of τ_N are smaller than the theoretical values by a factor of ~ 4.

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