Mesoscopic conductivity fluctuations in samples with magnetic impurities

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(Submitted 6 July 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **52**, No. 4, 873–876 (25 August 1990)

Submicron-size n^+-GaAs conductors with spin scatterers have been studied. The scatterers were implanted in the sample by plasma-chemical etching. The relaxation of the spins and the spin scattering are shown to suppress mesoscopic oscillations of the resistance. These oscillations are restored in a magnetic field as a result of Zeeman splitting.

At low temperatures, disordered conductors with small dimensions exhibit several quantum properties as a result of a coherence of electron states over the entire volume of the sample. Among these properties are the mesoscopic ("universal") fluctuations in the conductivity which are caused by a change in the microscopic realization of the sample upon a change in the magnetic field, a change in the Fermi energy, or the diffusion of an impurity.[1] The presence of magnetic impurities in a sample can fundamentally change the experimental picture of the mesoscopic properties, which has been studied quite thoroughly.[2,3] The spin scattering suppresses the component of the quantum conductivity due to the cooperon and the triplet part of a diffuson over a time scale τ_s and a length scale $L_s = (D\cdot\tau_s)^{1/2}$, but the singlet part of a diffuson "survives."[3] The presence of spin scatterers in a sample thus causes a catastrophic reduction of the magnitude of weak-localization effects,[4] but the dependence of the resistance of a small conductor on its particular realization remains. In an actual experiment, however, the mesoscopic properties of such samples are seen only very weakly, since the fluctuations undergo a self-averaging as time elapses because of the rapid evolution of the localized spins.[3] A spin flip leads to a change in the realization of the scattering potential,[2] while the spin-lattice relaxation time and the Korringa relaxation time τ_r are usually much shorter than the time scale of conductivity measurements.

If a sample with spin scatterers is placed in a magnetic field ($\mu_{imp}H \gg kT$) the spin scattering (and simultaneously the spin relaxation) will be suppressed:[3] $\tau_{s,r} \propto \exp(\mu_{imp}H/kT)$. The usual picture of mesoscopic properties should thus be restored in a strong field. Cooling can also restore the amplitude of mesoscopic fluctuations, as a result of the formation of a spin glass or the Kondo effect.

We have not studied the magnetoresistance of submicron-size n^+-GaAs conductors with magnetic impurities implanted during plasma-chemical etching of the sample. Wafers with an n^+-GaAs layer ≈ 0.15 μm thick and a density $\approx 5\times10^{17}$ cm^{-3} were the starting point for preparing the samples (the depth of the depletion layer was ≈ 500 Å). The inelastic length L_{in} was determined from the weak-localization magnetoresistance and was found to be ≈ 0.15 μm at 4.2 K and 0.3–0.4 μm at 1.3 K.

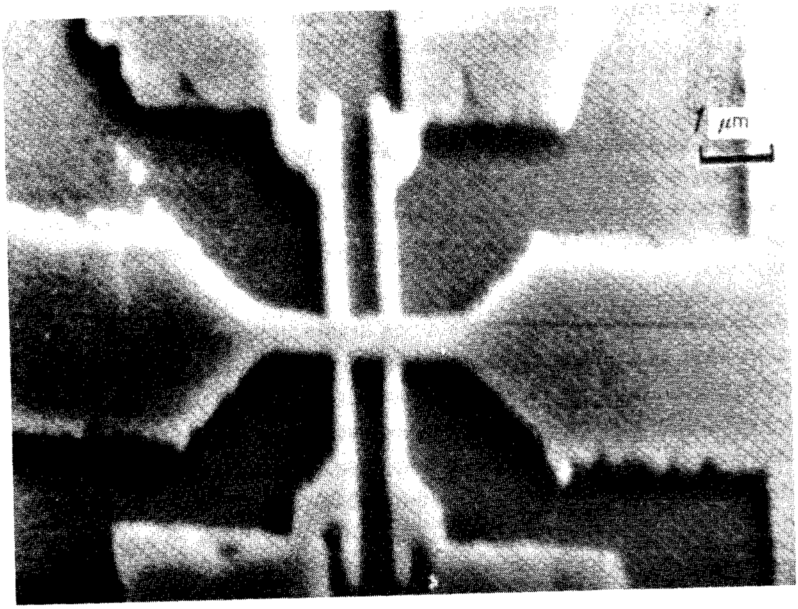

FIG. 1. Electron micrograph of one sample (the potential contacts are separated by ≅0.7 μm).

Electron-beam lithography was used to produce an aluminum mask on the surface of the wafer. The mask was used during the subsequent etching of a mesa structure of the desired configuration in the active layer. The mask also made it possible to use liquid etching ($1H_2O_2$, $1NH_4OH$, $80H_2O$) or a plasma-chemical etching (CCl_2F_2, 20% O_2). Figure 1 shows a photograph of one of the samples.

The samples prepared by liquid etching exhibit a behavior which corresponds well to that expected for samples of the given size [$\approx (0.2–0.4) \times 0.7\ \mu m$]: A negative weak-localization magnetoresistance is observed in weak magnetic fields, and there are mesoscopic oscillations in the conductivity of magnitude $\Delta G \approx e^2/h$. A similar behavior has been reported in many places in the literature (and also for GaAs; Ref. 5), so we will not describe it here.

In contrast, the samples etched in a plasma, with nearly the same geometric dimensions and the same resistance, exhibit an extremely unusual behavior, which is shown in Fig. 2. First, there is almost no magnetoresistance in weak fields, while the magnitude of the negative magnetoresistance for the samples prepared by liquid etching is several times the scale in Fig. 2. Second, the amplitude of the magnetoresistance oscillations is one or two orders of magnitude lower than expected. Finally, it is quite clear from Fig. 2 that the amplitude of the mesoscopic oscillations increases with increasing field. On the one hand, the suppression of the weak localization by itself supports the assertion (apparently unambiguously, since no other mechanism is known[4]) that there are spin scatterers in the samples. On the other hand, the absence of fluctuations in a weak field and their restoration in a strong field correspond to the proposed behavior of the magnetoresistance of a conductor with spin scatterers. We

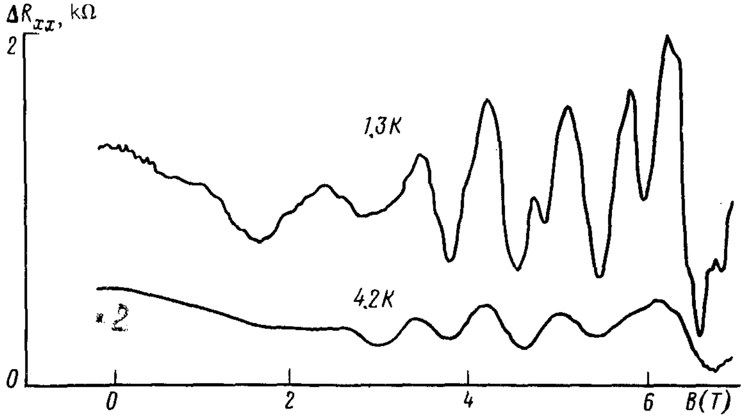

FIG. 2. The magnetoresistance ΔR_{xx} of an n^+ -GaAs sample 0.2 μm wide.

believe that the defects having a free spin are implanted in the sample during the plasma processing through the lateral faces of the mesa structure (their nature and formation mechanism are not important for the purposes of the present study).

The few oscillations on the magnetoresistance curves (Fig. 2) are completely insufficient for a determination of the field dependence of the rms magnitude of the conductivity fluctuations, $\Delta G(B)$. To find this dependence, we used a method consisting of passing current pulses through a sample. These pulses changed the particular realization of the sample through thermal diffusion (or electromigration) of the impu-

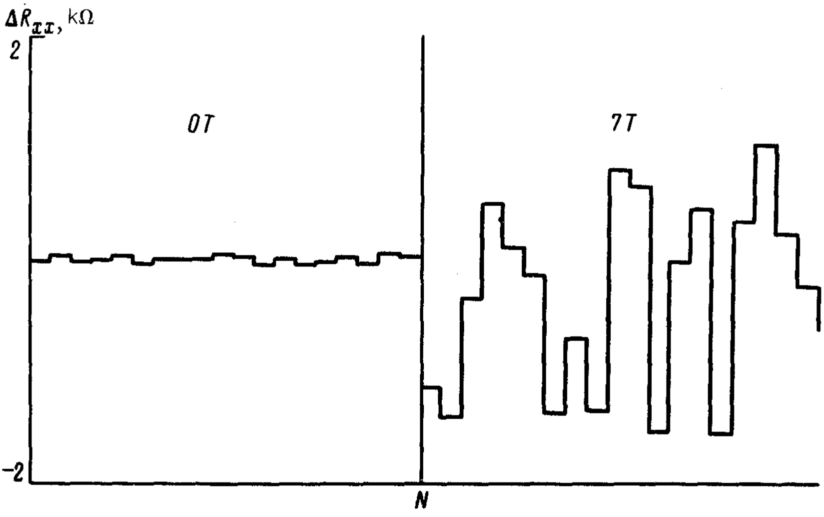

FIG. 3. Resistance fluctuations after the passage of a current of 1 mA (for 15—30 s) through a mesoscopic conductor in a zero field (at the left) and in a field of 7 T (at the right) at $T = 1.3$ K. A horizontal section of the line corresponds to each new value of the resistance.

rity. After the passage of a current of 0.1 mA, we observed a complete change in the positions of the extrema on the magnetoresistance curves. Figure 3 shows some examples of the resistance fluctuations caused by a current flow. In the absence of a magnetic field, the conductivity of the sample remains essentially constant, while in a field of 7 T($\mu_B H/kT \approx 3.5$) there is a significant scatter in the values of the resistance. Figure 4 shows a plot of $\Delta G(B)$. Each point here is an average over 20–30 resistance values. At 1.3 K, the oscillation amplitude increases sharply with the magnetic field; at 4.2 K, this increase is substantially weaker. Curves similar to those in Fig. 4 had been found previously by Washburn and Webb[6] for the amplitude of Aharonov–Bohm oscillations in submicron gold rings with a deposited layer of magnetic impurities (despite the corresponding citation in Ref. 6, the results were not published in full).

For a 2D sample, ΔG is described by[1,3]

$$\Delta G = ce^2/h(L_\varphi/L_x)^{3/2}(L_\varphi/L_y)^{-1/2}, \tag{1}$$

where the coefficient c is ≈ 1, and L_x and L_y are the length and width of the sample. The phase relaxation length L_φ is given by[4] $L_\varphi^{-2} = L_{in}^{-2} + 2L_s^{-2}$; there is a field dependence here through L_s. Assuming the magnetic moment of the impurity to be 1/2, we find—as a result of the change in the filling of the initial and final states in the field—$L_s \approx L_s^0 \cosh(\mu_B H/kT)$. Since there is essentially no negative magnetoresistance in these samples, we took L_s^0 to be equal to the electron mean free path l. The calculated results (Fig. 4) give a good description of the experimental behavior. The agreement could apparently be improved further by taking into account several additional factors (which would complicate the calculations), e.g., the change in the effective dimensionality of the sample upon a change in L_φ and the tendency of ΔG toward zero in weak fields as $L_\varphi \to l$.

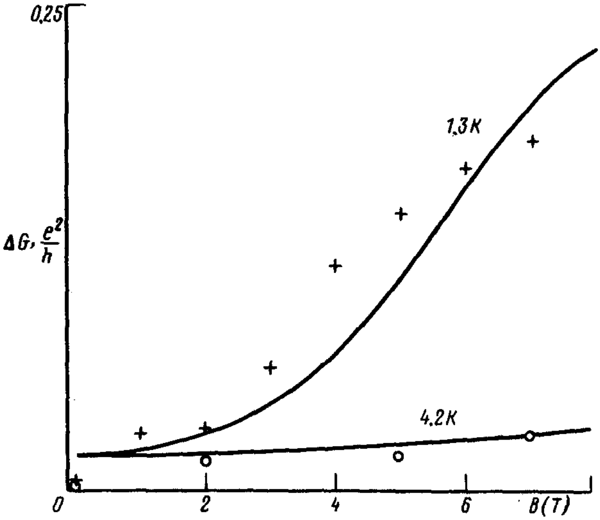

FIG. 4. Size of the conductivity fluctuations versus the magnetic field. +—1.3 K; O—4.2 K. The solid lines are theoretical.

On the curves of the magnetoresistance (Fig. 2) we see oscillations with a correlation field $B_C = 0.07$–0.15 T in a field above 3 T. Although this value corresponds to the known expression $B_c \approx (h/e)/\{L_{in}\min(L_{in},L_y)\}$, we believe that only fluctuations with a value $B_c \approx (h/e)/L_{\varphi}^2$ which varies greatly (as ΔG does) with the magnetic field can be observed, because of the time averaging. We attribute this difference to a nonuniform distribution of the spin scatterers in the sample, such that the interaction of the spins restores the usual picture of the fluctuations in part of the sample even in a relatively weak field. Another possibility is that the magnetic impurities are concentrated at the lateral faces of the mesa structure, so a length scale $\approx (h/e)/L_y^2$ arises.

In summary, we have succeeded in observing characteristic features in the behavior of mesoscopic conductors which are a consequence of the presence of free spins.

We wish to thank V. I. Fal'ko for discussions and for the opportunity to see the results of Ref. 3 before their publication.

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Translated by D. Parsons