Fluctuations in the conductance of mesoscopic bismuth conductors in a magnetic field

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Universal fluctuations of the conductance of semimetallic (bismuth) conductors in a magnetic field were observed for the first time. The fluctuation spectrum was found to exhibit dominant frequencies which are linked to the presence of ordering in the defective structure of the samples.

The conduction-electron interference plays an important role in conductors of small dimensions. Such conductors may be regarded essentially as electronic interferometers and their electrical conductivity may be expressed in terms of the quantum-mechanical transmission coefficient.[1] The transmission coefficient and hence the conductance are highly sensitive to the particular arrangement of the defects and impurities of other scatterers. Displacement of the scattering centers a distance on the order of the electron wavelength changes the conductance and causes it to fluctuate.[2] At low temperatures the mean-square fluctuation of the conductance G is, as was shown in Refs. 3 and 4, common to all samples and, in order of magnitude, is

$$\langle \delta G^2 \rangle \simeq (e^2/\hbar)^2 .$$

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The conductors whose fluctuations in the conduction compared with its average fluctuations cannot be ignored are customarily called mesoscopic conductors and the fluctuations themselves are called common type of fluctuations.

According to the ergodicity hypothesis advanced in Ref. 4, a change in the magnetic field in which a mesoscopic conductor is placed causes the conduction to fluctuate in a manner similar to the fluctuation which occurs as a result of the change of the scattering centers in the structure. The fluctuations in the conduction of mesoscopic metallic conductors (in gold and its alloys) were observed in Ref. 5 and fluctuations in the conduction of semiconductor systems were observed in Ref. 6.

In the present letter we report the observation of the common type of fluctuations in the conduction of semimetallic (bismuth) conductors and we show that the fluctuation spectrum has dominating frequencies which may be linked with the ordering in the imperfect structure of the samples.

We used bismuth strip samples 1–2 microns wide, 10–20 microns long, and 600 Å thick. The geometry of the samples is shown in the inset of Fig. 1. The samples were thermally deposited, and we used photolithography. The Wheatstone bridge, part of which included the sample, constituted the measurement layout. The potential contacts 2–4 were used to measure the difference in the resistances of sections 2–3 and 3–4. The monotonic part of the resistance in this case was largely cancelled. The measurements were carried out in the temperature range 0.02–0.9 K, at a frequency of 31 Hz, in magnetic fields up to 10 kHz perpendicular to the film surface, and a constant-amplitude measuring current $i \simeq 50$ nA. The impedance of the structure, $R = 1/G$, between contacts 2 and 4 was approximately 1.5 kΩ at liquid-helium temperature and it decreased to one-third that value upon raising the temperature to room temperature.

Figure 1 shows the particular cases of the experimental traces. The fluctuations in the magnetoresistance increase in magnitude with decreasing temperature. The shape of the curves can be reproduced with good accuracy. At 0.1 K the fluctuation amplitude is approximately 5×10^{-3}.

The random function $R(H)$ can be described by the autocorrelation function

$$K(\Delta H) = \langle R(H) R(H+\Delta H) \rangle - \langle R(H) \rangle^2 .$$

The value of $K(\Delta H)$ for the mesoscopic fluctuations was calculated in Ref. 7. The fluctuation amplitude depends on the relationship between the linear dimensions of the sample L_i ($i = x, y, z$) and the characteristic lengths $L_T = \sqrt{D\hbar/kT}$ and $L_\epsilon = \min\left\{\sqrt{D\tau_{\text{in}}}, L_x\right\}$, where L_x is the dimension of the sample in the direction of the current, D is the diffusion coefficient of the electrons, and τ_{in} is the time between the inelastic collisions:

$$K(\Delta H = 0) \simeq \left(\frac{e^2}{\hbar}\right)^2 R_0^4 \frac{1}{L_x^3} \begin{cases} L_z L_y L_T, & d = 3(L_T < L_i) \\ L_y L_T^2, & d = 2(L_z < L_T < L_{y,x}). \\ L_\epsilon L_T^2, & d = 1(L_{y,z} < L_T < L_x) \end{cases} \tag{1}$$

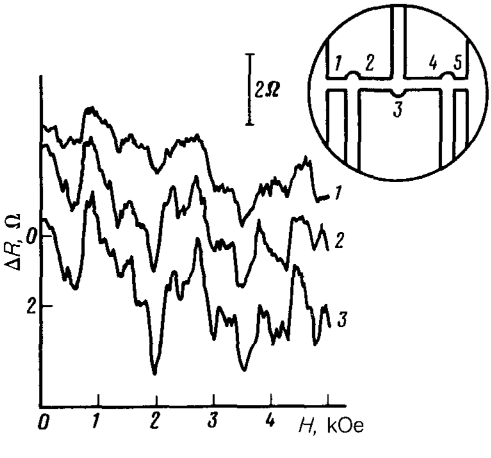

FIG. 1. Fluctuations in the magnetoresistance of bismuth conductors at various temperatures: 1—0.9 K; 2—0.5 K; 3—0.1 K.

The experimental dependence of $K(\Delta H = 0)$ on the temperature is plotted in the inset of Fig. 2.

Under our experimental conditions the diffusion coefficient was $D \simeq 100\ \mathrm{cm}^2/\mathrm{s}$, $L_T(T = 0.1\ \mathrm{K}) \simeq 1\ \mu$, and $L_\epsilon\ (T = 0.1\ \mathrm{K}) \simeq 1\ \mu$ (here we used the results of Ref. 8). According to (1), under our experimental conditions we have a two-dimensional diffusion and $K(\Delta H = 0)$ must change with the temperature according to T^{-1}. The saturation and even a slight decrease in the value of K at temperatures below 0.1 K may be linked, as the estimates based on the results of Ref. 8 show, with the heating of the electron system of the sample by the measuring current. At 0.1–0.9 K we have

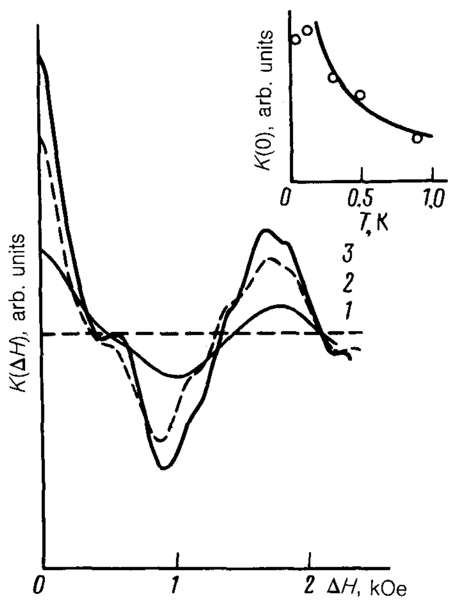

FIG. 2. Autocorrelation fluctuation function for $\Delta H = 0$ versus the temperature. The autocorrelation function $K(\Delta H)$ for various temperatures: 1—0.9 K; 2—0.3 K; 3—0.1 K.

$K(0)L_x^3/R_0^4L_yL_T^2 \simeq (e^2/\hbar)^2$, in good agreement with the predictions of the theory of typical mesoscopic fluctuations.[7]

Figure 2 is a plot of the autocorrelation function $K(\Delta H)$ for $\Delta H = 0$–2.5 kOe at various temperatures. Particularly interesting are the maxima on the curves, whose positions are reproduced at various temperatures and whose amplitudes increase with decreasing temperature. The presence of these maxima suggests that the fluctuation spectrum has dominating characteristic frequencies. We can conclude, therefore, that the sample has clearly identifiable electron-orbit areas.

Studying the samples with a scanning electron microscope, we found that the film has a pronounced defect structure which appears during the thermal deposition of bismuth. The defects can be described as microprotuberances, whose centers can be localized within 0.02 micron. We have calculated the pairing correlation function $P(D)$ which characterizes the distribution D between the various defect pairs. We found that, unlike the case of a completely random distribution, this function is not a constant and that its form corresponds to the short-range order with a characteristic distance between the nearest neighbors, $D_0 = 0.16 \pm 0.02$ μm. Regardless of the nature of the defects and of the mechanism for the interaction of conduction electrons with the defects in the system of electrons that diffuse through the sample, there must be clearly defined trajectories with a characteristic area $S_0 \simeq 0.026$ μm^2. The trajectories should correspond to the oscillation periods $\Delta H = 1600 \pm 400$ Oe with a flux quantum $\phi_0 = hc/e$ and the period $\Delta H'' = 800 \pm 200$ Oe for a "superconducting" quantum (fluxoid) $\phi_0/2$.

The period $\Delta H \simeq 1800$ Oe is the dominant fluctuation period in our case (Fig. 2). The most plausible explanation of these periods is the discrete trajectories which appear as a result of the interaction of the electrons with the defects, whose contribution to the conduction oscillates with the period corresponding to the flux quantum ϕ_0. Why these oscillations do not vanish after the averaging remains a mystery, possibly suggesting that there is a correlation between the contributions to the conductivity of the electron trajectories corresponding to them. This correlation may be the result of the fact that the scale diameters D_0 of the trajectories in the samples under study are much smaller than the length L_ϵ of the electron phase relaxation, while the wavelength λ of the conduction electrons are on the order of D_0 (in our case $L_\epsilon/D_0 \simeq 10$ and $D_0 \simeq \lambda \simeq 0.1$ μm).

The mesoscopic oscillations in ordered systems merit a further study.

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