Observation of the influence of the interelectron interaction on the temperature dependence of the resistivity of deformed bismuth in a magnetic field

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The temperature dependence of the resistivity $\rho(H, T)$ of bismuth placed in a constant magnetic field was measured in the ranges $0.4 < T < 4.2$ K and $0 < H < 33$ kOe at various residual-resistivity values obtained by deforming the sample at 80 K. It is observed that application of a magnetic field to samples whose $\rho(0; 0.4\text{ K})$ was increased by deformation at a value $(1.19–2.94)\times 10^{-4}\Omega$-cm) increases the negative square-root contribution to the temperature dependence of the resistivity (a similar contribution was observed by the author and Sharvin earlier [JETP Lett. **28**, 117 (1978); Sov. Phys. JETP **52**, 977 (1980)] in deformed bismuth at $H = 0$). In classically strong fields, at $\rho(H, T)/\rho(0, T) > 2$, this contribution increases linearly with $\rho(H, 0)$. It is shown that the effect depends little on the mechanism that limits the carrier mobility. A comparison is made with the theory of Al'tshuler and Aronov [JETP Lett. **27**, 682 (1978); Sov. Phys. JETP **50**, 968 (1979)], which predicts the appearance of an analogous contribution as a result of the influence of electron-electron interaction effects.

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INTRODUCTION

The properties of conductors having a small mean free path l are being intensively investigated theoretically and experimentally of late. In the theoretical papers[1-4] they calculated the contribution made to the conductivity by the interaction between the electrons, assuming that l is determined by scattering from static inhomogeneities of the lattice. For three-dimensional systems, this contribution can be represented in the form[2,5]

$$\frac{\delta\sigma}{\sigma} = f(x)\,\frac{2{,}5\,\sqrt{2}(kT)^{1/2}}{6\pi^2\nu(\hbar^3 D_1 D_2 D_3)^{1/2}}, \qquad (1)$$

$$f(x) = 1 - \frac{3}{2x}\ln(1+x), \quad x = \left(\frac{2p_F}{\varkappa}\right)^2,$$

where p_F is the Fermi momentum, $\varkappa = (4\pi e^2\nu/\varepsilon)^{1/2}$ is the reciprocal Debye screening length, ν is the state density on the Fermi level, ε is the dielectric constant, and D_i are the principal values of the diffusion-coefficient tensor. Equation (1) is valid under the condition that the motion of the electrons during the time of the interelectron interaction $\tau_{int} \sim \hbar/kT$ is diffuse, i.e., the inequality

$$L_T \gg l \qquad (2)$$

is satisfied, where $L_T = (D\tau\quad)^{1/2}$ is the diffusion length of the electrons during the time τ .

A temperature variation of the conductivity, close to the square-root dependence (1) predicted by Al'tshuler and Aronov[1,2] was observed, in the absence of a magnetic field, in experiments with bismuth plastically deformed at a temperature below 80 K (Refs. 6 and 7),[1)] with bismuth microjunctions,[6] and with silicon doped with phosphorus.[5] In the experiments with bismuth the square-root dependence was tracked all the way to temperatures at which $l/L_T \approx 0.5$. It should be noted that the temperature dependence of the resistivity was obtained in the theory[1,2] under the most general assumptions with respect to the anisotropy of the electronic spectrum and of the elastic-scattering mechanisms. Expression (1) describes in this case the dependence of $\delta\sigma$ on the electron temperature, and in the case when the electrons are hotter than the lattice the change of the resistivity should correspond to the change of the electron temperature rather than of the lattice temperature. The phenomenon was observed under these conditions in experiments with bismuth microjunctions.[6]

In experiments with doped silicon,[5] quantitative agreement was obtained with the estimates based on Eq. (1). In deformed bismuth, the square-root contribution to $\rho(T)$ agreed well with the estimate in accord with (1) only at the maximum attained value $\rho(0) = 1.9\cdot 10^{-3}\ \Omega\cdot$cm (the comparison is given in Ref. 2), while in the interval $2\cdot 10^{-4} \leq \rho(0) \leq 1.9\cdot 10^{-3}\ \Omega\cdot$cm the result in the low-temperature limit was[7]

$$\rho(T) - \rho(0) = -AT^m\rho(0)^n, \qquad (3)$$

where $m = 0.5 \pm 0.15$, $0.8 < n < 1.1$, $A = 5.7–8\cdot 10^{-3}\ \text{K}^{-m}\ (\Omega\cdot\text{cm})^{1-n}$,

i.e., the effect for bismuth is approximately linear in $\rho(0)$ in the indicated interval, whereas Eq. (1) would call for[2)] $\rho(T) - \rho(0) \sim -T^{1/2}\rho(0)^{5/2}$. Among the conjectural causes of this discrepancy one can point to the change of the electronic spectrum of the metal upon deformation, and the insufficient uniformity of the distribution of the defects over the volume of the sample. It should also be noted that when the function $f(x)$ was introduced in expression (1) no account was taken of the possibility of so strong an anisotropy of the Fermi surface as in bismuth, for which estimates averaged over the Fermi surface yield values $f(x) > 0$, but at the same time the Fermi surface has regions for which $f(x) < 0$ (for data on the electronic spectrum of bismuth see, e.g., Ref. 9).

There was also another difficulty in the interpretation of the results of the experiments on bismuth,[6,7] since it was impossible to state with assurance that they do not contain a contribution due to the localiza-

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tion of the noninteracting electrons. This contribution was determined in the theory[10,11] and is described by the expression

$$\frac{\delta\sigma}{\sigma}=\frac{1}{2\pi^2\nu\hbar(D_1D_2D_3\tau_\varphi)^{1/2}} \quad (4)$$

where τ_φ is the time of loss of phase stability of the electrons. If, e.g., it is assumed that the electron phase stability is lost as a result of damping of the electronic excitations because of electron-electron collisions, and if it is recognized that when condition (2) is satisfied the damping is proportional to the excitation energy raised to the 3/2 power,[12,13] it follows from (4) that

$$\rho(T)-\rho(0)\sim -T^{3/4},$$

which does not differ greatly from the experimental temperature dependence (3). For a more accurate interpretation of the data for bismuth it is of interest to measure the temperature dependence for a sample placed in a sufficiently strong magnetic field, for in this case the localization of the noninteracting electrons is disrupted.[4] An experiment in a transverse magnetic field would also make it possible to verify one more consequence of the theory. It was noted in Ref. 2 that, in analogy with the situation in which the electrons are scattered by static inhomogeneities of the lattice, a decrease of the diffusion coefficient of the electrons upon superposition of classically strong magnetic fields $\Omega\tau \geq 1$ (Ω is the cyclotron frequency and τ is the electron relaxation time) should influence the contribution of the electron-electron interaction effects to the temperature dependence of the resistivity, while expression (1) should retain the same form when account is taken of the dependence of the diffusion coefficient on the magnetic field. An experiment in a magnetic field would offer also the advantage that it would make it possible to vary the diffusion coefficient with the aid of the magnetic field, without changing at the same time significantly the electronic spectrum and the spatial distribution of the defects. In the experiment with the magnetic field, we again used bismuth which has, besides a high effectiveness of electron scattering by lattice defects,[14,15] also a strong magnetoresistance.

EXPERIMENT

In the initial form the samples were bismuth single crystals in the form of rectangular parallelepipeds measuring $0.25\times 0.36\times 16$ mm, grown from the melt by the same method as in Ref. 7. The orientation and the resistance ratio of the initial samples are listed in Table I (the orientation of the crystallographic axes, measured accurate to 5°, is given by the angle θ between the axis and the 16 mm edge and the angle φ between the axis and the 0.25 mm edge). Electric contacts of indium-coated copper wire of 50 μm diameter were welded to the lateral faces of samples 1 and 2, and soldered with indium to the faces of sample 3. The leads on one face were for the current and on the opposite face for the potential.

TABLE I.

Sample No.	$\rho(293K)/\rho(0.4K)$	C_2 Axis		C_3 Axis	
		θ, deg	φ, deg	θ, deg	φ, deg
1	138	7	−83	99	19
2	91	6	−80	98	20
3	162	−10	−87	89	48

In the present study we used the instrument described in Ref. 7 to investigate the temperature dependence of the resistivity of bismuth plastically deformed at low temperature. That part of the instrument section which contained the investigated sample was placed in a superconducting solenoid in such a way that the solenoid axis was perpendicular to the length of the sample (to the 16 mm edge) and parallel to its lateral surfaces on which the electric contacts were fastened. To operate in the frozen-in field regime, the solenoid had a superconducting shunt.[16] The magnetic field intensity was measured with a low-temperature Hall pickup placed in the solenoid cavity. A germanium resistance thermometer was used for the measurements at helium temperatures. The thermal contact between the thermometer and the sample was produced by soldering together one potential lead of the thermometer to a potential lead of the sample. Before measuring the temperature the thermometer was graduated at $H=0$ (see Ref. 7); at $0<H<33$ kOe the error in the estimate of the temperature was less than 0.01 K.

Samples 1 and 3 were deformed by compression along the 0.37 mm edge, while sample 2 was compressed along the 0.25 mm edge, all at 80 K. After removing the stress, we measured the temperature dependence of the resistance at constant H, and the magnetoresistivity $\rho(H)$ at constant T in the ranges 0.4 K $<T<$ 4.2 K, $0<H<33$ kOe. For comparison, similar measurements were made also prior to the deformation.

The samples were not heated to above 80 K prior the end of the measurement run (when the samples were kept at 80 K for several days, ρ did not change noticeably). Just as in Ref. 7, the samples retained their rectangular cross section after deformation. The total change of the transverse dimensions as a result of the deformation was not more than 60%, and $\rho(0.4\text{ K})$ for samples 1, 2, and 3 increased by 184, 143, and 409 times, respectively. After prolonged annealing at room temperature, the residual resistivity of the samples approached the initial value, still exceeding the latter by 5–7 times.

At $\rho>5\cdot 10^{-6}$ $\Omega\cdot$cm the measurements were made with a bridge circuit similar to that described in Ref. 17, which made it possible to measure the changes of ρ with approximate accuracy $(1\cdot 10^{-4})\rho$ (an alternating 900-Hz measurement current 0.01–2 mA was used). At $\rho<5\cdot 10^{-6}$ $\Omega\cdot$cm this circuit could not be used because of the influence of the skin effect, and the measurements were made with an R-363 potentiometer (measurement with 2–10 mA d.c.); the measurement accuracy was somewhat decreased thereby. Direct current was also used to measure $\rho(H)$ of the undeformed samples.

The measured $\rho(H)$ dependence at constant T of the samples prior to the deformation agreed with the known data for pure bismuth (see, e.g., Ref. 18). The de-

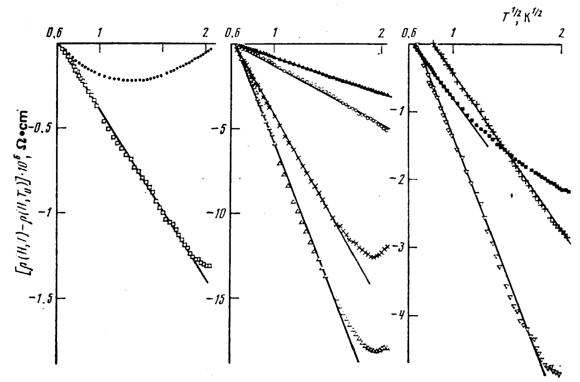

FIG. 1. Dependence of $\rho(H,T)$ on $T^{1/2}$ for sample 2, in $\Omega\cdot$cm: ●—$\rho(0; 0.4\text{K}) = 1.55\cdot10^{-4}$; □—$\rho(1.22\text{kOe}; 0.4\text{ K}) = 2.68\cdot10^{-4}$; ▲—$\rho(3.68\text{ kOe}; 0.4\text{ K}) = 5.24\cdot10^{-4}$; ○—$\rho(9.46\text{ kOe}; 0.4\text{ K}) = 1.15\cdot10^{-3}$; ×—$\rho(27.7\text{ kOe}; 0.4\text{ K}) = 3.25\cdot10^{-3}$; △—$\rho(32.7\text{ kOe}; 0.4\text{ K}) = 3.83\cdot10^{-3}$; for sample 3 in $\Omega\cdot$cm: ■—$\rho(0; 0.4\text{ K}) = 2.94\cdot10^{-4}$; +—$\rho(9.27\text{ kOe}; 0.7\text{ K}) = 7.85\cdot10^{-4}$; ▽—$\rho(25\text{ kOe}; 0.4\text{ K}) = 1.54\cdot10^{-3}$.

formation changed the $\rho(H)$ dependence: the Shubnikov–de Haas oscillations were no longer observed, the resistivity of the sample increased with increasing H in the indicated range by not more than 25 times, and (as follows from this range of increase of ρ with increasing magnetic field[19,20,21]) the $\rho(H)$ plot approached a straight line.

Figure 1 shows the measured temperature dependence of the resistivity of various constant values of H for samples 2 and 3, deformed to such an extent that a negative temperature dependence of the resistivity was observed at $H=0$. The abscissas are graduated in $T^{1/2}$ and the ordinates in $[\rho(H,T)-\rho(H,T_0)]\cdot10^6\ \Omega\cdot$cm, while T_0 stands for the lowest temperature in the measurement run. The data obtained with sample 1 are similar to those shown in Fig. 1 and were used on the summary plot in Fig. 2. It is seen from Fig. 1 that at $H=0$ the experimental points land on a plot linear in $T^{1/2}$ for sample 3, which has a larger residual resistivity, up to $T\approx1.2$ K. This is not observed for sample 2 in the investigated temperature range, but application of a magnetic field increased the fraction of investigated temperature range in which the resistivity had a square-root dependence. The square-root contribution to the temperature dependence of the resistivity increased approximately linearly with increasing $\rho(H,T_0)$ in the region $\rho(H,T)/\rho(0,T)>2$. This is illustrated in Fig. 2, in which the quantity $B=\Delta\rho(H,T)/\Delta(T^{1/2})$, determined from the slopes of the straight

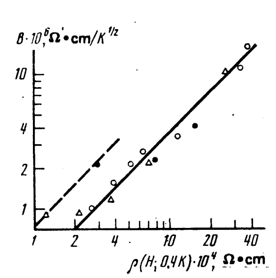

FIG. 2. Dependence of B on the resistivity in a magnetic field: △) sample 1, ○) sample 2, ●) sample 3.

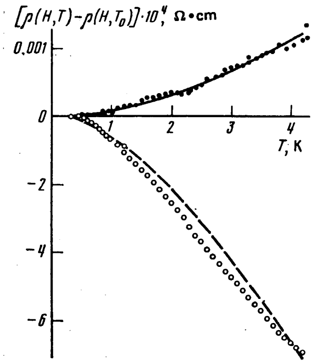

FIG. 3. Dependence of $\rho(H,T)$ on T, measured on sample 3 prior to deformation: ●—$\rho(0; 0.4\text{ K}) = 5.74\cdot10^{-7}\ \Omega\cdot$cm; ○—$\rho(1.68\text{ kOe}; 0.4\text{ K}) = 4.13\cdot10^{-3}\ \Omega\cdot$cm.

lines in Fig. 1 for samples 2 and 3 and obtained in similar fashion for sample 1, is plotted against $\rho(H,T_0)$ (the solid line in the plot corresponds to a linear dependence

$$B=A'\rho(H,T_0),\qquad(5)$$

while the dashed line shows the dependence (3) observed at $H=0$, with $A'=0.5$ A).

Typical temperature dependence of the resistivity at $H\geqslant0$, observed prior to the deformation of the samples, are shown in Fig. 3 for sample 3. The measurements at $H>0$ represented in Fig. 3 were made at values of ρ close to those in Fig. 1 in the magnetic-field region where Shubnikov–de Haas oscillations were not yet observed.

DISCUSSION OF RESULTS

For undeformed samples, the dependence of the resistivity on the temperature at constant H does not obey the square-root law (Fig. 3). It appears that in the investigated temperature range the dominant role in the temperature dependence of the resistivity of undeformed samples at $H>0$ is played by the contribution due to the variation of τ with temperature, since the experimental curves (Fig. 3) are in fair agreement with the values calculated from the formula

$$\rho(H,T)=\rho(0,T)+[\rho(H,0)-\rho(0,0)]\rho(0,0)/\rho(0,T),\qquad(6)$$

which is readily obtained if it is assumed that the resistivity at $H=0$ and the resistivity at $H>0$ are connected by the relation $[\rho(H,T)-\rho(0,T)]/\rho(0,T)\sim\tau^2$ (Ref. 21). To calculate the $\rho(H,T)$ dependence represented in Fig. 3 by the dashed line, we substituted in Eq. (6) the averaged values of $\rho(0,T)$ represented in Fig. 3 by the solid line, as well as the values of $\rho(H,0)$ and $\rho(0,0)$ obtained by extrapolating the experimental relations to $T=0$ K.

The experiments in a magnetic field offer additional proof that the square-root temperature dependence of the resistivity of deformed samples cannot be regarded as a result of variation of τ with temperature. Substituting, e.g., Eq. (3) in (6) we obtain, taking into account the smallness of $A\sqrt{T}$,

$$\rho(H,T)=\rho(H,0)+[\rho(H,0)-2\rho(0,0)]A\sqrt{T}.\qquad(7)$$

It follows from (7) that application of a magnetic field should decrease of the negative square-root contribution to the temperature dependence of the resistivity (at least for sample 3, for which the dependence (3) is already observed at $H=0$ and $T<1.2$ K). However, the converse is obtained in experiment. We note also that such a dependence of the effect in deformed samples on the magnetic field excludes the possibility of attributing it to the Kondo effect.

Observation of the square-root contribution to the temperature dependence of the resistivity in deformed samples, both at $H=0$ and at $H>0$, seems to offer evidence of the presence of electron-electron interaction,[1,2] and application of a perpendicular magnetic field increases the square-root contribution, since the magnetic field decreases the coefficients of diffusion in directions perpendicular to the field. To observe the effect, however, some initial deformation is necessary to decrease the diffusion-coefficient component parallel to H, which depends little on the magnetic field (Ref. 22). Starting from these assumptions, we can obtain the form of the function $B(\rho)$. Bearing in mind that $D_i=\sigma_i/e^2\nu$, and assuming that only D components perpendicular to H depend on the magnetic field, we find from (1) that the contribution to the diagonal conductivity component perpendicular to H does not vary with the magnetic field:

$$\delta\sigma_\perp(0, T)=\delta\sigma_\perp(H, T). \tag{8}$$

Taking (8) into account, as well as the fact that for bismuth at $\Omega\tau>1$, in the case of components perpendicular to H, we can assume the estimate $\sigma_1\approx\sigma_2\approx 1/\rho$ (Ref. 23), and assuming that this calls for satisfaction of the condition $\delta\sigma_\perp(H,T)/\sigma_\perp(H,T)\ll 1$, which ensures applicability of the theory of Refs. 1 and 2, we easily find that B must be proportional to $\rho(H,0)^2$. Yet experiment yields the approximately linear relation (5). It must be emphasized that the linear relation (5) was observed for the given degree of deformation when $\rho(H,T_0)$ was varied using a magnetic field. Thus, in contrast to the method of successively increasing the deformation, which was used in Ref. 7 to obtain the analogous relation (3), the relation (5) was determined at one end and the same spatial distribution of the defects. It is remarkable that a nearly linear dependence of the effect on ρ was observed in both methods of varying ρ. Although we did not investigate directly the degree of homogeneity of the distribution of the defects at low-temperature deformation, the results obtained in a magnetic field allow us to assume that the lowering of the degree of the equation of the effect vs ρ is not due to some significant microscopic inhomogeneities in the defect density. It appears that the assumption that the change of the electric spectrum with changing $\rho(H,0)$ is the cause of the discrepancy with the theory should also be refuted, since the applied magnetic fields were apparently unable to change the spectrum significantly. It can be assumed, as noted in the introduction, that the deviation from the theory is due to the strong anisotropy of the Fermi surface of bismuth. To clarify this question it would be desirable to carry out more detailed theoretical investigations of the influence of the anisotropy on the square-root contribution to the temperature dependence of the resistivity.

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1) There is a misprint in Ref. 6: the ordinate axis of Fig. 2 should be marked not $[R(T)-R(1.3\text{ K})]/R(1.3\text{ K})$ but $\frac{R(T)-R(1.3\text{K})}{R(1.3\text{K})}\cdot 10^3$.

2) Tunnel experiments on films of granulated aluminum[8] have shown that the state-density correction, necessitated by the interelectron interaction has a weaker dependence on $\rho(0)$ than would follow from the theory.[1,2]

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