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Increase of resistance of bismuth deformed at 80 K when the temperature is lowered to the helium region

I. L. Bronevoĭ

Institute of Physics Problems, USSR Academy of Sciences
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The temperature dependence of the resistivity $\rho(T)$ of bismuth is measured in the range $0.4<T<8$K at various values of the residual resistivity obtained by deforming the sample at 80 K (the value of ρ in the helium region increased upon deformation by 300–900 times). With increasing deformation, the $\rho(T)$ plot first becomes steeper and then, at low temperature, $d\rho/dT$ begins to decrease and reverses sign. In the low temperature limit, $\rho(T)-\rho(0)\sim -T^n\rho(0)^m$, where $n=0.5\pm0.15$ and $0.8<m<1.1$. A comparison is made with theory of Al'tshuler and Aronov [Sov. Phys. JETP 50, 968 (1979) and JETP Lett. 27, 662 (1978)], according to which $n=0.5$.

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Sharvin and the author[1] observed an increase of the resistivity $\rho(T)$ when the temperature of a bismuth wire, strongly deformed at 80 K, was lowered to the liquid-helium region. Since the appearance of the anomaly was not due to introduction of magnetic impurities, it can be assumed that it was not caused by the Kondo effect.

The observed effect, as noted by Al'tshuler and Aronov, was of the same order as estimated by their theory (see Ref. 2 and the earlier Ref. 3), which deals with the effect of the interference between the electrons and of their elastic scattering by lattice inhomogeneities According to their theory[2,3] the contribution of this mechanism to the $\rho(T)$ dependence for an isotropic model takes at $kT\ll\hbar/\tau$ the form

$$[\rho(T)-\rho(0)]/\rho(0)=C(T\tau)^{1/2}(p_Fl)^{-2}, \quad (1)$$

where l and τ are the electron mean free path length and time, p_F is the Fermi momentum, and the constant C is negative for a repulsion interaction between the electrons.

By deforming bismuth at low temperatures it is possible to obtain values of $\rho(0)$ large enough to satisfy at helium temperature the condition $kT\ll\hbar/\tau$ (the value obtained in Ref. 1 for a deformed wire was $\rho=1.9\times10^{-3}$ Ω-cm, leading to the estimate $\hbar/k\tau=190$ K; for the data on the electron spectrum of bismuth see, e.g., Ref. 4).

For a more detailed study of the effect and for a comparison of the results with the theory of Refs. 2 and 3, we have measured $\rho(T)$ in a larger temperature interval $0.4<T<8$ at various degrees of plastic deformation.

EXPERIMENT

In the initial form, the samples were bismuth single crystals in the form of rectangular parallelepipeds measuring 0.25×0.37×18 mm, growth from the melt in a dismountable mold of construction similar to that described in Ref. 5. The parts of the mold were made of glass and stainless steel. Prior to the casting the mold was coated with a thin layer of vacuum grease and

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TABLE I.

	Sample number		
	1	2	3
ρ (293 K)/ρ (1.3 K)	77	134	157
C_2 axis	$\theta=71°$, $\varphi=30°$	$\theta=71°$, $\varphi=30°$	$\theta=90°$, $\varphi=-20°$
C_3 axis	$\theta=84°$, $\varphi=-60°$	$\theta=84°$, $\varphi=-60°$	$\theta=0°$

lampblack. The orientation and the resistivity ratios of the initial samples are listed in the table (the orientation of the crystallographic axes is defined, accurate to 5°, by the angle θ between the 18-mm edge and the axis, and by the angle φ between the 0.25 mm edge and the projection of the axis on a plane perpendicular to the 18 mm edge.

A diagram of the apparatus used to investigate the temperature dependence of the resistivity of bismuth plastically deformed at room temperature is shown in Fig. 1. This unit was used in the experiments with sample No. 3. Sample *1* was placed between the horizontal plates *2*, which were separated from the sample by a lavsan film *3* of thickness 10 μm. The upper plate could be moved relative to the lower along vertical guides *4*. A compression force was applied to the plates *2* by rotating, from the outside, the rod *5*, which was threaded on its lower end and passes through the tube *6* (which served simultaneously to pump out the vacuum chamber *7*), through by means of lever *8* and rod *9*. The friction in the screw thread was decreased with graphite powder. A multistrand copper cord *10* soldered to the rod *5* fed the heat transmitted along the rod from the outside into a dewar with He^4, in which the chamber was placed. Other parts of the described straining unit were connected by a similar cord to the housing *11*, which was screwed to the He^3 bath *12*. The design of the straining unit provided for the possibility of placing the samples in a solenoid.

The electric contacts were four indium-dipped copper wires *13* and *11* of 50 μm diameter, each with one end welded to the lateral faces of the sample; the other end of one wire (*13*) was soldered to the housing *11*,

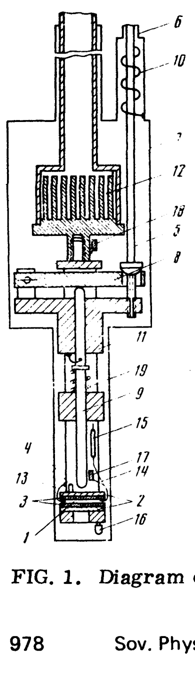

FIG. 1. Diagram of setup.

and the other three were soldered to copper foil strips *15* glued through capacitor paper to the housing. A type-KGG resistance thermometer was screwed into the housing and was used to measure temperatures $T>2.3$ K. The thermometer was calibrated against the temperature of the superconducting transition of lead and against the vapor pressure of He^4. Temperatures below 2.3 K were measured with a germanium resistance thermometer *17* secured to the housing. To improve the thermal contact with the sample, one potential lead of thermometer *17* was soldered at the point with the potential lead of the sample. The thermometer *17* was calibrated at $T>1.25$ K against the vapor pressure of He^4 and at $T<1.25$ against the resistance of a germanium thermometer *18* soldered to the bath with the He^3 (the rod *5* was removed during the calibration). The thermometer *18* was calibrated against the magnetic susceptibility of potassium chrome alum.

Sample No. 3 was deformed in the described apparatus by compression along the 0.37 mm edge at 80 K. After removal of the stress, we measured $\rho(T)$ at $0.4<T<8$ K. The sample was then again deformed at 80 K and $\rho(T)$ was measured.

The experiments with samples 1 and 2 were performed in a simpler unit without an He^3 bath. These samples were also deformed at 80 K, No. 1 along the 0.37 mm edge and No. 2 along the 0.25 mm edge, and $\rho(T)$ was measured at $1.3<T<4.2$ K with the samples located in liquid He^4.

The samples were subjected to 10–15 stages of deformation and were not heated above 80 K until the end of the experiment (ρ did not change noticeably when the samples were stored at 80 K for several days). The total change of the transverse dimensions as a result of the deformation was about 30% for samples 1 and 2 and 64% for sample No. 3, while the $\rho(1.3)$ increased by 301, 369, and 906 times, respectively. The cross section of the deformed samples remained rectangular.

At $\rho>5.6\times10^{-6}$ Ω-cm the measurements were made with a bridge circuit similar to that described in Ref. 6. It made it possible the changes of ρ with accuracy not worse than $1\times10^{-1}\rho$ (measurement current 0.1–2 mA of frequency 900 Hz). At $\rho<5.6\times10^{-6}$ Ω-cm, this circuit could not be used because of the skin effect, and the measurements were made with an R363 potentiometer (dc measurement current 2–20 mA), at a somewhat lower accuracy.

The increase of the residual resistivity was accompanied also by a change of the $\rho(T)$ dependence. Figure 2 shows the measured $\rho(T)$ of sample 3 (experimental points separated by not more than 0.1 K are joined by a solid line). With increasing deformation, the $\rho(T)$ plot becomes steeper (curves 1–4), and then at low temperatures (curves 5–11) the resistivity begins to decrease with increasing temperature, the decrease becoming stronger the larger $\rho(0)$ (it is assumed that the value of $\rho(0)$ can be deduced from $\rho(0.4)$, since the changes of $\rho(T)$ observed after the deformation do not exceed several per cent of $\rho(0.4)$. After annealing at $T\approx293$ K for 30 days, $\rho(0)$ decreased by a factor 15, the minimum of the resistivity shifted towards lower temperatures ($T_{min}=0.5$ K), and $\rho(4.2)-\rho(0.4)$ became 3.6 times larger than for the non-annealed sample with the same value of $\rho(0)$. The values of $d\rho/dT$ for the previously investigated samples 1 and 2, at given values of ρ and T, differed from the values for sample 3 by not more than 30% in the entire range of ρ and T.

DISCUSSION OF RESULTS

The experimentally observed appreciable increase of $\rho(0)$ as a result of deformation can be attributed to the fact that, as shown in Ref. 7, the electrons in bismuth are scattered by dislocations 10^4 times more effectively than in typical metals. It should be noted that in our experiments the defect structure of the samples was not determined, since it changed greatly when heated to room temperature, so that the ordinary experimental methods of investigating this structure could not be used.

Introduction of dislocations, as shown by theoretical calculations,[8] deforms the phonon spectrum of the crystal, and as a result the temperature component of the resistivity $\rho(T)$ acquires the increment observed for a number of metals (Cu, Mo, Zn, Al, and others)[9,10] at $20<T<100$ K. For the low-temperature limit, it is noted in the theory[8] that $\rho(T)$ contains terms with T of not higher than the first power. It is possible that the increase of $d\rho/dT$ with increasing $\rho(0)$, observed by us during the initial stages of the deformation, is connected with the mechanism considered in Ref. 8.

In the region where $d\rho/dT<0$, our data can be compared with the theory of Al'tshuler and Aronov.[2,3] The condition $T \ll \hbar/k\tau$ does not make it possible to determine exactly the temperature below which $\rho(T)$ should vary in accord with (1) (to this end it is also necessary that the other temperature-dependent contributions to

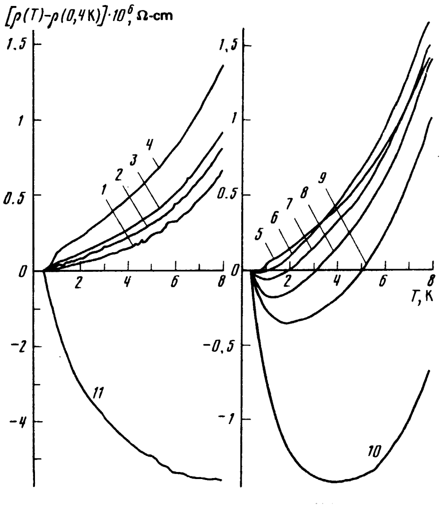

FIG. 2. Measured $\rho(T)$ dependence of sample 3 at different values of $\rho(0)$ in Ω-cm. Curves: 1) $\rho(0.4\text{ K})=6.86\times10^{-7}$, 2) 2.99×10^{-6}, 3) 5.66×10^{-6}, 4) 1.04×10^{-5}, 5) 2.83×10^{-5}, 6) 4.35×10^{-5}, 7) 5.97×10^{-5}, 8) 7.36×10^{-5}, 9) 1.13×10^{-4}, 10) 2.47×10^{-4}, 11) 6.22×10^{-4} (curve 11 is plotted to a smaller scale in ρ).

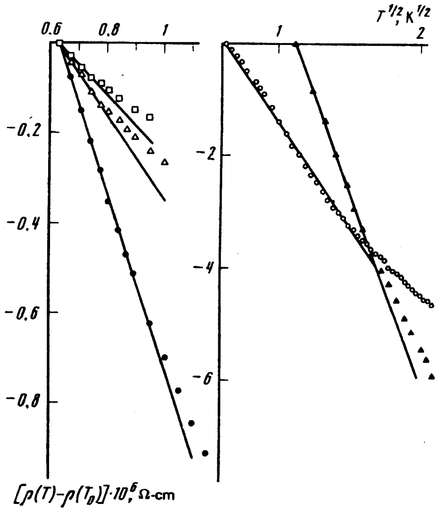

FIG. 3. Dependence of ρ on $T^{1/2}$ for sample 3 in Ω-cm: □) $\rho(0.4\text{ K})=7.36\times10^{-5}$, △) 1.13×10^{-4}, ●) 2.47×10^{-4}, ○) 6.22×10^{-4}, ▲) $\rho(1.3)=1.9\times10^{-3}$.[1]

the resistivity become small compared with (10). Approximating our results by relations of the form

$$\rho(T)-\rho(T_0)=-A(T^n-T_0^n). \qquad (2)$$

where T_0 is the lowest measurement temperature, we obtain, say for curve 11 of Fig. 2 (for which $\rho(0.4)=6.22\times10^{-4}$ Ω-cm and $\hbar k\tau=61$ K), at $T<2.4$ K and $n=0.5\pm0.15$, a mean squared deviation of the experimental points not larger than $1.5\times10^{-4}\rho(0.4)$ (an $n=0.5$, the ratio amounted to $1\times10^{-4}\rho(0.4)$), which is approximately equal to our estimates of the attained measurement accuracy.

Plotting ρ as a function of $T^{1/2}$ at different values of $\rho(0)$ satisfying the condition $\tau<10^{-1}\hbar/kT_0$, we can see that in the low-temperature limit the change of ρ with temperature does not contradict (1) (examples are shown in Fig. 3, and for the lowest value $\rho(0.4)=7.36\times10^{-5}$ Ω-cm shown on the figure we obtain the estimate $\hbar/k\tau=7.27$ K).

The value of A determined from the slopes of the lines in Fig. 3, in relation (2) at $n=0.5$ is shown in Fig. 4 as a function of the residual resistivity (it was determined in similar fashion for samples 1 and 2). We note that the observed approximately linear dependence (the line on the figure corresponds to $A\sim\rho(1.3)^{0.84}$) does not follow directly from formula (1). Assuming

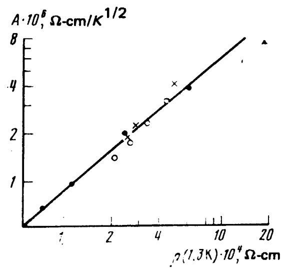

FIG. 4. Dependence of A on the residual resistivity under the assumption that $n=0.5$: ×) sample 1, ○) 2, ●) 3, △) taken from Ref. 1.

that p_F and the Fermi velocity are not changed by the deformation, one could expect $A \sim \rho(0)^{5/2}$. In the case of strongly deformed bismuth there are not enough grounds for these assumptions. On the other hand, the temperature dependence was obtained in Refs. 2 and 3 under the most general assumptions concerning the electronic spectrum and the anisotropy of the scattering. Consequently the observed square-root dependence on the temperature for deformed bismuth can be regarded as a confirmation of the substantial influence of the interference mechanism considered by Al'tshuler and Aronov on the $\rho(T)$ dependence at low temperatures.

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