Resistance of bismuth microcontacts at low temperatures

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A maximum of the differential resistance $(\partial U/\partial J)(U)$ was observed in bismuth microcontacts at $U=0$. With decreasing temperature $(\partial U/\partial J)(0)$ increases like the resistance of strongly deformed bismuth. The shape of the maximum agrees with the notion that the electron gas near the contact is heated to an effective temperature higher than the lattice temperature.

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The microcontacts were prepared by bringing in contact a wire of 100 μm diameter with a bulky sample or with another wire, and welding them with current at liquid

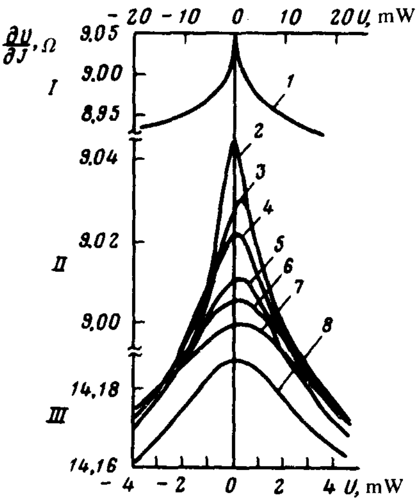

FIG. 1. Plots of $(\partial U/\partial J)(U)$: 1) single-crystal+wire contact, $T=1.34$ K (upper scale for U and scale I for $\partial U/\partial J$), 2–7) the same contact in enlarged scale of U at temperatures 2–1.34 K, 3–1.95 K, 4–2.41 K, 5–2.92 K, 6–3.53 K, 7–4.2 K. 8) contact in a crack produced in the wire at helium temperatures. $T=2.41$ K (III-scale for $\partial U/\partial J$).

nitrogen or liquid helium temperature, at a voltage 100 V and using a 1-MΩ ballast resistor. In the investigation of the current-voltage characteristics $(\partial U/\partial J)(U)$ of contacts between a sample of pure bismuth with $(\rho_{239K}/\rho_{4.2K}) > 200$ and wires of different metals (Cu, W, Bi) a singularity appeared persistently near $U = 0$, and its shape was simplest and symmetrical in the case of pure bismuth wire (Fig. 1, curve 1). The variation of the shape of the peak in the interval $-4 < U < 4$ mV as a function of temperature is shown by curves 2–7 of Fig. 1. Similar curves were obtained in the case of contacts between two crossed bismuth wires, with two ends serving as current leads and the other two as potential leads, as well as in the case of contacts produced by mechanically cracking the wire in liquid helium (curve 8, Fig. 1). Magnetic fields weaker than 4 kOe had practically no effect on the shape of the peak. The effect was not observed in control experiments with Cu–Cu contacts. The measurements were made by a modulation method[1] at a frequency 975 Hz at a modulation amplitude 0.02–0.04 mV.

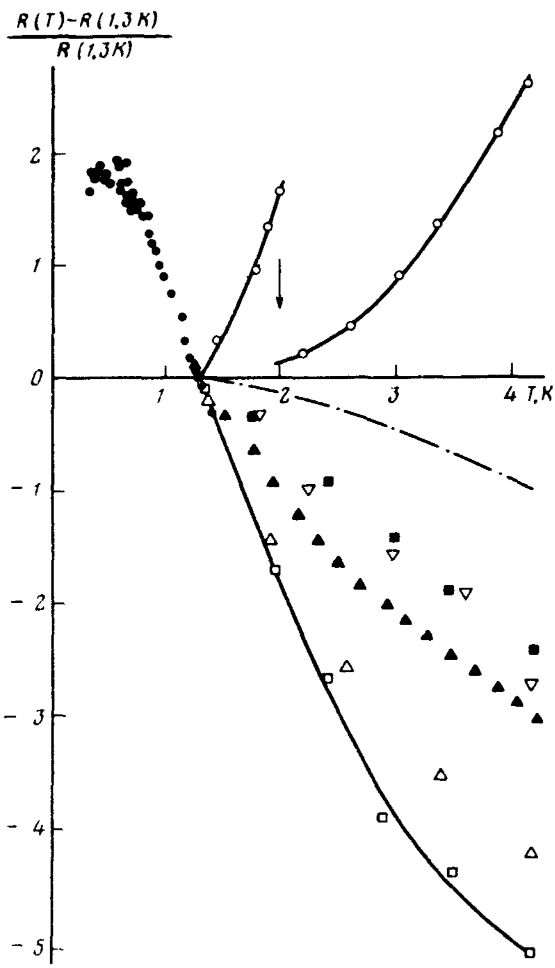

FIG. 2. Plots of $R = (\partial U/\partial J)_{U\to 0}$ against temperature. For the following microcontacts: (□)—single-crystal + wire (curves 2–7 on Fig. 1); (■)—contact inside a crack in the wire (curve 8 on Fig. 1); ◇, ●, Δ—crossed wires with contact resistances 55, 15, and 3.5 Ω, respectively, at 4.2 K. For the following wires: ○—underformed wire. The scale in the right-hand part is decreased by a factor 10; ▲—flattened wire.

The temperature dependence $(\partial U/\partial J)_{U\to 0} = R\ (T)$ is shown for five contacts in Fig. 2. Despite the substantial differences in the values of the resistance, the relative changes do not vary strongly from contact to contact. This suggests that the temperature dependence is connected with special properties of the medium in the region of the contact rather than with its shape or dimensions. The initial wire had $\rho = 3.3\times 10^{-6}\ \Omega$-cm at 4.2 K and the usual $\rho(T)$ dependence shown in Fig. 2. We have performed a number of preliminary experiments aimed at determining the resistance of strongly deformed bismuth. A wire of 100 μm diameter was flattened at helium temperature to a thickness $\sim 50\ \mu$m over a length ~ 1 cm. After removal of the deforming compression, the wire retained its acquired superconducting properties (e.g., $R\,(4.2\ \text{K}) = 4\Omega$ but $R\,(1.3\ \text{K}) = 0.3\ \Omega$). After annealing for several hours at nitrogen temperature the superconductivity seemed to disappear—the resistance at 4.2 K was serveral times larger than prior to annealing, and its temperature dependence became close to the characteristics of the contacts. Figure 2 shows the data for a deformed wire with $\rho = 1.9\times 10^{-3}\ \Omega$-cm. It is possible that the saturation of the growth of the microcontact resistance at 0.5 K, shown in Fig. 2, is evidence of the onset of a superconducting transition, as is also the instability that leads to the scatter of the points at $T < 0.7$ K.

The number of defects in the metal near the microcontact is apparently so large that the electron mean free path l_D is already small compared with the contact diameter d. Under this condition we have $R = \rho/d$.

The decrease of $\partial U/\partial J$ with increasing U can be attributed to heating of the electrons that diffuse in the region of the contact to an effective temperature Θ determined from the temperature dependence on the resistance of the given contact, i.e., from the relation $R\,(\Theta) = (\partial U/\partial J)(U)$.

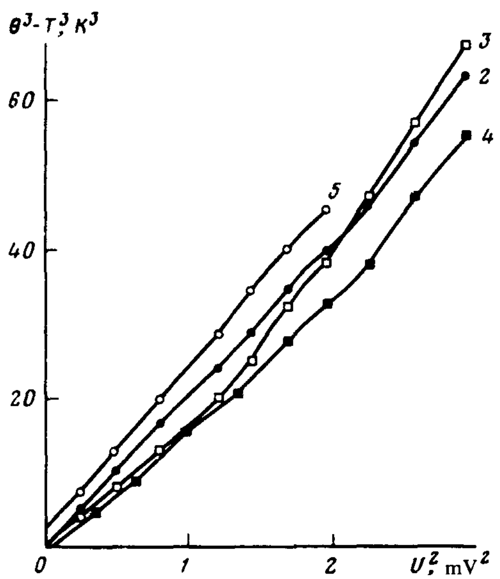

FIG. 3.

On the other hand, the quantity Θ is contained in the equation for the heat transfer from the electron system to the lattice, which is assumed to have the same temperature T as the helium bath. According to[2,3] the density of the power transferred to the bismuth lattice is $w=\alpha(\Theta^3-T^3)$, where $\alpha=7.6$ W/cm^3 K^3. From this we get, in order of magnitude

$$\frac{U^2}{R} \cong d^3\alpha\,(\Theta^3 - T^3).$$

Figure 3 shows the quantity Θ^3-T^3, determined for the curves 2–5 of Fig. 1 with the aid of the lower curve of Fig. 2, as a function of U^2. The use of the second or fourth powers of Θ and T to plot the curve would lead to a large deviation of the curves from a straight line. From the slopes of the curves we can determine, for the given contact, the values $d=10^{-3}$ and $\rho=10^{-2}$ Ω-cm. Assuming for bismuth $\rho l=2.8\times10^{-8}$ Ω cm^2,[4] we get $l_D=3\times10^{-6}$ cm$\ll d$. The diffusing electron negotiates a distance $\sqrt{l_D l_{eph}}$ on the order of d between two electron-phonon collisions (for bismuth we can assume $l_{eph}=1.9\times T^{-2}$ cm).[5] The electron thus gives up its energy to the lattice near the contact, and this justifies the use of the equation of local heat transfer for estimates. The estimate of the thermal conductivity of a lattice with a defect density determined from the value of ρ shows, according to[6], that the lattice temperature near the contact is practically equal to the bath temperature.

It is difficult at present to make definite assumptions concerning the mechanism that governs the observed increase of resistance with decreasing temperature. The change of the carrier density as a function of temperature, calculated according to[7], results in a much smaller effect (dash-dot curve on Fig. 2).

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