Observation of "hot" electrons with the aid of microcontacts

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Overheating of the electron gas relative to the crystal lattice was observed experimentally upon injection of carriers into bismuth through microcontacts. The electron temperature was determined by measuring the amplitude of the quantum oscillations of the microcontact resistance. The experimental results agree with a calculation carried out with the aid of the heat-balance condition for electrons that absorb the electric-field energy in the sample and release this energy to the lattice via phonon emission.

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We have observed over heating of the carrier system relative to the crystal lattice upon injection of electrons into bismuth through microcontacts. The presence of the overheating was revealed by the decrease of the amplitude of the Shubnikov–de Haas oscillations for the microcontact resistance.

The experiments were performed with a pure bismuth single crystal in the form of a right parallelepiped measuring 2×2×3 mm. The trigonal and binary axes C_3 and C_2 of the crystal were perpendicular to the rectangular faces of the parallelepiped. One microcontact each was placed on the faces perpendicular to the C_3 axis, so that the line joining the contacts was in the C_2C_3 plane and made an angle ≈ 15° with the C_3 axis. The microcontacts were made of copper wire of 20 μ diameter, welded to the sample by electric discharge. Far from the microcontacts, a current lead of 0.1 mm diameter was soldered to the sample. The dc voltage on the microcontacts was measured with an F-116 millivoltmeter and was plotted with an automatic x-y recorder as a function of the magnetic field **H**. The vector **H** could be rotated in the C_2C_3 plane through any angle ϕ relative to the line joining the microcontacts. The position $\phi = 0$ was set against the minimum voltage U between the contacts at $H = 20$ kOe.

The voltage U depended on the magnitude and direction of the magnetic field. At $H = 0$ the resistance was $R_0 = U/I \approx 1\ \Omega$, and increased by ≈ 10% at $H \approx 20$ kOe and $\phi = 0$. At $\phi \gtrsim 30'$, the function $U(H)$ was determined by the transverse magnetoresistance of the sample, while the quantity $R_H = [U(H) - U(0)]/I$ reached 5 Ω at $\phi \gtrsim 5°$ and $H \approx 20$ kOe. Figure 1 shows the magnetic-field-dependent part of the voltage between the microcontacts at the small $\phi = 16'$. At larger angles ϕ, the monotonic part of R_H was proportional to H^2.

The observed oscillations of the voltage U are obviously of the Shubnikov—de Haas type. By varying the orientation of **H** relative to the C_3 axis it was possible to observe oscillations corresponding to different parts of the Fermi surface. The oscillations observed near $\phi = 0$, similar to those shown in Fig. 1, are due to the central sections of the hole ellipsoid elongated along the C_3 axis. The period of the oscillations in the reciprocal field, its anisotropy, and the magnitude of the effective mass m^* estimated from the temperature dependence of the oscillation amplitudes all agree with the known data.[1]

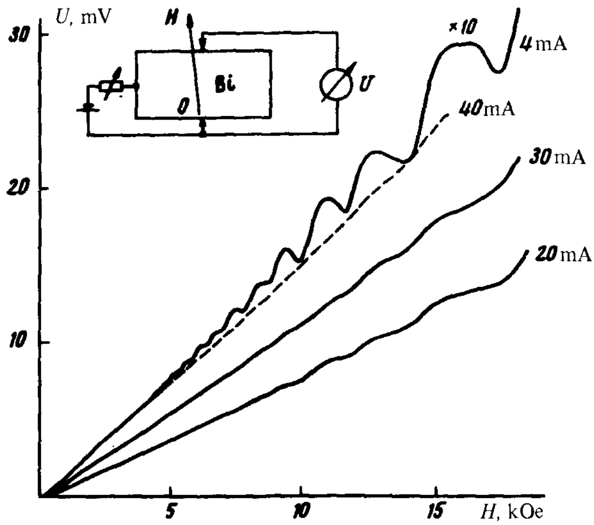

FIG. 1. Plots of $U(H)$ at different values of the measuring current I. To plot the curve at $I = 4$ mA, the sensitivity of the setup was increased tenfold. The dashed line is part of the plot at $I = 40$ mA, and does not agree with the curve at 4 mA. The sample temperature is $T = 1.5$ °K. The angle ϕ equals 16′.

At measurement currents $I \lesssim 1$ mA, the amplitude of the resistance oscillations, within the limits of the measurement accuracy, does not depend on the value of the current. For currents $I > 5$ mA, the oscillating term of the resistance, as seen from Fig. 1, decreases noticeably. The decrease of the amplitude of the quantum oscillations can be attributed to overheating of the electrons that absorb the energy of the electric field.

Assume that various scattering processes establish in the electronic system a certain momentum distribution that is close to an equilibrium Fermi distribution with temperature T^*, but shifted in momentum space in accordance with the carrier drift in the electric and magnetic fields. This assumption allows us to calculate the power density w transferred from the electron system to a lattice of temperature $T < T^*$ on account of acoustic-phonon emission. Using the calculation method of[2] as applied to the case of bismuth at helium temperatures, we obtain

$$w = a(T^{*3} - T^3). \quad (1)$$

The coefficient α is determined by the dimensions of the Fermi surface, by the value of the carrier effective mass, and by the frequency of the collisions of the carriers with the phonons. According to the data of [1,3,4] we obtain $\alpha = 7.6 \times 10^7$ erg/cm^3 K^3 sec. We separate in the sample a microcontact channel of length $L = 2$ mm and diameter 10^{-2} mm, in which the distance r to the line passing through the contact parallel to H (the line OH in Fig. 1) satisfies the condition $r \leq d/2$. The electrons in the interior of the channel absorb a power $Q \approx I^2 R_0$ and transfer it to the lattice. The heat-balance condition written with the aid of (1) yields $T^* \approx 7$ °K at $I = 30$ mA. At $r \approx d$, on the basis of the measured value

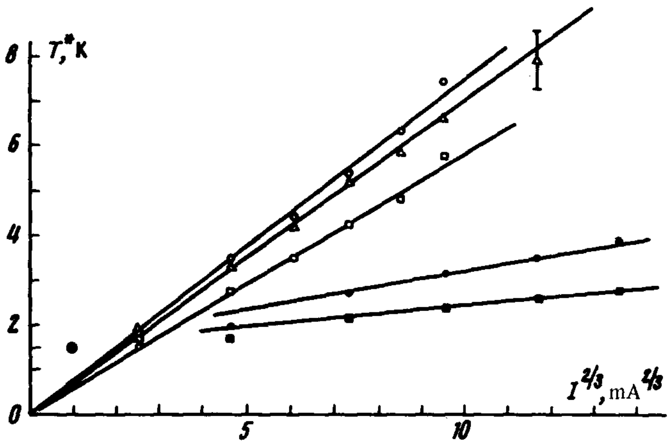

FIG. 2. The quantity T^* corresponding to the measured ratio of the oscillation amplitudes $A(I)/A(1\text{ mA})$. At $I = 1$ mA it is assumed that the oscillation amplitude is determined by the lattice temperature $T = 1.5$ °K. The different symbols correspond to different values of the magnetic field: circles—$H = 17.4$ kOe, triangles—$H = 14$ kOe, squares—$H = 10$ kOe. The light symbols correspond to measurements of the voltage between the microcontacts at $\phi = 16'$. The filled symbols correspond to measurements of the voltage between one of the contacts and a peripheral point of the sample at $\phi = 0$.

of $R_H(\phi)$, we can obtain the estimate $T^* = 6$ °K at $I = 30$ mA and $H = 17.4$ kOe. At $d/2 < r \ll L$, the equipotential surfaces in the interior of the sample are, at $H \gtrsim 10$ kOe, coaxial cylinders with axis OH, the monotonic part of the voltage is given by the relation $[U(\phi) - U(0)] \sim \ln\phi$, $w \sim r^{-2}$, and the temperature of the electron gas approaches rapidly the lattice temperature as the distance from the hot channel of the microjunction increases.

The experimental value of T^* for a certain current I was determined from the ratio of the amplitudes of the resistance oscillations $A(I)/A(1\text{ mA})$ in accordance with the Lifshitz—Kosevich formula at a known value of m^*.[5] The results of the measurement of the temperature of the electrons in the hot channel of the microjunction is shown in Fig. 2. It is seen that formula (1) describes correctly the experimental results. Measurements of T^* at $I = 10$ mA and at a lattice temperature rising to 4.2 °K also agree, within the limits of errors, with the calculations. At higher values of ϕ, the measured value of T^* is the result of a complicated averaging over the region of the sample between the contacts. Data on the dependence of the relative oscillation amplitude on the angle ϕ are shown in Fig. 3. It is seen that at $H = 17.4$ kOe, in accord with the calculation, the

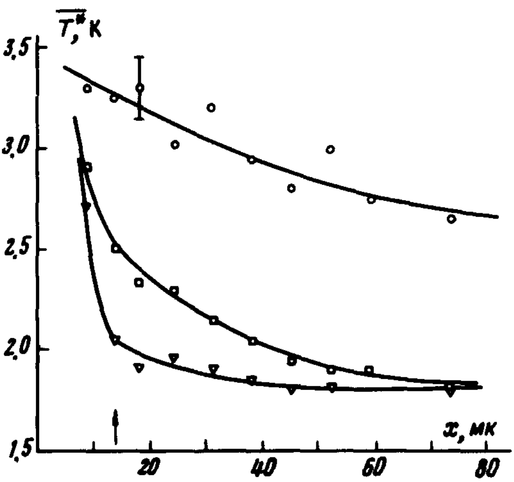

FIG. 3. Data on the dependence of $A(10\text{ mA})/A(1\text{ mA})$ on the rotation angle ϕ, represented in the form of the function $T^*(x)$, where $x = L\phi$. The arrow marks the value $x = d$. Different symbols correspond to different values of H as in Fig. 2. (The new symbol ∇ stands for $H = 7.8$ kOe), $T = 1.5$ °K.

quantity T^* changes insignificantly when the boundary of the hot channel is crossed. To the contrary, in weaker fields the temperature decreases at $r > d/2$. According to formula (1), $T^* \approx 2$ °K at $H = 7.8$ kOe, $r \approx d$, and $I = 10$ mA; this agrees with the measurement results. If we measure the voltage between one microcontact and a peripheral point of the sample, then the observed oscillations are determined by averaging over the entire volume of the sample, and the effect of overheating of the electron gas is much weaker. In addition, as is clear from Fig. 2, the relation $T^{*3} \sim I^2$ is no longer directly applicable.

We estimate now the overheating of the lattice as a result of absorption of power from the electron system. The power released in the microcontact channel, $Q = 10^{-3}$ W, produces a temperature drop $\Delta T \approx 10^{-3}$ °K between the OH axis and a remote point of the sample. We used for this estimate the data of[6] on the bismuth thermal-conductivity coefficient $\kappa \approx 5$ W/cm °K. We note that the phonon mean free path here is $l \gtrsim 1$ mm. The temperature drop on the boundary between the bismuth and the liquid helium, according to the data of[7], at $T = 1.5$ °K and $Q = 10^{-3}$W, amounts to $\Delta T_b \lesssim 10^{-2}$ °K for our sample. The presented estimates show that the observed decrease of the oscillation amplitude is connected not with the heating of the lattice, but with the overheating of the electron system.

We note in conclusion that we have measured the temperature of only one group of carriers. However, numerical estimates show that the total number of carriers in the channel of the microcontact, and the number of electrons injected from the contact during the characteristic cooling time of the carrier system $t_0 \approx 10^{-7}$ sec, are comparable in order of magnitude. Thus, all the carriers in the microcontact channel are "hot."

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[1]L. A. Fal'kovskiĭ, Usp. Fiz. Nauk **94**, 3 (1968) [Sov. Phys. Usp. **11**, 1 (1968)].
[2]M. I. Kaganov, I. M. Lifshitz, and L. V. Tanatarov, Zh. Eksp. Teor. Fiz. **31**, 232 (1956) [Sov. Phys.-JETP **4**, 173 (1957)].
[3]V. F. Gantmakher, Rep. Prog. Phys. **37**, 317 (1974).
[4]A. M. Friedman, Phys. Rev. **159**, 553 (1967).
[5]I. M. Lifshitz, M. Ya. Azbel', and M. I. Kaganov, Élektronnaya teoriya metallov (Electron Theory of Metals), Moscow, 1971.
[6]V. N. Kopylov and L. P. Mezhov-Deglin, Fiz. Tverd. Tela **15**, 13 (1973) [Sov. Phys. Solid State **15**, 8 (1973)].
[7]J. D. Cheeke, B. Hebral, J. Richard, and R. Turkington, Phys. Lett. **46A**, 81 (1973).