Ballistic temperature point-contact spectroscopy in copper at 0.7 K

M. Reiffers, K. Flachbart, and Š. Jánoš
Ustav Experimentalnej Fyziky, Slovenska Akademia Vied, Kosice, Czechoslovakia

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An asymmetry has been observed in the heating of the bulk metal banks of a point contact. This asymmetry results from a relaxation of ballistic electrons. Nonlinear structural features are seen on the voltage dependence of the bank temperature. These features are associated with N and U scattering of ballistic electrons.

Point-contact spectroscopy is used for directly studying the energy dependence of the electron-quasiparticle interaction in metal contacts of small dimensions d (Ref. 1). If d is small in comparison with the mean free path (elastic or inelastic) of the electrons, the electrons pass ballistically through the point-contact region, after acquiring a certain amount of energy from the voltage applied to the point contact. After the transit, the electrons lose their excess energy through scattering and through the production of nonequilibrium quasiparticles (e.g., phonons) near the contact. These processes can be studied by measuring the second derivative of the current-voltage characteristic, i.e., the point-contact spectrum. Bogachek *et al.*[2] have predicted that structural features in the phonon state density should be manifested on the plot of the second derivative of the heat flux with respect to the voltage in a study of the Peltier effect at a point contact.

In the present letter we report a study of a manifestation of this effect in the temperature of the banks.

Polycrystalline copper point contacts were fabricated by the displacement technique[1] and cooled to 0.7 K under the assumption that the heat evolution at the contact could be ignored. The experimental arrangement is shown in Fig. 1. We studied jointly the second derivatives of the I–V characteristic and the temperatures of both bulk electrodes as functions of the voltage. The time over which the voltage was swept from

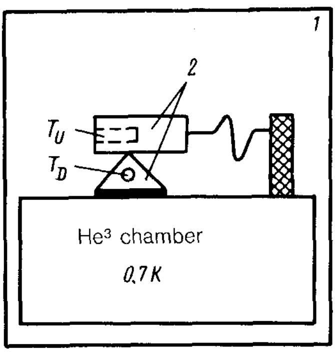

FIG. 1. The experimental arrangement. 1—Vacuum chamber; 2—copper electrodes; T_D, T_U—thermometers.

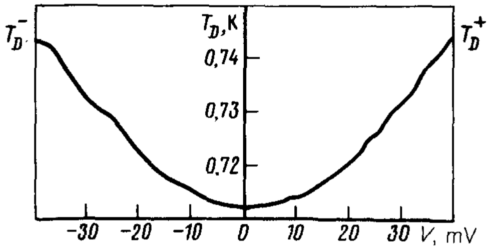

FIG. 2. The bank temperature T_D versus the voltage for two polarities of V.

0 to ω_D (the Debye energy of the phonons) was chosen to allow the thermometer to accurately keep up with the changes in the contact temperature. The resolution in the measurement of the point-contact spectrum was $\delta \sim 0.4$ meV. The error in the determination of the gradient of the point-contact temperature was 0.1 mK.

Figure 3a shows a point-contact spectrum which corresponds to approximately ballistic conditions. In the clean-aperture model,[1] the point-contact constant of the electron-phonon interaction is $\lambda_{PC} = 0.1$. The other parameters of the point contact are given in the caption of Fig. 3a. Figure 2 shows the bank temperature T_D of this contact versus the voltage V for both polarities. It can be seen from these curves that nonlinearities associated with the emission of nonequilibrium T- and L-phonons by ballistic electrons arise at the characteristic phonon energies. This figure also shows that the curve of $T_D(V)$ is asymmetric with respect to $V = 0$ mV. This asymmetry in the heating of the bulk banks of the point contact as a function of the voltage is itself evidence of a ballistic motion of the electrons through the point-contact region, since the place where they relax depends on the polarity of the voltage. Figure 3b shows a plot of $\Delta T_D(V) = T_D^+(V) - T_D^-(V)$, which makes the asymmetry of the heating more striking. We should point out that for the positive polarity of V a current of

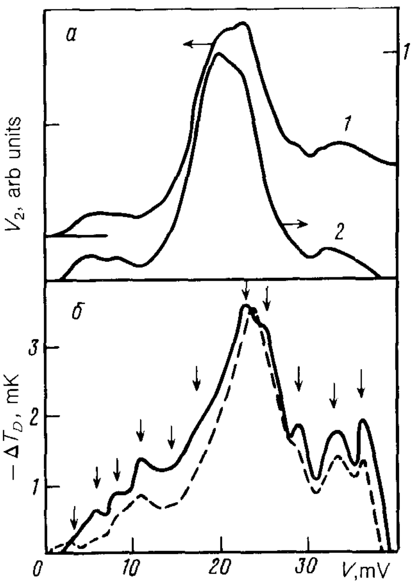

FIG. 3. a: Point-contact spectrum of the electron-phonon interaction in copper. 1—$V_2(V)$; 2—G_{PC}(eV); ($R_0 = 0.84$ Ω, $T = 0.72$ K, $\delta = 0.42$ meV, $\lambda_{PC} = 0.1$). b: The temperature asymmetry ΔT_D versus the voltage V.

electrons flows out of the electrode with the temperature T_D into the other electrode, in agreement with the negative value found experimentally for $\Delta T_D(V)$. The asymmetry of the temperature measured by the thermometer at the upper electrode, $\Delta T_U(V)$, has positive values. The structural features in the asymmetry are less obvious because of the poorer heat removal from this electrode and thus the greater heating of the electrode. If we subtract from the curve of $T_D^-(V)$ in the case of the negative polarity of V the component due to Joule heating, proportional to V^2/R_0, we find the curve shown by the dashed line in Fig. 3b, which is similar to $-\Delta T_D(V)$.

Figure 3b shows that in addition to the peaks at the characteristic energies of the T- and L-phonons, there are structural features here at other energies (marked by the arrows). These features are apparently due to different mechanisms for the scattering of ballistic electrons, which come into play at these energies. The positions of the features observed correlate well with the positions of the maxima and minima on the noisy point-contact spectra of copper.[3,4] Working from this comparison, we can explain the anomalies in the behavior of ΔT_D in the following way: The peaks at the energies ~23.5 and ~33 meV are due to a stimulated emission of T- and L-phonons. The different intensities of the peaks (the T-phonon peak is more intense than the L-phonon peak) are evidence that the ballistic electrons interact more strongly with the T-phonons than with the L-phonons, as is well known from the point-contact spectroscopy of copper.[1] The peak at ~11 meV is probably due to the thresdhold energy for U processes in copper. The other structural features, whose positions correlate with the positions of maxima in the noisy point-contact spectra, are due to U processes of electron scattering by phonons; the other features, whose positions correlate with the positions of the minima, are due to N scattering processes. The peak at ~36 meV seems to correspond to multiphonon processes of scattering of ballistic electrons by phonons.

In conclusion, we can assert that ballistic temperature point-contact spectroscopy, i.e., a study of the asymmetry of the temperatures of the banks of a point contact during a ballistic crossing of the contact by electrons, is another new tool for obtaining further information on the subtleties of the energy dependence of the electron-phonon interaction, for observing various types of electron scattering, and for generating nonequilibrium phonons with a particular energy. The results which we have observed, obtained for the first time in a metal by this new technique, simultaneously confirm the results of noisy point-contact spectroscopy.[3,4]

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