Microcontact anisotropy spectroscopy of electron-phonon interactions in metals

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We measured the dependences of the second derivative of the current-voltage characteristics on the voltage for point contacts of single crystals of Cu and Zn with various orientations. The observed anisotropy of the microcontact spectra agrees qualitatively with the anisotropy of the phonon spectra of these metals.

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In contrast to tunnel spectroscopy, microcontact spectroscopy is based on the study of small nonlinearities of the current-voltage characteristics of a contact between two metals connected by a conducting bridge of microscopic dimensions ($\lesssim 100$ Å).[1]

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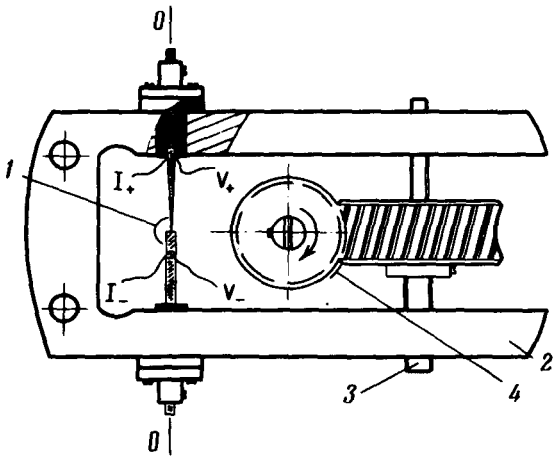

FIG. 1. Construction of adjustable point contact: 1–single-crystal electrodes with identical orientation along the axis 00, 2–brace, 3–differential screw, 4–worm gear.

The theory of this effect[2,3] predicts the possibility of investigating the anisotropy of the electron-phonon interaction (EPI) if the electrodes are chosen to be sufficiently pure single crystals. It was shown in[4] that the observation of microcontact (MC) spectra is possible also in the case of a point contact between two bulky metals. We report here observation of the MC spectra of EPI using Cu and Zn with various orientations. The observed anisotropy of the EPI functions $G(\omega)=\tilde{\alpha}^2(\omega)F(\omega)$[1)] agrees qualitatively with the anisotropy of the phonon spectra of these metals.

Two identical single crystals with dimensions $10\times2\times2$ mm were used to prepare by electrolytic etching and polishing the electrodes of the point contact, namely a needle with a tip angle 22–53° and curvature radius[2)] 50 μm, and an "anvil" having a flat face (position 1 in Fig. 1). The electrodes were brought in contact in liquid helium with the aid of a brace 2 with a differential screw 3 regulated from the outside of the cryostat through a worm gear 4. The resistance of the stable contacts was varied in controlled fashion in a range from several tenths to several dozen ohms. The investigated crystallographic orientation coincides with the sample axis. The measurement of the current-voltage characteristics and of their derivatives was carried out by a four-contact method using a standard tunnel spectrometer.

Figure 2 shows plots of the second harmonic of the modulating voltage V_2, which are proportional to the second derivative of the current-voltage characteristic, against the dc component of the voltage across the contact for the Cu in the three principal orientations. According to[2,3], these dependences are proportional to the microcontact EPI spectra–$G(eV)$. The MC spectra of single crystals are, in the main, similar to the MC spectra obtained earlier with polycrystalline copper film contacts,[5] and differ from the latter in that the background level is much lower at high voltages.

As expected, the changes of the MC of the EPI spectra at different orientations of the high-symmetry metal Cu are small, and their intensities are approximately equal. Nonetheless, in view of the rather high reproducibility of the results,[3)] it is possible to register reliably small shifts of the maxima at $eV^{(1)}\approx16$ meV and $eV^{(2)}=29$–31 meV, due to the anisotropy of the phonon spectrum (see Table I).

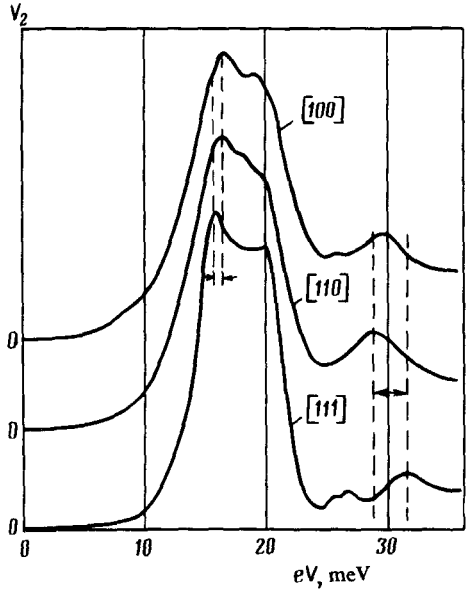

FIG. 2. Microcontact spectra of copper for different crystallographic orientations. The temperature, resistance of the contacts, and the amplitude of the modulation are respectively: [100]–1.5K, 6.25 Ω, 0.7 mV; [110]–4.2 K, 10.5 Ω, 0.56 mV; [111]–1.5 K, 1.0 Ω, 0.7 mV.

Since the electrons in the contact region are scattered most effectively by phonons having the maximal wave vectors and propagating opposite to the current, it follows that the positions of the singularities on the MC spectra should be compared with the phonon energies near the boundary of the Brillouin zone in the given direction. For these phonons usually $\partial\omega/\partial q \cong 0$ and the state density is maximal. These considerations explain the following correlations between the phonon and the MC spectra in identical directions: The maxima of the state densities of transverse acoustic (TA) phonons in the directions [110] and [100] approximately coincide and are located at higher energies than in the [111] direction. On the other hand, the LA maximum in the [111] direction is shifted towards higher energies, and the corresponding maximum in the [110] direction is located at the lowest energies. The corresponding shifts of the

TABLE I. Position of the maxima $V^{(1)}$ and $V^{(2)}$ on the microcontact spectra, and phonon energies corresponding to the singularities $\partial\omega/\partial q=0$ on the dispersion curves for copper.

Orientation	Microcontact spectra		Position of singularities on the dispersion curves for the phonons (from the data of [8])	
	$V^{(1)}$, meV	$V^{(2)}$, meV	TA, meV	LA, meV
[111]	15.7 ± 0.1	31 ± 0.4	14.1 ± 0.4	30.2 ± 0.8
[110]	16.2 ± 0.1	28.8 ± 0.2	21.2 ± 0.6 30.0 ± 0.8	26.5 ± 0.6
[100]	16.4 ± 0.1	29.8 ± 0.2	21.2 ± 0.6	30.0 ± 0.8

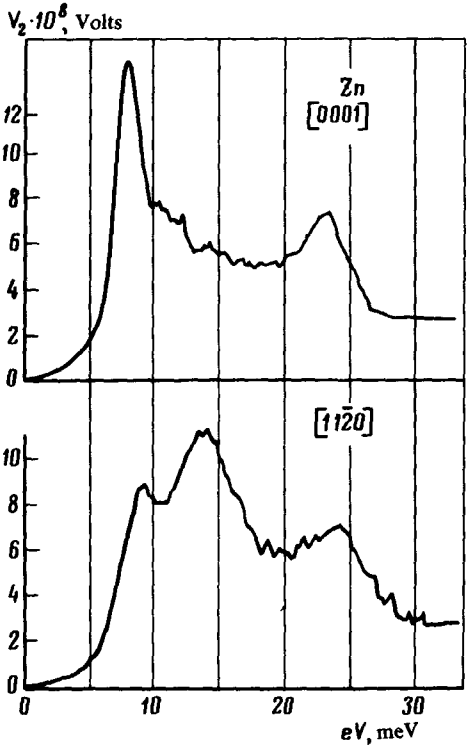

FIG. 3. Microcontact spectra of zinc for two mutually perpendicular orientations, $T = 1.5$ K. The contact resistance and the modulation amplitude are respectively [0001]–9.7 Ω, 0.42 mV; [11$\bar{2}$0]–9.8 Ω, 0.7 mV.

maxima $V^{(1)}$ and $V^{(2)}$ were observed also in the MC spectra obtained in different directions (Table I). It follows therefore that some disparity between the positions of the LA maxima on the MC and on the phonon spectra, noted in[4] for silver and in[5] for film contacts of copper, is apparently due to the texture of the metal in the region of the contact.

The additional maximum at $eV \cong 26$ meV is observed in the MC spectra of Cu in the [111] direction and less frequently along [100] (Fig. 2). It can be attributed to the maximum of the state density of the phonons in the [110] direction. The disparity between these directions is not surprising, since a direct comparison of the MC spectrum with the singularities of the dispersion curves for phonons in this direction is only quite rough. A more accurate comparison of experiment with theory is possible only as a result of a rather numerical calculation on the basis of the formulas obtained in[2,3].

The angular dependence of the MC spectra of the EPI can be best revealed by using strongly anistropic metals as an example. Figure 3 shows the characteristics $V_2(eV)$ of a point contact with two mutually perpendicular orientations. The MC spectrum plotted along the c axis contain an intense high-frequency peak at $eV \approx 8$ meV, which was observed also for polycrystalline film samples in[6]. In the central part of the spectrum, the value of the effective EPI function is relatively small. The spectrum obtained in the basal plane, to the contrary, has the highest intensity in the central region, whereas the intensity of the low-frequency peak is substantially de-

creased. The maxima of both spectra at high energies correspond to the maxima of the state density of the optical phonons.

The anisotropic EPI functions $g_{\mathbf{k}}(\omega)=\alpha^2_{\mathbf{k}}(\omega)F_{\mathbf{k}}(\omega)$ were calculated for Zn in[7]. Despite the fact that these functions from the EPI transport functions $G(\omega)$ measured in MC spectroscopy, one can expect their anisotropies to agree qualitatively. In fact, the above mentioned singularities of the MC spectra of Zn, taken in mutually perpendicular directions, coincide with the predicted anisotropy of the vector functions $g_{\mathbf{k}}(\omega)$.

Thus, the comparison of the microcontact spectra with the known phonon spectra or with the isotropic functions of the electron-phonon interaction allows us to conclude that the anisotropy of the microcontact spectra indeed reflects the anisotropy of the electron-phonon interaction in metals.

[1)]For a definition of the EPI function $G(\omega)$ see Refs. 2 and 3.

[2)]The effective diameter of the contact is much less than this value. It is estimated by Sharvin's formula $d\sim(\rho(R_0)^{1/2}$ and amounts to 70–700 Å.

[3)]The mean square deviations of the positions of the singularities $V^{(1)}$ and $V^{(2)}$ on the MC spectra are indicated in the form of errors in the table.

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