Trajectory effects in microcontact spectroscopy of the electron-phonon interaction

I. K. Yanson, N. N. Gribov, and O. I. Shklyarevskiĭ
Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR

(Submitted 2 July 1985)
Pis'ma Zh. Eksp. Teor. Fiz. **42**, No. 4, 159–161 (25 August 1985)

New effects have been observed in the microcontact spectroscopy of the electron-phonon interaction. These effects arise because the orbital radius of the electron in the magnetic field is comparable to the contact diameter, and the de Broglie wavelength is comparable to the elastic mean free path.

Strong electric fields ($\sim 10^4$ V/cm) can be produced at microcontacts with a diameter $d \sim 10^{-5}$–10^{-6} cm, but in normal metals these fields do not curve the trajectories of electrons in ballistic motion through the aperture or change the diffusion coefficient D in the case of a short mean free path l_i, because the energy acquired by the electron in the field is small in comparison with the Fermi energy. A static magnetic field also has essentially no effect on the trajectories of electrons in the region of the effective interaction with phonons, since the radius $r_H = cp_F/eH$ for the fields which are actually attainable is large in comparison with the linear dimensions of the interac-

0021-3640/85/160195-05$01.00

tion region, $\sim d$. The situation should be different in semimetals or degenerate semiconductors, in which we would have $r_H \sim d$, and in which the wavelength of Fermi electrons, $\lambda_F = \hbar / p_F$, might be comparable to the diameter of the contact or to the elastic mean free path l_i.

In a study of microcontact spectra of antimony we have observed that in pure contacts the intensity of the peaks due to the electron-phonon interaction depends strongly on the strength and orientation of the magnetic field. At dirty contacts the sign of the second derivative of the current-voltage characteristic changes, and instead of peaks at the characteristic phonon energies we observe valleys, whose depth is essentially independent of the field.

Pure microcontacts with l_i, $l_\epsilon \gg d$ (l_ϵ is the inelastic mean free path of the electrons) are generally formed in liquid helium during the first instances of contact of electrodes cleaned beforehand. Figure 1a shows the microcontact spectrum of the electron-phonon interaction for such contacts. This spectrum consists of peaks due to intravalley (at $eV \sim 2$ meV) and intervalley (7.5 and 17.0 meV) transitions of electrons accompanied by the emission of phonons. In a first approximation, the energies 7.5 and 17 meV correspond to phonons with a wave vector ΓX which induces intervalley transitions. This simple picture becomes more complicated when we take into account the splitting of the hole Fermi surface into six subbands. We note in this connection that there are shoulders at 4 and 11 meV, which are seen in a magnetic field (curve 3 in Fig. 2).

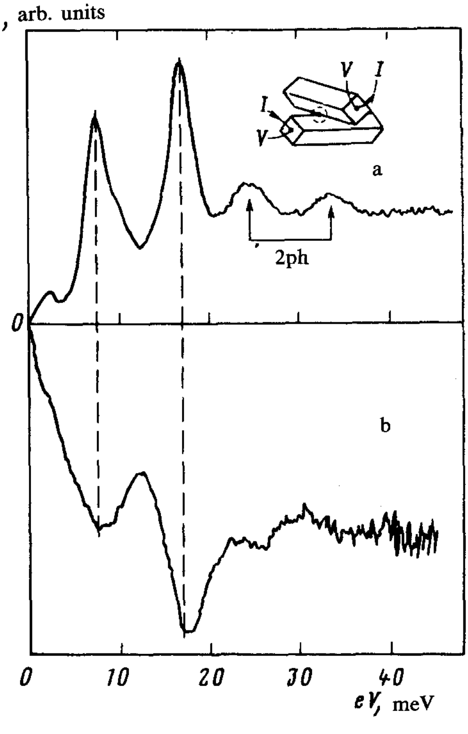

FIG. 1. Microcontact spectra of antimony. a: Pure contact, $R_0 = 0.75\ \Omega$, $V_{1,0} = 0.85$ mV. b: Dirty contact, $R_0 = 6.1\ \Omega$, $V_{1,0} = 0.898$ mV. $V_{1,0}$—Modulating voltage at $V = 0$; V_2—second-harmonic voltage, proportional to d^2V/dI^2. $T = 4.2$ K. 2ph—Two-phonon peaks ($H = 0$).

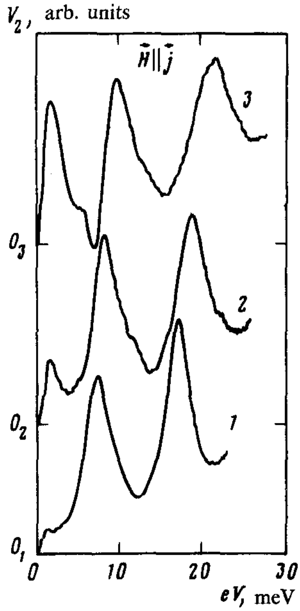

FIG. 2. Effect of a magnetic field parallel to the contact axis on the microcontact spectra of antimony. $R_0 = 1.65\ \Omega$, $T = 4.2$ K. 1, 2, 3—Magnetic fields of 0, 25.7, and 44.1 kOe and modulation voltages (at $V = 0$) of 0.724, 0.769, and 0.859 mV at a constant magnitude of the modulating current.

After repeated instances of contact, as a result of a cold working, l_i becomes substantially shorter in the region of the constriction. The curvature of the I-V characteristic changes sign, and instead of the peaks in d^2V/dI^2 we see valleys at the characteristic phonon energies (Fig. 1b).

This phenomenon can be explained in the following way. In semimetals, by virtue of the relation $eV \sim \hbar\omega_{\max} \sim \epsilon_F$, the microcontact spectrum is affected significantly by the energy dependence of the diffusion coefficient of "hot" electrons.[1] In particular, under the conditions $l_i \gtrsim d$ and $l_\epsilon \gg d$, the peaks corresponding to many-phonon processes are anomalously high (Fig. 1a).

The increment in the differential resistance as eV is varied from 0 to $\hbar\omega_{\max}$ is on the order of[2] d/l_ϵ and does not exceed 2–3% for our samples. The intensities of the two-phonon peaks should be of the same order of magnitude with respect to the single-phonon peaks in the ballistic regime.[3] In fact, as can be seen easily from Fig. 1a, the relative intensity of the two-phonon peaks, 2 ph, is a few tenths of 1% of that of the single-phonon peaks.

In the impure limit $l_i \ll d \ll \sqrt{l_i \cdot l_\epsilon}$ ($l_i \sim 10^{-7}$ cm, $l_\epsilon \sim 10^{-4}$ cm), the diffusion contribution to the microcontact spectrum is predominant; the mean free path is comparable to λ_F ($\sim 10^{-7}$–10^{-6} cm), and the diffusion is limited to a large extent by weak-localization effects.[4] In the limit $eV \to \hbar\omega_{\max}$, there is a decrease in the lifetime in the given energy state; the localization is disrupted; and the conductivity increases. Since $\Lambda_\epsilon \sim \sqrt{l_i \cdot l_\epsilon} \gg d$, the energy distribution of the electrons has a step of width eV, and at voltages corresponding to the characteristic phonon energies the increase in the conductivity accelerates, giving rise to a minimum of d^2V/dI^2. The magnetic field for impure contacts [under the assumption $\tau_\varphi \sim \tau_\epsilon \sim 10^{-13}$ s, $D = (1/3)v_F l_i$] is weaker

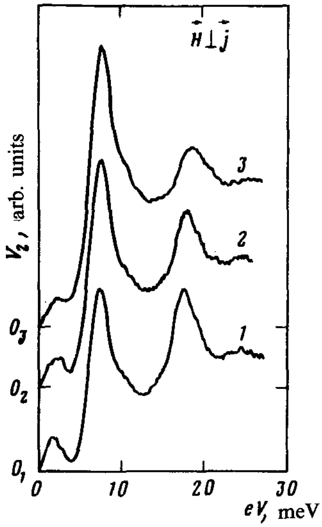

FIG. 3. Effect of a magnetic field perpendicular to the contact axis on the microcontact spectra of antimony. $R_0 = 3.3\ \Omega$. 1, 2, 3—Magnetic fields of 0, 19.4, and 23.3 kOe and modulating voltages $V_{1,0}$ (at $V = 0$) of 0.863, 0.913, and 1.008 mV at a constant magnitude of the modulating current ($T = 4.2$ K).

than the characteristic value that would disrupt the localization, $H_c = c\hbar/e(D\tau_\varphi)^{-1} \sim 2\times 10^5$ Oe, and it does not affect the intensity of the extrema in the spectrum.

Figures 2 and 3 show how a magnetic field affects the intensities of the peaks in the spectra of comparatively pure contacts ($l_i \gtrsim d$) for various orientations of the field with respect to the contact axis. In the case of the parallel orientation, we see a qualitative difference in the behavior of peaks caused by intravalley and intervalley transitions (Fig. 2), while in the case of the perpendicular orientation, we see that the intensity of the intravalley peak does not increase with the field, while the intensity of the first intervalley peak does increase (Fig. 3). It is interesting to note the field-induced shift of the peaks along the energy scale. This shift is retained even in the four-probe measurement arrangement. It is also interesting to note the broadening of the lines (see curve 3 in Fig. 2, for example), by an amount on the order of $\hbar\omega_H$, where ω_H is the cyclotron frequency.

In a homogeneous metal with a closed Fermi surface, the imposition of a weak transverse field is in a sense equivalent to a shortening of the elastic mean free path of the electrons. In microcontact spectroscopy, the result is a decrease in the intensity of the peaks of the electron-phonon interaction which are caused by inelastic processes (the intervalley peaks in Fig. 2 and the intravalley and intervalley optical peak in Fig. 3). In the inhomogeneous geometry of a microcontact, however, a magnetic field may also play another role: that of increasing the effective volume of the electron-phonon interaction.[2] Even in weak longitudinal magnetic fields ($r_H > d$), the large groups of electrons corresponding to extremal values of $v_\parallel T_H$ ($v_\parallel$ is the velocity component parallel to the field, and T_H is the cyclotron period), which have passed through the aperture, collect at the contact axis (Sharvin focusing[5]). Accordingly, for a longitudinal orientation of the field, the hot electrons near the contact (or aperture) do not spread out into a solid angle of 4π over a distance $\sim d$ but instead execute a quasi-one-dimensional motion along the field. The result is to increase the effective generation volume by a factor of about l_ε/d.

The intensification of the first peak of intervalley phonons in transverse fields (Fig. 3) is difficult to explain on the basis of simple considerations. We might also note that the effects described above are reproducible qualitatively at all the contacts studied which have a random orientation of crystallographic axes. The microcontact spectra do not depend on the polarity of the applied voltage.

We note in conclusion that for pure contacts we have observed Shubnikov oscillations of the resistance and also traces of a superconductivity, which arises under pressure, predominantly in contacts with a needle-plane geometry, and which disappears in a magnetic field of a few kiloersteds.

[1] I. F. Itskovich and R. I. Shekhter, Fiz. Nizk. Temp. **10**, 437 (1984) [Sov. J. Low Temp. Phys. **10**, 229 (1984)].

[2] I. O. Kulik, A. N. Omel'yanchuk, and R. I. Shekhter, Fiz. Nizk. Temp. **3**, 1543 (1977) [Sov. J. Low Temp. Phys. **3**, 789 (1977)].

[3] I. O. Kulik, A. N. Omel'yanchuk, and I. G. Tuluzov, Fiz. Nizk. Temp. **10**, 929 (1984) [Sov. J. Low Temp. Phys. **10**, 484 (1984)].

[4] B. L. Altshuer and A. G. Aronov, in: Modern Problems in Condensed Matter Science (ed. A. L. Efros and M. Polak), North-Holland, Amsterdam, 1984.

[5] Yu. V. Sharvin, Zh. Eksp. Teor. Fiz. **48**, 984 (1965) [Sov. Phys. JETP **21**, 655 (1965)].

Translated by Dave Parsons