POINT-CONTACT SPECTROSCOPY OF SUPERCONDUCTORS

I.K. YANSON
B. Verkin Institute for Low Temperature Physics and Engineering
National Academy of Sciences of Ukraine, 310164 Kharkiv, Ukraine

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1. Introduction

In this review we describe the current-voltage spectroscopy of superconductors which, in contrast to the tunneling spectroscopy, considers contacts with direct conductivity, without any barrier. These contacts are usually called point contacts as their lateral dimension should be smaller than some microscopic lengths such as the coherence length in superconductors and the inelastic mean free path of conduction electrons in normal metals. Some of 3-dimensional metallic constrictions are schematically depicted in Fig.1. A shorted thin-film tunneling junction (a) was historically the first structure in which the point-contact spectroscopy was discovered [1]. A much more sophisticated thin-film structure is displayed in (b) where the tiny controlled orifice was made in the insulating diaphragm of Si₃N₄ by means of ion-beam nanolithography [2]. Point-contacts with bulk electrodes are shown in Fig1 (c-e) for different geometries. The simplest are the pressure-type contacts in which two sharp edges (c) [4] or a needle and an anvil (d) [5] are forced to touch each other gently. Most point-contact spectroscopic studies were made just with these very simple experimental devices. The mechanically controlled break-junction (MCB) (Fig.1 (e)) gives an experimentalist new advantages [3]. A small rode of a metal 1 is glued by the Staycast varnish 3 to the bending beam 4. The latter can be bent by a piezo driver 5 so that the notch 2 at the centre of the sample becomes stretched and the cross-section area of the constriction is gradually decreased. This device allows us to study the contact properties as a function of constriction size.
In this review we do not concern the so-called Andreev-reflection spectroscopy of superconducting energy gap. The reader can find this in Refs. [6, 7, 8] and later extensions [9, 10]. Our focus will be on the above-gap energies where one could expect nonlinearities caused by the electron-boson interactions responsible for the formation of Cooper pairs. The problem unsolved yet is that in standard superconductors (lead, tin, Nb₃Sn and many others) the above-gap nonlinearities give the evidence about the electron-phonon-interaction mechanism of Cooper pairing [11], whilst the tunnel junctions of unconventional superconductors (high-Tₘ’s, heavy fermions, organic superconductors, etc.) do not show any noticeable nonlinearities for energies larger than the superconductor energy gap [12, 13] (albeit see Ref.[14]). On the contrary, the point contacts do manifest strong nonlinearities at above-gap energies which in many cases correlate with the boson density of states known, for instance, from neutron study [15, 16].

We thus think that the study of nonlinearities of point contacts is the alternative way of investigating the spectral functions of the electron-boson interaction which in many cases is more productive and simpler than tunneling.

2. Point-contact spectroscopy in the normal state

First, we consider the point-contact spectroscopy (PCS) of electron-boson interaction (EBI) in the normal state [17]. Many superconductors can be driven into the normal state by magnetic field, and the PCS theory is more fundamental and transparent in this case. As a model for 3D constrictions, we consider a circular channel of length \( L \) and diameter \( d \) connecting two bulk metallic half-spaces (Fig.2). If \( L \ll d \), we have an orifice in nontransparent infinitely thin partition, while for the opposite case \( (L \gg d) \) a one-dimensional channel appears. Since contact sizes \( L, d \) are much less than the mean free path of conduction electrons \( e^- \) the latter move through the constriction ballistically on applying the voltage bias \( eV \). The resistance of such a ballistic contact was first derived by Sharvin [18] and is equal to

\[
R_{Sh} = R_q \left( \frac{16}{d^2 k_F^2} \right); \quad R_q = \frac{\pi \hbar}{e^2} \simeq 12.9 \text{ k} \Omega
\]

Suppose that there are some seldom elastic scatterings off static defects or impurities (⋆) or inelastic processes with emission phonons and other quasiparticles shown in Fig.2 as a wavy line with momenta \( q \). Let us call this regime quasi-ballistic. The nonequilibrium distribution function in the momentum space consists, like in the ballistic regime, of two spherical segments which are displaced in energy by \( eV \) and which have the form of two semispheres at the central cross-section of the constriction [19]. At
low temperatures we can neglect the smearing of the Fermi edge. Then, the energy conservation sets a sharp threshold $\hbar \omega \leq eV$ on the quasiparticles which can be emitted by the inelastic transition of conduction electron with momenta $p$ to $p\,'$. This backscattering processes create opposite current which depends strongly on the bias because of the energy dependence of the quasiparticle density of states and matrix element of EBI. This current is the basis of PCS. To be complete, we must note that in some cases the elastic scattering can also depend on the energy like, for instance, the scattering off the paramagnetic impurities (in Fig.2 these are shown with $\nearrow$) due to the Kondo effect or to two-level systems.

In the quasi-ballistic regime ($l > \max \{d, L\}$) the differential resistance of the point contact is equal to

$$R(eV) = R_{Sh} + \Delta R(eV); \quad \text{where} \quad \Delta R(eV)/R_{Sh} = (8/6\pi) [d/l_i(eV)].$$

For the second derivative of the current-voltage characteristic, which is usually called the point-contact spectrum, we obtain at $T \simeq 0$ a simple relation [19]:

$$\frac{d \ln R(eV)}{d(eV)} = \frac{8}{3} \frac{ed}{\hbar v_F} g_{PC}(eV)$$

(1)

where $g_{PC}(eV)$ is the transport EBI function which in many cases appears to be the electron-phonon-interaction (EPI) spectral function similar to the Eliashberg EPI function [19]. The point-contact EPI function can be expressed as $g_{PC}(\omega) = \alpha_{PC}^2(\omega) F(\omega)$, where $\alpha_{PC}^2(\omega)$ is the averaged electron-phonon matrix element with kinematic restrictions imposed by the point contact geometry and $F(\omega)$ is the phonon density of states. Thus, we see that PCS allows direct recording of the transport version of EBI (EPI) spectral function which is responsible for the formation of Cooper pairs in superconductors. We show here only one example for tin although many pure metals, alloys and compounds have already been studied by means of PCS [20, 21, 22, 23, 17, 16]. In Fig.3 (upper panel) the directly recorded PC spectrum of tin is shown by a solid line which is compared with the EPI spectral function (dots) reconstructed from the Eliashberg integral equations by means of the Rowell-McMillan procedure from the superconducting tunneling experiment. Both curve are smeared by the PCS resolution which is shown by the horizontal segment on the graph and which is equal to

$$\delta(eV) = \sqrt{(5.44k_F T)^2 + (1.72eV_1)^2}.$$
The PCS resolution depends on the temperature $T$ and modulation voltage $V_1$ which is used for recording the second derivative of current-voltage characteristic with a lock-in technique.

For symmetrical heterocontacts (point contact with dissimilar electrodes), the PC spectrum at $T \simeq 0$ takes the form:

$$\frac{d \ln R(eV)}{d(eV)} = \frac{4 e d}{3 \hbar} \left\{ \frac{g^{(1)}_{PC}(eV)}{v_F^{(1)}} + \frac{g^{(2)}_{PC}(eV)}{v_F^{(2)}} \right\}$$

where the superscript $(i)$ refers to particular metal. This formula is used for a S-c-N contact.

The heavy elastic scattering around the contact is not necessarily detrimental to PCS as long as the energy relaxation length remains much larger than the contact size:

$$d \ll \sqrt{\ell_e}.$$

In the case of diffusive movement of charge carriers through the contact ($\ell_e \ll d$), the contact size $d$ in formula (1) should be replaced by the elastic mean free path $\ell_e$. The interpolation curve of the spectrum intensity is shown on the lower panel of Fig.3 [24]. It can be used for estimation of $\ell_e$ inside the contact by measuring the intensity of the PC spectrum. This is important since during making a contact one could introduced a lot of defects into the contact region.

3. Excess current: dependence on purity

If one or two of the electrodes of a point contact become superconducting, the excess current emerges, which is superimposed on top of the normal state current. The mechanism is called the Andreev transformation and is as follows: a quasiparticle coming through the constriction has a certain probability to find another electron to form a Cooper pair in the superconducting electrode. This process leads to reflection of quasiparticles which have opposite signs of charge and velocity in the normal metal (in case of S-c-N junction) but the same excitation energy [25]. For biases larger than gap energy this current is constant if strong-coupling, inelastic and nonequilibrium processes are disregarded. Below we consider all of them, but now let us focus on the undisturbed excess current which spreads not too far from the gap region. In The IVC of S-c-S tin junction is plotted in Fig.4 (upper panel) [26]. The normal-state zero-bias resistance is compensated by a bridge circuit, hence the deflection of the real IVC in the normal state from the Ohmic behaviour is shown by curve 2. Curve 1 presents the superconducting state of the same contact ($H = 0$). The critical (Josephson) current is clearly visible at $V = 0$, and a small dip is seen at $eV = 2\Delta$. This
is because the small barrier appears at the interface between the electrodes due to introduced inhomogeneities while making the contact. The difference between curves 1 and 2 presents the excess current for biases greater than $2\Delta$ which is seen to be approximately constant up to the energies near 5 meV. We shall discuss the nonlinearities of excess current

$$I_{\text{exc}}(V) = I_{\text{exc},0} + \delta I_{\text{exc}}(V) \quad (3)$$

later on and now concentrate on the dependence of $I_{\text{exc},0}$ on purity of the metal. Here we have to consider the purity inside the constriction region which could be quite different from that of the bulk. As a criterion of purity, we may take the maximum intensity of PC spectra which depends on the elastic mean free path averaged over the contact region, as shown by the curve in Fig.3 (lower panel). The dependence of $I_{\text{exc},0}$ in $\Delta/eR_0$ units is shown in the lower panel of Fig.4 as a function of $g_{\text{PC}}^{\text{max}}$, where $g_{\text{PC}}^{\text{max}}$ is the value of the PC spectrum at the bias around 15 meV (see Fig.3 (upper panel)). $I_{\text{exc},0}$ starts approximately from 1.47 for dirty contacts (i.e. for small $g_{\text{PC}}^{\text{max}}$), as was predicted theoretically by Artemenko, Volkov and Zaitsev (AVZ) [7], and rises with $g_{\text{PC}}^{\text{max}}$ up to the value predicted by Zaitsev and BTK [8, 6] for clean contact. In Fig.4 (lower panel) we show this ultimate value at $g_{\text{PC}}^{\text{max}} = 0.41$ taken from Ref.[27], as a dot in a circle. From the graph $g_{\text{PC}}/g_{\text{PC}}^{\text{max}}(l_e/d)$ of Fig.3 (lower panel) we find that $l_e/d \simeq 0.5$ is quite sufficient to transform a clean S-c-S junction into a dirty one. On the other hand, the BTK theory dealing with clean junctions gives the AVZ-dirty value for $I_{\text{exc},0}$ at the barrier parameter $Z \simeq 0.5$ and, what is the most strange, the BTK-fitting leads to approximately the same $Z$ for large diversity of materials, including high-$T_c$, heavy fermions and conventional superconductors. One might suspect that application of the clean BTK procedure to dirty junctions gives the same $Z \simeq 0.5$ value irrespective of the kind of material.

The parallel study of excess current and intensity of PC spectra allows one to conclude whether the impurities are homogeneously distributed or they are located as a thin barrier at the interface between the electrodes. Indeed, the relative intensity of PC spectra does not saturate for $l_e/d \ll 1$ being proportional to $l_e/d$, while the excess current does. The same is true when we consider the $Z$-parameter, instead of the excess current, while fitting the IVC by the BTK theory.

$^1$For a S-c-N contact the excess current is equal to half of the theoretical values shown in Fig.4 (lower panel).
4. Elastic contribution to excess current

Further on we consider S-c-N junctions which are simpler to interpret due to the absence of the Josephson effect. To be more definite, we restrict ourselves to the electron-phonon interaction. According to Refs.[28, 29], one can write the IVC in the superconducting state as

\[ I(V) = V/R_0 - \delta I_{ph}^N(V) + I_{exc}(V) \]  

(4)

where \( \delta I_{ph}^N(V) \) is the backscattering current in the normal state whose second derivative is given by Eq.(2) and \( I_{exc}(V) \) is equal to Eq.(3). The order of magnitude of \( \delta I_{ph}^N(V) \) is \( I(V) \times (d/l_{in}) \). The voltage dependent part of \( \delta I_{exc}(V) \) can be decomposed in elastic and inelastic parts:

\[ \delta I_{exc}(V) = \delta I_{exc}^{el}(V) + \delta I_{exc}^{in}(V) \]

Correspondingly, the order of magnitude of the \( \delta I_{exc}^{el}(V) \) and \( \delta I_{exc}^{in}(V) \) terms amounts to

\[ I_{exc,0} \times (\Delta/\hbar \omega_{ph}) \quad \text{and} \quad I_{exc,0} \times (d/l_{in}) \quad \text{where} \quad I_{exc,0} \simeq \Delta/eR_0. \]  

(5)

Let us consider the elastic component which is essential for strong coupling superconductors when \( \Delta \) is not much less than \( \omega_{ph} \). Fig.5 shows the experimental second derivatives of IVC for lead in the superconducting state of Pb-Ru and Pb-Os point contacts (curves 2 and 4, respectively). Normal metals Ru and Os were chosen since their phonon density of states can be neglected in the energy range where Pb has the highest intensity [30]. The normal state EPI-PC spectrum for contact 2 is shown as dotted curve 3 on the same ordinate scale like that for the superconducting state (curve 2). It is clearly seen that in the superconducting state the phonon peaks are shifted to the higher energies roughly by \( \Delta(Pb) \simeq 1.3 \text{ mV} \). Moreover, the intensity of the peaks is larger than that in the normal state. Importantly, the phonon peaks for noticeably dirtier contact (curve 4) are not much smaller, as could be expected from the measurements of EPI-PC-spectrum intensity in the normal state (not shown). These properties qualitatively contradict the theoretical predictions [28, 29] if only the inelastic processes are taken into account.

Let us compare quantitatively the spectra for a clean contact (curve 2) with the predictions of Ref.[31] which takes into account the strong-coupling effect of the superconducting energy gap dependence on energy. For the ballistic S-c-N junction with a strong-coupling superconductor the theory gives the expression of the first derivative of IVC:
\[
\left\{ \frac{dI}{dV}(eV) \right\}_{S-c-N} = \frac{1}{R_0} \left\{ \frac{\Delta(eV)}{eV + [(eV)^2 - \Delta^2(eV)]^{1/2}} \right\}
\]

for the total differential conductance at \( T = 0 \). The derivative of this curve is displayed as curve 1 in Fig. 5 where we used the strong-coupling gap versus energy dependence for lead determined by tunneling spectroscopy [32]. The smooth weak-coupling BCS background (corresponding to \( \Delta(eV) = \text{const} \)) is shown as a dashed line superimposed on curve 1. The experimental characteristic (curve 2) agrees reasonably well with theoretical predictions (curve 1) both in shape and in amplitude. The latter can be estimated by the deflection from the smooth background. The total order of magnitude of the elastic correction to the conductance amounts to \( [\Delta(eV)/\hbar \omega_{ph}]^2 \) for \( \Delta(eV) \ll \hbar \omega_{ph} \), just as in the tunneling spectroscopy of superconductor. Since the elastic term of excess current \( \delta I_{el}^{\text{exc}}(V) \) does not depend on the contact diameter \( d \) (5), it can be higher than the inelastic contribution \( \delta I_{in}^{\text{exc}}(V) \). This situation occurs just for lead. Below we consider another case which holds for weak-coupling superconducting tin, where the inelastic term prevails. We conclude this section with the notion that the Eliashberg EPI spectral function can be extracted from the superconducting point-contact characteristic in the same way as in tunneling spectroscopy provided that one should be sure that the inelastic terms are negligible.

5. Inelastic processes in excess current

For a weak-coupling superconductor (\( \Delta(eV) \ll \hbar \omega_{ph} \)) the elastic contribution to the excess current is negligible. Consider the Sn-Cu S-c-N point contact which is shown schematically as an inset in Fig. 6 [33]. First of all, in the normal state Sn and Cu have approximately the same electronic parameters \( (v_F) \) and overlapped energy regions of the phonon density of states. Their PC EPI spectra are shown as curves 5 and 6 for Sn and Cu, respectively. In a symmetrical heterocontact their spectral functions enter almost equally according to the formula (2) \( g_{PC}(\text{Sn-Cu}) \simeq (1/2) [g_{PC}(\text{Sn}) + g_{PC}(\text{Cu})] \) which is shown as dotted curve 4. Accordingly, the measured PC spectrum in the normal state of the heterocontact looks like curve 3 which (with a small smooth background subtracted) leads to solid curve 4. The coincidence between dotted and solid curves 4 not only in shape but also in amplitude is fairly well. In the superconducting state of the same contact the excess current appears, which is shown by curve 1 in Fig. 6 as the difference between the total current and the Ohmic term \( V/R_0 \) in superconducting and normal states, respectively. Evidently, the excess current is not constant. We disre-
gard the large hysteresis-like drop at high voltage (larger than the phonon energy band) due to heating and concentrate our attention on the smooth decrease along the phonon energy range. The second derivative (PC spectrum) of IVC in the superconducting state is shown as curve 2. Apart from the smooth background which steeply rises when the voltage approaches the energy gap ($\Delta(Sn) \approx 0.6$ meV) from above, one sees the curve which almost reproduces the features seen in the normal-state spectrum (curve 3). We thus conclude that the main nonlinearities in the superconducting state come from the backscattering current the same as in the normal state. Yet, there are small peculiarities such as the small shift of the maxima to the lower energy (shown by the vertical dashed line in Fig.6) and a slight broadening of peaks. These peculiarities are predicted by theory [28]. The unexpected shift to the lower energy by the superconducting energy gap is due to electron-hole relaxation as a result of the Andreev reflection from the N-S boundary. The inelastic processes with emission of phonons occur when an electron quasiparticle with energy of the order of $eV$ relaxes to the hole state appearing due to Andreev reflection of another electron with energy of the order of $\Delta$. For an infinitely narrow peak in the EPI function the theory leads to the maximum shifted down by $\Delta$ with the width of the order of $\Delta$ as well. Hence, in the clean S-c-N contact based on a weak-coupling superconductor the main contribution to formula (4) comes from the normal term $\delta I_{ph}^N(V)$ with slight modifications due to $\delta I_{exc}^N(V)$ term.

6. Nonequilibrium phenomena

As soon as the diameter of the contact becomes comparable with the superconducting coherence length $\xi_0$, the nonequilibrium phenomena may occur which lead to suppression of the gap by i) nonequilibrium populations of normal electrons and phonons with energies greater than $2\Delta$, ii) entering the magnetic flux vortices generated by the current through the contact, or iii) simply by heating of the contact region.

In Fig.7 the PC spectra of Ta-Cu contact are shown both in the normal (curve 1) and superconducting (curve 2) states [34]. Since the Fermi velocity of Ta is noticeably less and the strength of EPI in Ta is essentially higher than for Cu, only the EPI spectrum of Ta is seen in the experiment: $g_{PC}^{(Ta-Cu)} \approx \frac{1}{2} g_{PC}^{(Ta)}$ (see Eq.(2). Although the relatively high resistance of contact ($R_0 = 80 \ \Omega$) implies a small size ($d \approx 78 \ \text{Å}$), the ultimate (at $eV > \hbar \omega_{ph}$) electron-phonon mean free path is also small ($l_{in} \sim 120 \ \text{Å}$) and the reabsorption of nonequilibrium phonons may occur. Also the superconducting coherence length in Ta ($\xi_0 = 90 \ \text{nm}$) is smaller than in Sn ($\xi_0 = 270 \ \text{nm}$), especially for the dirty Ta-contact region. This is more favourable for nonequilibrium transitions in the superconducting state and
assists, by decreasing $H_{c1}$, the current-generated vortices to enter the contact area. All this makes the EPI spectrum in the superconducting state of Ta quite different from what is observed in Sn. There is no shift of the phonon peaks by $\Delta$ to lower biases. Instead, the lower is the contact resistance (the smaller is the size), the more fixed are the transverse (T) and longitudinal (L) phonon peaks at energies of 11.3 and 18 meV with very small scattering of $\pm 0.1$ meV. The peak of T-phonon (see curve 2 in Fig.7) grows narrower instead of broadening and with increase of the contact size all the peaks become sharpened (Fig.8). This contrasts to the behaviour of phonon peaks in clean Ta point contacts in the normal state where one observes the spreading of energy positions in the limit of $\pm 1$ meV probably due to the random anisotropy of the microcrystal orientation with respect to the contact axis. The explanation is as following. The nonequilibrium phonons slowly diffuse from the dirty contact region effectively averaging their direction in the momentum space. The phonon peaks at reproducible fixed positions appear due to the slow phonon group velocity (corresponding to the maximum of the averaged phonon density of state) which are accumulated in the contact region and thus effectively depresses the superconducting energy gap and excess current. In addition to the common energy-gap feature at $eV \simeq 0.6$ meV, a new peculiarity appears at $V_1$ (at about 5÷7 meV in Fig.7), which has strong intensity (note that the ordinate of this fragment has a factor of 0.01!), and whose voltage satisfies the relation $V_1^2/R_0 = const$. The latter means that either the power input by the current or the magnetic field generated at the contact achieve the threshold value. The threshold value increases with temperature and external magnetic field which is just opposite to the behaviour expected for destruction of superconductivity by simple heating or critical current conditions. We infer that at larger biases the superconductor turns into the nonequilibrium state and the increase in threshold value is explained by enhanced relaxation of nonequilibrium quasiparticles which demand a stronger injection to fulfil the threshold conditions. In this state the phonon features remain at the proper energies and are seen as a sharp singularity on IVC and its derivatives (Fig.8), whilst in the normal state only the smooth background without any spectral features is observed. Although there is no theory explaining quantitatively these phenomena yet, the experimental extension of the superconducting PCS to the materials with a short inelastic mean free path and coherence length seems to be very encouraging in view of studies on exotic superconductors, such as high-$T_c$, heavy fermions and organic compounds.
7. Concluding remarks

We have briefly described the state of the art of point-contact spectroscopy in the superconducting state. It allows one to penetrate into the mechanism of electron-quasiparticle interaction which may mediate the Cooper pairing. Contrary to tunneling spectroscopy, the point-contact spectroscopy needs not any barrier which inevitably interrupts the homogeneity of the material studied and often hampers investigation of many complicated compounds. At the expense of this, PCS results in principle to the highly nonequilibrium state which in case of superconductors leads to many complications. We hope that with development of new technique of producing well controlled constrictions of nanoscale size and elaborating a new theoretical approach the PCS will conquer more and more supporters and will become in the future as important as the tunneling spectroscopy.

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**Figure 1.** The three-dimensional constrictions made by different techniques: (a) shorted thin-film tunneling structure [1]; (b) thin-film point contact made by nanolithography [2]; (c) contacted sharp edges of bulk metals; arrows show the movement of electrode to choose the proper spot for measuring [4]; (d) "spear-anvil" geometry of the bulk electrodes [5]; (e) mechanically controllable break-junction [3]; arrow shows the movement of piezo drive 5 in order to bend the substrate 4.

**Figure 2.** Schematic illustration of quasi-ballistic electron flow. Two metallic half spaces are connected by a circular orifice of diameter $d$ in a partition of thickness $L$. Voltage bias $eV$ is applied between them. Most of the electrons flow ballistically through an orifice but some of them experience rare collisions off static (denoted by stars) and dynamic (denoted by wavy lines) scatterers. Small arrows superimposed on stars denote the impurities with magnetic moments. The dashed circle approximately denotes the area where the nonlinear information to IVC comes from. In the lower part, the nonequilibrium distribution function in the momentum space at the central cross section is drawn. Inelastic backscattering from $p$ to $p'$ with emission of quasiparticle (phonon) with momentum $q$ is shown. These processes have a sharp threshold $\hbar \omega \leq eV$ at low temperatures.

**Figure 3.** (upper panel): Comparison of electron-phonon-interaction spectral functions determined by the superconducting tunneling reconstruction technique [32] (dotted curve) and directly recorded by the point-contact spectroscopy [26] (solid curve). The small horizontal bar denotes the resolution for given parameters. (lower panel): Interpolation curve for spectral intensity between the ballistic limit ($l_e \gg d$) and diffusive regime ($l_e \ll d$) [24].
Figure 4. The parallel study of S-c-S contacts in superconducting ($H = 0$) and normal ($H = 0.9$ kOe) states of tin [26]. (Upper panel): the excess current as a difference between curves 1 and 2 is plotted versus the voltage bias. Contact resistance $R_0 = 2.55$ Ω. (Lower panel): Dependence of excess current in units of $\Delta/eR_0$ on the value of spectral EPI function (determined in the normal state) at the bias of $\approx 15$ meV. Two horizontal straight lines determine the dirty and clean limits according to Refs. [7, 8].

Figure 5. Phonon features on the PC spectra of S-c-N contacts for the strong-coupling superconductor. Curves 2 and 4 correspond to the clean Pb-Ru contact and the dirty Pb-Os one, respectively. They are compared with theoretically predicted curve 1 which in turn should be compared with the weak-coupling BCS limit shown with the dashed curve. Dotted curve 3 is the EPI PC spectra of junction 2 with the same ordinate scale for both cases. The curves are shifted vertically for clarity. The letters T and L with arrows mark the positions of transverse and longitudinal phonon peaks in lead, respectively.

Figure 6. Inelastic phonon peculiarities for weak coupling superconductor in Sn-Cu S-c-N junction (see inset). The upper curve shows the dependence of excess current on voltage bias for contact with $R_0 = 8.8$ Ω with $d = 10$ nm. The second derivative of IVC in superconducting state is shown as curve 2. Curve 3 gives the EPI spectrum for the same contact in the normal state. It results in the EPI spectral function shown by solid line in curves 4 which should be compared with the calculated one plotted as a dotted curve. Curves 5 and 6 display the PC EPI spectra of Sn and Cu homocontacts, respectively. The curves are displaced vertically for convenience. Note the different zeros along the ordinate axis for each of them.

Figure 7. Nonequilibrium phenomena in PC spectrum of Ta-contact in the superconducting state. The Ta-Cu contact is made by the “edge-edge” geometry as shown in the inset. It has $R_0 = 80$ Ω and $d = 78$ Å. In the normal state ($H = 3$ kOe) the spectrum is directly recorded as curve 1. Its shape practically coincides with the EPI spectral function calculated from the superconducting tunneling [35]. In the superconducting state (curve 2) anomalous features are seen. The transverse phonon peak at 11.5 meV sharpens, and a part of the spectrum becomes negative. There appears a strong nonlinearity at $\approx 6$ meV which looks like a peak on the differential resistance curve and a sharp decrease of excess current on the IVC.

Figure 8. The evolution of nonequilibrium peculiarities with decreasing contact resistance (increasing size). Curve 1: contact Ta-Cu, $R_0 = 26.5$ Ω, $d = 13.6$ nm. Curves 2 and 3: contacts Ta-Au with $R_0 = 19$ Ω ($d = 16$ nm) and $R_0 = 0.76$ Ω ($d = 80.3$ nm), respectively.
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