Manifestation of electron-phonon interaction effects on tunnel curves of normal junctions

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(Submitted May 8, 1975)
ZhETF Pis. Red. **21**, No. 12, 701–704 (June 20, 1975)

Theoretical results are presented, which point to a way of interpreting the experimental tunnel curves of *N–I–N* junctions for the purpose of extracting information on the phonon density of states of the electrodes.

PACS numbers: 73.40.R, 71.85.C

Electron tunneling has become an increasingly informative method of investigating the electron-phonon interaction function $g(\omega)$ in the *S* electrodes of *S-I-N* junctions[1] (*S*—superconductor, *N*—normal metal). However, the procedure of[1] is restricted to strong-coupling superconductors. It is therefore of interest to determine $g(\omega)$ from the fine structure of the current-voltage characteristic of an *N-I-N* junction. From this point of view, this question was discussed by Hermann and Schmid,[2] who have separated the contribution of the self-energy effects in the expression for the tunnel conductivity of a normal junction (temperature $T = 0\,^\circ$K):

$$\frac{\Delta\sigma_{oo}(\Omega)}{\sigma_0} = \frac{\alpha N(0)}{\epsilon_0}\int_0^\infty d\omega\, g(\omega)\ln\left|\frac{\omega+\Omega}{\omega-\Omega}\right| . \qquad (1)$$

Here σ_0 is the conductivity without allowance for the interactions in the system, $N(0)$ is the density of the electron states on the Fermi surface, $\alpha \approx 30$ is a constant, and $\Omega = eU$, where U is the voltage on the junction.

However, the results of experiments[3,4] performed after[2] did not agree with relation (1). Thus, in[3] an unexpectedly small value of the coefficient α ($\alpha \sim 1$) was obtained for an $Al-Al_2O_3-Pb$ junction. An appreciable qualitative discrepancy between (1) and the experimental data for the odd part of the differential conductivity $\Delta\sigma_{odd}$ was observed by Burrafato *et al.*[4] This discrepancy called for a review of results of[2] on the basis of a generalization of the model approach with an ordinary tunnel Hamiltonian T_0,[5] which was used in the calculation of[2], to include the case of the principal Hamiltonian of the aggregate of the conduction electrons of the junction.

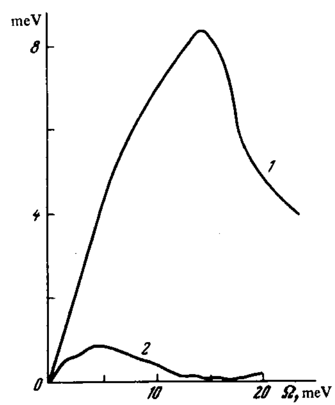

FIG. 1.

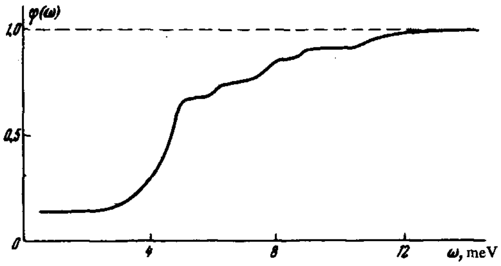

FIG. 2.

Following the procedure of[6], we determined for the electron-phonon interaction an operator T_1, which supplements $T_0=\Sigma T_{pg}a_p^+b_g$ and contains, besides the operators for the creation and annihilation of electrons on opposite sides of the barrier (a_p^+ and b_g, respectively), also a boson-excitation operator β_k and a new matrix element $T_{pg}(\mathbf{k})$ ($\mathbf{k}$ is the phonon wave vector). It is easy to verify that in the modified scheme the expression for the current will be a sum of three terms: an elastic term $J_{00}\sim\langle T_0^+|T_0\rangle$ (with allowance for the contribution ΔJ_{00} from the self-energy effects considered in[2]), an "interference" current (so named because of its origin) $J_{10}\sim\langle T_1^+|T_0\rangle$, and an inelastic increment $J_{11}\sim\langle T_1^+|T_1\rangle$.

Whereas the contribution ΔJ_{00} is due to the emission and absorption of phonons inside the electrode, J_{10} corresponds to the "redressing" of the electron on the boundary between the electrode and the dielectric. Their first derivatives ($\Delta\sigma_{00}$ and σ_{10}, respectively) are odd functions of the voltage and consequently, $\Delta\sigma_{\text{odd}}=\Delta\sigma_{00}+\sigma_{10}$ can be experimentally separated by investigating the odd and even parts of the differential conductivity of the junction. Calculation has shown that

$$\frac{\sigma_{10}(\Omega)}{\sigma_0}=-\frac{aN(0)}{\epsilon_0}\int_0^\infty d\omega\,\phi_1(\omega)\,g'(\omega)\ln\left|\frac{\omega+\Omega}{\omega-\Omega}\right|, \tag{2}$$

where the dimensionless quantity $1\geqslant\phi_1>0$ is the result of averaging of the quantity $\mathrm{Re}\{T_{pg}^*T_{p-k,g}(\mathbf{k})\}$ over the angles of the vectors $\mathbf{p}$ and $\mathbf{g}$, taken on the Fermi surface, and a subsequent normalization, while $g'(\omega)$ in (2) is determined with allowance for the barrier excitations.

Figure 1 shows an estimate of the cancellation of ΔJ_{00} by the current J_{10}, and for comparison the function $\int d\omega\, g(\omega)\ln|(\omega+\Omega)/(\omega-\Omega)|$ (curve 1) is plotted together with the corresponding term $\int d\omega[1-\phi_1(\omega)]g(\omega)\ln|(\omega+\Omega)/(\omega-\Omega)|$ (curve 2). This cancellation explains the anomalously small value of α obtained in[3] in the interpretation of the experiment on the basis of the result (1). The function $\phi_1(\omega)$ was obtained (see Fig. 2) from the experimental data[4] for $\Delta\sigma_{\text{odd}}$ of the Al-Al_2O_3-Sn junction by inverting formulas (1) and (2) relative to $[1-\phi_1(\omega)]$. In this case $g(\omega)$ of Sn was assumed known (these data, obtained from superconducting tunnel experiments, were taken from[7]). By way of control, we used another experiment from[4], where the role of the oxide Al_2O_3 was played by formvar, which has a low-energy (~2 meV) spike in the density of states of the Bose excitations. With the aid of the obtained function $\phi_1(\omega)$ and the relation $g'(\omega)=g(\omega)_{\text{Sn}}+$ the singularity connected with the formvar, we calculated the $\Delta\sigma_{\text{odd}}$ curve, which is shown together with the experimental data (solid curve) in Fig. 3.

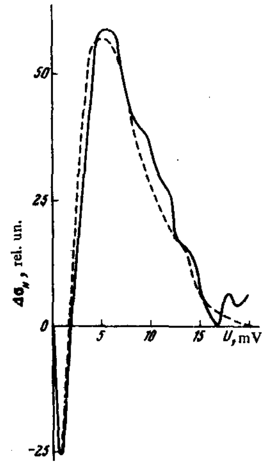

FIG. 3.

The agreement between the developed theory and experiment is convincing. It must be emphasized here that the negative spike and the extinction of the singularity near the second peak of the phonon density of states of Sn contradicts in general the result of (1), but follows from the theoretical relations for $\Delta\sigma_{\text{odd}}$.

For the even part of the conductivity ($\sigma_{11}=dJ_{11}/d\Omega$), we obtain the expression

$$\frac{\sigma_{11}(\Omega)}{\sigma_0}=\chi\frac{\pi N(0)}{\epsilon_0}\int_0^\Omega d\omega\,\phi_2(\omega)g'(\omega). \tag{3}$$

The constant χ is here of the order of $\alpha^2\omega_D/\epsilon_0$ (ω_D is the Debye energy), while $\phi_2(\omega)$ is determined by the ratio of the squares of the matrix elements $|T_{p-k,g}(\mathbf{k})|^2$ and $|T_{pg}|^2$, averaged on the Fermi surface (over $\mathbf{p}$ and $\mathbf{g}$).

As seen from relations (2) and (3), an investigation of the conductivity of the *N-I-N* junction does not make it possible to extract directly the initial information, since $g(\omega)$ is normalized either by the function $\phi_1(\omega)$ in the expression for the odd part of the conductivity, or by $\phi_2(\omega)$ for the even part. Nonetheless, the analysis instills assurance that the dependences of ϕ_1 and ϕ_2 on the frequency ω are stable for junctions prepared by one and the same method. Further experiments in this field are promising.

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