Some features of tunnel conductivity in normal junctions

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The effect of high hydrostatic pressures up to 15 kbar on the differential conductivity of normal metal-insulator-metal junctions is investigated. It is shown that allowance for the band structure of the insulator explains the change of the tunnel conductivity under pressure as well as the amplitude of the self-energy effects in the measured plots. A new method of reconstructing the electron-phonon interaction function of a normal metal from tunneling data is developed. The results obtained for lead, bismuth, and a lead-bismuth alloy by the described method are discussed.

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1. INTRODUCTION

Investigations of the differential conductivity of three-layer metal (M) - insulator (I) - metal (M) structure have yielded by now extensive information on the spectra of the elementary excitations of the metal banks and the effect of external action on them. Nevertheless, the properties of the insulator layer that produces the potential barrier for the electron tunneling remains unexplained to this day. The tunnel barrier, known to be the most important element, is at the same time most difficult to describe. Progress achieved by the tunneling technique was due to the fact that all the basic spectroscopic measurements were restricted either to low voltages (several dozen MeV) or to relatively by large amplitude changes of the investigated characteristics. As for the effects due to the barrier properties, they have not been satisfactorily explained within the framework of the existing theoretical premises.

The present paper is devoted to an elucidation of the nature of these effects. It consists of two parts. In the first we discuss the influence of the properties of the barriers on the form of the differential conductivity $\sigma(U)$ of the tunnel junction and in particular to the position of the minimum of the $\sigma(U)$ curve. The second part of the paper is devoted to small singularities of $\sigma(U)$ in the region of the phonon energies of the investigated metals; these singularities result from the dependence of the barrier transparency on the energy of the tunneling electron. An analysis of the corresponding curves has made it possible to determine the electron-phonon interaction functions for metals (Pb, Bi, and Pb-Bi alloy) in the normal state. To obtain reliable data on the small nonlinearities in the $\sigma(U)$ curves it was necessary to develop a combined measurement and computation facility that is described in the next section together with some details of the experiment.

2. EXPERIMENTAL TECHNIQUE

The injector for the investigated tunnel junctions, which were prepared by a standard precedure described earlier,[1] was an aluminum film with critical superconducting transition temperature ≈ 2 K. The insulating layer was produced by oxidizing the film in a rarefied (10^{-1} Torr) atmosphere of dry oxygen for several minute. The investigated substance (Pb, Pb-Bi alloy, or Bi) was condensed from above. The junction resistances ranged from several dozen to several hundred ohm. The results reported here were obtained for five junctions with Pb, three with $Pb_{70}Bi_{30}$, and four with Bi.

The experiments were performed in a cryostat at temperatures from 2.2 to 4.2 K. The superconductors (lead and its alloys) were restored to the normal state by applying a magnetic field up to 10 kOe. Hydrostatic compression of the samples up to 15 kbar was produced in an Itskevich chamber at room temperature, followed by cooling to helium temperatures. The pressure was determined accurate to $\pm$ 1% from the change of the critical temperature of an indium sensor.

To separate the weak nonlinearities in the current-voltage characteristics $I(U)$ of the investigated samples, a combined measuring and computing facility was developed: its structural block diagram is shown in Fig. 1. The derivatives of $I(U)$ with respect to U were obtained by a modulation method using a GZ-105 frequency synthesizer a the modulator. In addition, a block was developed that shaped two selective-amplification signals, shifted 90° relative to each other, with prescribed selective-amplification frequency, used to operate the synchronous detector and to synchronize all the generated signals in phase. This system could record very weak signals corresponding to a relative change of the junction resistance on the order of 10^{-5}–10^{-6} at a modulation amplitude 300–1000 μV.

Connecting the investigated tunnel junction in a bridge circuit canceled out the background component of the signal. The bridge consisted of two transformers and two operational amplifiers of type K 816 UD 1A with low temperature drift, which applied to the sample a specified voltage, or a bias current and voltage, or a modulation-signal current, independently of the change of the junction resistance during the measurement. The bridge unbalance signal was fed to a selective amplifier with central frequency 1 kHz, whose stages comprised two active band filters with Q on the order of 200, based on operational amplifiers with a twin-T bridge in the feedback circuit. Provision was made for increasing the Q of the amplifier channel to 10^4 by adding two quartz

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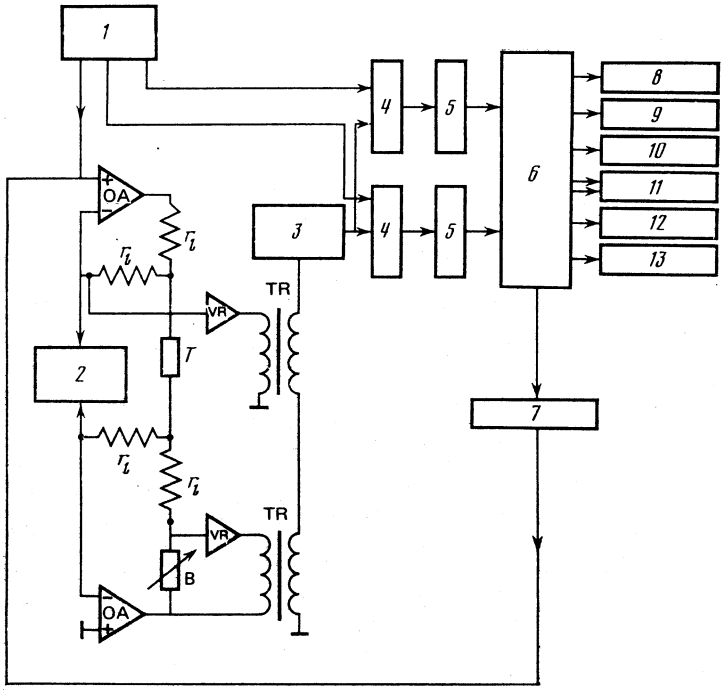

FIG. 1.Structural block diagram of measurement facility: T—tunnel junction, r_l - resistance of lead-in conductors and of film, B-resistor box, OA-operational amplifier, TR-transformer, VR-voltage repeater, 1-modulator, 2-digital voltmeter, 3-selective amplifier, 4-synchronous detector, 5-analog-digital converter, 6-minicomputer processor, 7-digital-analog converter, 8-printout unit, 9-oscilloscope, 10-perforator, 11-automatic x-y plotter, 12-display panel, 13 channel for connection to ES computer.

filters. This regime was used effectively to record small singularities in the tunnel characteristics.

The synchronous detectors separated respectively the sine and cosine components of the measured signal, transformed them into direct current, and fed them through an analog-digital converter to the processor of a minicomputer. The computer shaped the data in accord with a definite value set by the step and rate of the bias voltage, and stored of the data in the memory. The operating speed of the analog-digital converters was high enough to perform, at the same voltage, up to 1000 measurements whose results were then averaged. This increased the equivalent Q of the entire measurement channel to several tens of thousands, and increased the sensitivity of the system by more than 100 times. In addition to the foregoing, the minicomputer determined the signal from its orthogonal components, performed some arithmetic operations on the assembly of the measured data, and fed the final information to one of the external devices: oscilloscope screen, printout unit, perforator, automatic plotter, and channel of communication with the ES computer.

3. BARRIER CHARACTERISTICS OF TUNNEL JUNCTIONS

1. It is known that the form of the differential conductivity $\sigma(U)$ of *M-I-M* tunnel junctions is determined, in a wide range of voltages, by the dependence of the electron wave vector **k** on its energy ε in the effective potential barrier. The relation usually employed in some cases is

$$-k^2(z,\ \varepsilon)=(2m/\hbar^2)\,[\varphi(z,\ U)-\varepsilon], \qquad (1)$$

where m is the electron mass, $\varphi(z, U)$ is the height of the potential barrier, and the z axis is perpendicular to the insulator plane. As seen from (1), the calculated $\sigma(U)$ depends primarily on the form of the function $\varphi(z, U)$, i.e., on the shape of the potential barrier. It was found[1,2] that the experimental $\sigma(U)$ curves are parabolas

$$\sigma(U)=\sigma_0+AU+BU^2, \qquad (2)$$

whose minima are shifted in most cases by a value $U_{\min}$ along the voltage axis. The suggestion made that this shift is due to asymmetry of the potential barrier is fully confirmed by the results of numerical calculations of the tunnel characteristics of junctions with trapezoidal barriers.[2] In this case the following relation was obtained between the difference $\Delta\varphi$ of the barrier heights, the average height $\bar{\varphi}$, and the thickness d, on the one hand, and the value of the shift, on the other:

$$U_{\min}=0.65\Delta\varphi/d\bar{\varphi}^{1/2}.$$

Here and elsewhere the energy and voltage are expressed in eV and the thickness in Å. This result explains the asymmetry of the tunnel curves, but is insufficient to describe the large shifts $U_{\min} > 200$ meV observed, in particular for Al-I-Pb junctions. In all this cases its use led to absurd values of the parameters $\bar{\varphi}$, $\Delta\varphi$, and d. The cause of these shifts, as suggested by the authors of Ref. 2, is the substantial barrier inhomogeneity, due to molecular impurities it acquired in the course of preparation. This viewpoint was further developed in Ref. 3, where a thin rectangular barrier of great height was considered in addition to the trapezoidal one.

2. The use of the insulator thickness d as the variable parameter has made it possible to verify the extent to which these concepts conform to the real situation. To this end, an experimental investigation was made of the influence of high pressures up to 15 kbar on the tunneling characteristics of Al-I-Pb junctions. The data point directly to a strong sensitivity of the asymmetry of the differential conductivity (U) to the applied hydrostatic compression.[1] Thus, under pressure the value of $U_{\min}$ changed from 230 meV at $P=0$ to 110 meV at $P=12.2$ kbar. The relative change of the barrier thickness, estimated from the simplest formulas for a rectangular barrier, is approximately 3%, and its height changes by 2%. The rate of the shift of the parabola center with

changing pressure was determined directly from experiment and was found to be

$$d \ln U_{min}/dP = -(4.1-4.5)\,10^{-5}\ \text{bar}^{-1}.$$

3. We attempt now to explain this result within the framework of the aforementioned inhomogeneous-barrier model. We investigate two possible situations — random distribution of the impurities in the barrier, and the case when they form a single monolayer.

Consider elastic below-barrier collisions with randomly distributed impurity centers having a low density $n \ll (2m\bar{\varphi})^{3/2}/\hbar^3$. We use for this purpose Eq. (4.27) of Ref. 4 for the tunnel transparency of such an inhomogeneous system, confining ourselves to the exponentially damped terms.[1)] If, in accord with the initial assumptions, we regard as small the quantity $\eta = n\mu\hbar^2/4m\bar{\varphi}$, where μ is the amplituede of scattering from one center, we obtain for $U_{\min}$

$$U_{\min} = 0.65\Delta\varphi(1-\eta)/d\bar{\varphi}^{1/2}. \tag{3}$$

The shift of the $\sigma(U)$ curves is determined by the sign of μ and, as follows from (3), differs substantially from the results of the trapezoidal model if the number of scattering centers is large enough.

We analyze the other situation, in which the inhomogeneous insulator is described by two barriers with heights φ_1 and φ_2 and respective thicknesses d_1 and d_2. The final expression for $U_{\min}$ is rather complicated, but in the particular case $d_1 \gg d_2$ it takes the much simpler form

$$U_{\min} = \frac{7.8\varphi_1^{1/2}}{d_1}\frac{d_2}{d_1}\left[1-\left(\frac{\varphi_1}{\varphi_2}\right)^{1/2}\right]. \tag{4}$$

We estimate, in accord with (3) and (4), the effect of pressure on $U_{\min}$. To describe large shifts of $U_{\min}$ with the aid of relation (3) we must assume that $\Delta\varphi \sim \bar{\varphi}$. But then we cannot explain the decrease of $U_{\min}$ by one-half when the sample is compressed. Indeed, at the pressures used by us, on the order of 10 kbar, the change of $\Delta\varphi$, $\bar{\varphi}$, or d should be only several percent and the change of $U_{\min}$ should consequently be of the same order. A similar conclusion follows also from (4), in which φ_1 and φ_2 should differ by several times.

Thus, the models considered above explain the appreciable experimentally observed shifts of the parabola $\sigma(U)$, provided that it is not assumed that the pressure causes a radical change in the number of organic impurities and in their distribution [i.e., in the parameter η of (3) and in the ratio d_2/d_1 in (4)]. One might expect here that similar changes will be reflected in the tunnel spectra of the impurity molecules, which manifest themselves as a result of the inelastic tunneling. However, the singularities observed at $P = 0$ in the second derivatives d^2U/dI^2 did not change noticeably when high pressure was applied, and vanished when the pressure was removed.

4. An analysis of the experiments indicates unequivocally that the presence of the organic layer is insufficient to explain the anomalously large asymmetry of the $\sigma(U)$ curves. As will be shown below, it is necessary in addition to take into account the band structure of the real insulating layer. It is most important here to take into account the presence of a valence band in the insulator, which leads in the simplest form (see, e.g., Refs. 5 and 6) to the following dispersion law:

$$-k^2(z,\varepsilon) = \frac{2m^*}{\hbar^2 E_g}[\varphi(z,U)-\varepsilon][\varepsilon+E_g-\varphi(z,U)], \tag{5}$$

where E_g is the band gap of the insulating layer; $\varphi(z, U)$ is the distance from the level of the chemical potential in the insulator to the bottom of the conduction band, which we assume, in analogy with the trapezoidal model, to be linearly dependent on m; m^* is the electron effective mass, and the masses of the electrons in the conduction and valence bands are assumed equal. Substitution of (5) in the general expression for the tunnel current makes it possible[6] to find $U_{\min}$, the expression for which in this case is more complicated:

$$U_{min} = {}^1/_3\Delta\varphi\left\{1+0.51d\left[\frac{m^*}{m}\bar{\varphi}(1-x)\right]^{1/2}(1-2x)^2\right\}^{-1}, \tag{6}$$

where $\bar{\varphi}$ is the mean value of $\varphi(z, U)$, $x = \bar{\varphi}/E_g$, and $\Delta\varphi = \varphi(d, 0) - \varphi(0, 0)$.

According to Harrison,[7] it is more correct to regard the metal oxide in the tunnel junction as an amorphous semiconductor, in which the chemical-potential level is not far from the center of the forbidden band. In this case x is close to 1/2 and the voltage $U_{\min}$ is a maximum and reaches $U_{\min} = \frac{1}{3}\Delta\varphi$.

As applied to Al-I-Pb junctions this means that $\Delta\varphi = 3U_{\min} = 700$–$750$ meV. Such values of $\Delta\varphi$ explain the substantial changes of $U_{\min}$ with pressure for small variations of the parameters $\varphi(d, 0)$ and $\varphi(0, 0)$. Thus, to decrease $U_{\min}$ by one-half it suffices for the derivative $d\ln\varphi/dP$ of at least one of these quantities to have a reasonable value of the order of 7×10^{-2} kbar^{-1}. The validity of the relation $U_{\min} = (1/3)\Delta\varphi$ is confirmed also by the fact that despite the appreciable differences between the resistances of the Al-I-Pb junctions (i.e., essentially different d), the values of $U_{\min}$ are practically the same (see Refs. 1, 2, and others).

Consequently, when describing the form of the differential conductivity of tunnel junctions, it is necessary to take the presence of the valence band of the insulator into account.

4. SELF-ENERGY EFFECTS IN TUNNEL CURVES

1. The use of the two-band approximation eliminates one more contradiction between theory and experiment, connected with the amplitude of the self-energy effects in the elastic part of the normal tunnel current.

If account is taken of the dependence of the transparency of the barrier on the energy of the tunneling electron, the odd part of the differential conductivity of the normal junction takes according to Hermann and Schmid[8] the form

$$\sigma_-(U) = -C\sigma_0\,\mathrm{Re}\,\Sigma(U), \tag{7}$$

where $\Sigma(\omega)$ is the self-energy part of the electronic excitations in one of the metals (we assume for simplicity that the self-energy effects in the other are negligibly small), and $\sigma_0 = \sigma(U = 0)$. The coefficient C depends only on the parameters of the barriers and is found, within the framework of the rectangular model, to equal

$$C=C_{HS}=(d/\hbar)\,(m/2\bar{\varphi})^{1/2}. \qquad (8)$$

For convenience, the authors of Ref. 8 represented the coefficient C in the form $C=\alpha/\varepsilon_F$, where ε_F is the Fermi energy of the investigated metal; according to their estimates the parameter α for typical metals should be $\alpha_{HS}\sim 30$. Tunnel investigations of lead films have shown that the $\sigma(U)$ corrections odd in the voltage indeed agree well in form with expression (7), but their value was much smaller than that theoretically predicted in Ref. 8 (a value $\alpha\sim 1\ll\alpha_{HS}$ was obtained for Al-I-Pb junctions).[2)]

The two-band approximation made it possible to eliminate this discrepancy. The expression obtained with the aid of (5) for the coefficient α is

$$\alpha=\alpha_{HS}\left[\frac{m^*}{m(1-x)}\right]^{1/2}\left[1-2x+\frac{\Delta\varphi}{8(1-x)\bar{\varphi}}\right], \qquad (9)$$

where $x=\bar{\varphi}/E_g$; relation (9) is valid at $0.1<x<0.9$, i.e., far from the immediate vicinity of the boundaries of the forbidden band. If $E_g\gg\bar{\varphi}$, we obtain the earlier result $\alpha=\alpha_{HS}$ at $\Delta\varphi\ll\varphi$. A more realistic case, however, is $E_g\approx 2\bar{\varphi}$ (see above), and α turns out to be very small, as was observed in fact in Refs. 9 and 10. It is interesting that at $x>1/2$, i.e., $2\bar{\varphi}>E_g$, the usual vacuum-gap approximation (1) can yield even an incorrect sign for the effects discussed.

2. Relations (7) and (9) can be used to solve the inverse problem—obtaining information on the phonon-phonon interaction in the N metal. Indeed, measurement of the function $\sigma_-(U)$ in the region of phonon energies of the investigated metal yields for it $\mathrm{Re}\Sigma(\omega)$. Connected directly with the electron-phonon interaction function $g(\omega)$ of the N metal is

$$\mathrm{Im}\,\Sigma(\omega)=\pi\int_0^\infty g(\omega')\,d\omega',$$

which can be determined from the dispersion equation

$$\mathrm{Im}\,\Sigma(\omega)=\frac{2}{\pi}\int_0^\infty\frac{\mathrm{Re}\,\Sigma(\omega')\,\omega'}{\omega^2-\omega'^2}\,d\omega'. \qquad (10)$$

After suitable transformations we obtain

$$g(\omega)=\frac{2\varepsilon_F\omega}{\alpha\sigma_0\pi^2}\int_0^\infty\frac{d\sigma_-(U)}{dU}\frac{dU}{U^2-\omega^2}. \qquad (11)$$

In the actual use of (11), account must be taken of two circumstances.

First, although formally the integration in (11) extends to infinity, it suffices to have data only up to $U=U_c\approx 3\omega_0$, where ω_0 is the upper limit of the phonon spectrum, and use at $U>U_c$ the asymptotic relation

$$d\sigma_-/dU=-(2\alpha\sigma_0/\varepsilon_F)\,(\bar{E}/U^2),\qquad \bar{E}=\int_0^\infty g(\omega)\,\omega\,d\omega.$$

The constant $\bar{E}$ is determined from the condition that $d\sigma_-/dU$ is continuous at the point $U=U_c$. Simple estimates show in this case that the error in the reproduced $g(\omega)$ is less than one percent.

Second, in the odd part of the conductivity of N-I-N junctions there exists as a rule, besides the increment (7), also an appreciable linear background. It is due to the fact that the function $\sigma(U)$ is described in a large voltage interval by the parabola (2) with $A\neq 0$. To determine the sought function $d\sigma_-/dU$ in (11) it is necessary to subtract the quantity A from the corresponding contribution to the derivative $d\sigma/dU$ of the odd part $\sigma_-(U)$. In principle, the latter should be obtained by fitting formula (2) to the experimental $\sigma(U)$ measured up to $|U|\gtrsim 10\omega_0$. In practice, it is more convenient to use for this purpose the condition

$$\int_0^\infty\frac{d\sigma_-}{dU}(U)\,dU=0, \qquad (12)$$

which follows from the definition (7) of $\sigma_-(U)$ and from the equation

$$\lim_{\omega\to\infty}\mathrm{Re}\,\Sigma(\omega)=\mathrm{Re}\,\Sigma(0)=0.$$

It is then easy to find that the relation between A and the experimentally obtained curve is of the form

$$A=\frac{1}{2}\left[\frac{1}{U_c}\int_0^{U_c}\left(\frac{d\sigma_-}{dU}\right)_{\exp}dU+\left(\frac{d\sigma_-}{dU}\right)_{\exp}\Big|_{U=U_c}\right]. \qquad (13)$$

3. To reconstruct the electron-phonon interaction function of a normal metal we investigated the tunnel characteristics of junctions of aluminum + aluminum oxide + the investigated material, the latter being lead, bismuth, and a Pb-Bi alloy with Bi concentration $\approx$ 30 at. %. The principal measurements were made at a temperature 2.3 K above the critical superconducting-transition temperature of aluminum, and to bring Pb and Pb-Bi back to the normal state we applied a magnetic field of strength up to 10 kOe. The choice of lead for the investigation was due primarily to the fact that its electron-phonon interaction function is known in detail from data on superconducting tunneling[1] and is to some degree a standard for checking the tunnel experiment. The function $g(\omega)$ for the $Pb_{70}Bi_{30}$ alloy was determined in Ref. 11 likewise from superconductivity measurements, so that its reconstruction with the aid of the procedure described above can serve as an additional control on the correctness of the proposed approach. As for bismuth, the corresponding relations were obtained only for the superconducting modifications, namely amorphous bismuth[12] and the high-pressure phase Bi III (Ref. 13), so that particular interest attaches to reconstructing the electron-phonon interaction function for crystalline Bi I at atmospheric pressure and in the normal state.

The experimental differential conductivity $\sigma(U)$ was measured in the interval from -40 to 40 mV, which is several times larger than the region of phonon singularities in the considered metals. The $\sigma_-(U)$ increments calculated from these data are shown in Figs. 2 and 3. The sets of experimental points were approximated by rational fractions on individual sections by least squares.[14] We obtained thus in each case smooth curves, which are also shown in Figs. 2 and 3. The results of their numerical differentiation were substituted, after making the correction described above, in Eq. (11).

Comparison of the obtained $g(\omega)$ for lead and for its alloy with bismuth with those previously determined from

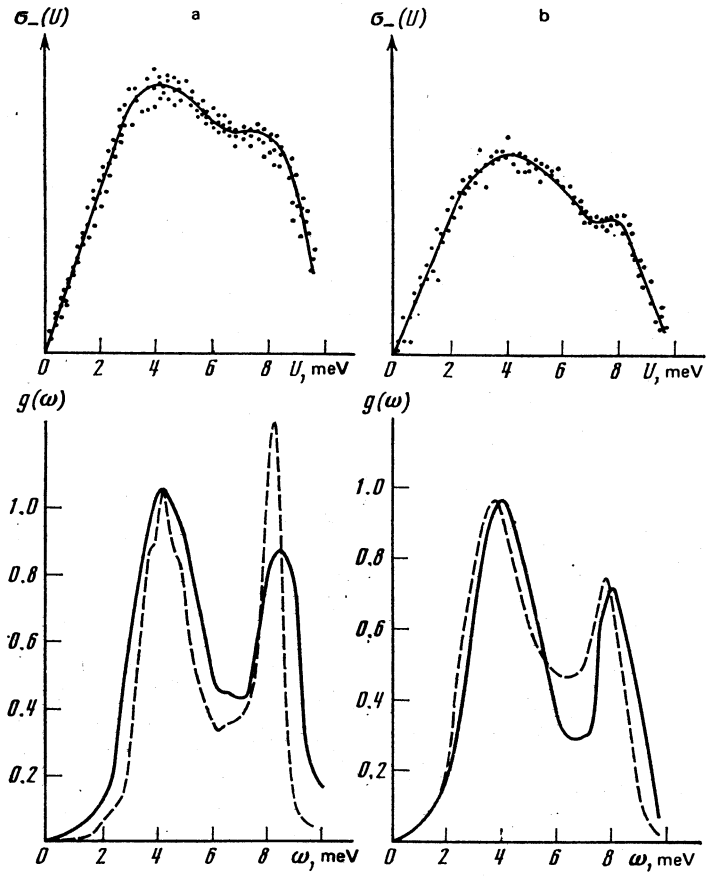

FIG. 2. Odd parts $\sigma_-(U)$ of tunnel conductivity (in arbitrary units) and the electron-phonon interaction functions $g(\omega)$ reconstructed from them (solid lines) for normal metals: lead (a) and $Pb_{70}Bi_{30}$ alloy (b). Dashed curves—the functions $g(\omega)$ for Pb and $Pb_{70}Bi_{30}$ known from the superconductivity measurements (Refs. 1 and 11).

superconducting-tunneling data (Fig. 2) demonstrate the reliability of the results. One of the causes of the noticeable difference between the two curves for lead in the region of the peak of the longitudinal lattice vibrations may be the temperature broadening, which has in normal junctions at an experiment temperature $T = 2.3$ K and at a modulation amplitude $V_1 = 0.3 - 1.0$ mV an appreciable value, equal according to Ref. 15 to $[(5.4kT)^2 + (1.22eV_1)^2]^{1/2} \approx 2$ meV.

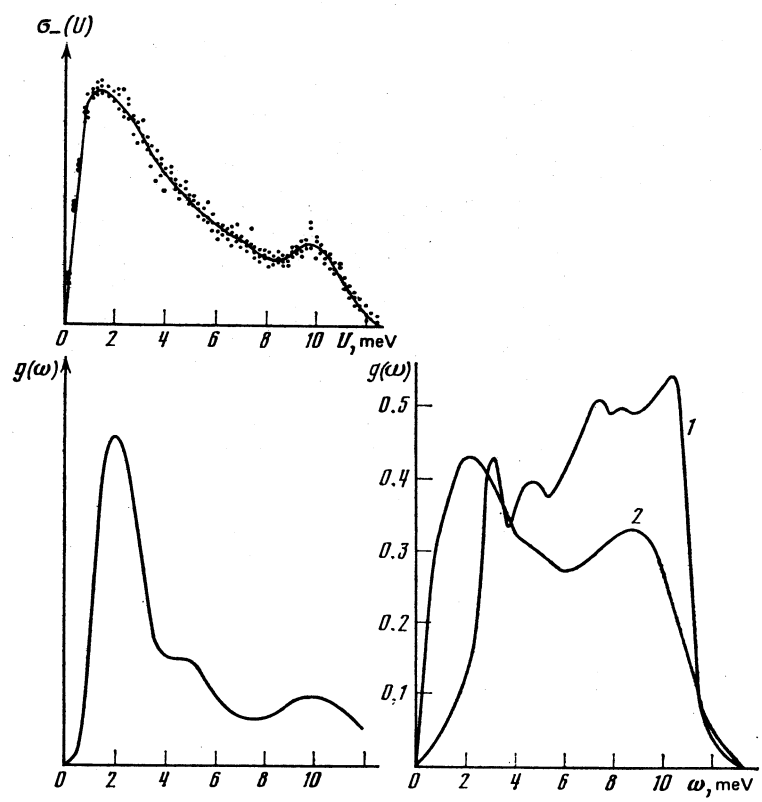

FIG. 3. Odd part of tunnel conductivity $\sigma_-(U)$ and the reconstructed electron-phonon interaction function $g(\omega)$ for bismuth (both curves are in arbitrary units). For comparison are shown separately the normalized functions $g(\omega)$ of the superconducting high-pressure phase[13] Bi III (curve 1) and of superconducting amorphous bismuth[12] (curve 2).

The same circumstance causes the obtained functions $g(\omega)$ to be much more smoothened compared with the corresponding curves for superconducting junctions. Finally, one must point out also the role of the interference increment to the odd part of the tunnel conductivity, which is similar in form to the relation (7) but is of opposite sign.[16] As shown in Ref. 16, allowance for this additional mechanism of electron tunneling decreases the observed effect and lowers the amplitude of the effective electron-phonon interaction function in the high-energy region.

We note that the $g(\omega)$ curves shown in Figs. 2 and 3 for normal metals are not normalized, inasmuch as it is impossible at present to determine with sufficient accuracy the coefficient C. In the case of lead and of the Pb-Bi alloy they were brought into coincidence with the known $g(\omega)$ at the point of the maximum of the low-frequency peak of the transverse oscillations.

We dwell now on the amplitude of the investigated effects. For the investigated $Pb_{70}Bi_{30}$ samples with junction resistances that differ by more than one order of magnitude, the ratio $\sigma_-(U)/\sigma_0$ turned out to be approximately equal and reached a value 0.000 53 in the region of the principal maximum at $U\approx 4$ meV. Using the calculated value of $\mathrm{Re}\Sigma(\omega)$ at this point,[11] we obtain $\alpha\approx 0.5$ for Al-I-$Pb_{70}Bi_{30}$ junctions. In the case of lead the ratio $\sigma_-(U)/\sigma_0$ varied noticeably from sample to sample; in particular, at the point of the maximum corresponding to the transverse phonons, it amounted to 0.000 48 to 0.000 66, corresponding to $\alpha\approx 0.5$ to 0.7. Owing to the indicated scatter of the values of α, the $\sigma_-(U)$ curves for the different samples with lead were brought into coincidence at the maximum point (≈ 4.4 meV) independently of their absolute values. We point out that our values of α agree with those observed earlier in Ref. 9, where this parameter was of the order of unity.

The amplitude of the main low-frequency peak of $\sigma_-(U)/\sigma_0$ in bismuth turned out to be very large. It exceeded by an order of magnitude the corresponding value for lead and its alloys. From the viewpoint of Eq. (7) this means that either the force of the electron-phonon coupling in Bi or the parameter C in Al-I-Bi junctions is anomalously large (in the latter case the cause may be the penetration of the bismuth into the aluminum-oxide region). If, however, the described analysis is applied to the second peak at $U\approx 10$ meV and it is assumed, as before, that $C\sim 10^{-4}$, we obtain as a result at $\omega_0 = 10$ meV the perfectly reasonable value $\mathrm{Re}\Sigma(\omega_0)\sim 10$ meV. This contradiction can be attributed, with the large value of C retained, to the influence of the interference increment, but in our opinion it is more probable that in our case the peak at ≈ 2 meV is not connected with phonons but is a manifestation of some other electron-tunneling mechanism. If we subtract it arbitrarily from the obtained $g(\omega)$ curve, two broad maxima are left in it at energies close to 4 and 10 meV. This agrees qualitatively with neutron-measurement data[17] for crystalline bismuth, as well as with the function $g(\omega)$ for the superconducting Bi III phase (Fig. 3). The final answer to this question calls for further research.

5. CONCLUSION

We observed and explained on the basis of the two-band approximation (5) the appreciable shift of the minimum of the differential conductivity $\sigma(U)$ under pressure. The same model turned out to be capable of eliminating the earlier disparity between the theory and the measured self-energy effects in the odd part of $\sigma(U)$. A new procedure was developed for reconstructing the electron-phonon interaction function of the normal metal. The results obtained by this procedure for lead and its alloys with bismuth agree well with the known functions $g(\omega)$ determined from superconductivity measurements. It becomes thus possible to determine directly in experiment the true electron-phonon interaction function, which enters in the Éliashberg equations, for a normal metal.

Naturally, not all the questions connected with the barrier properties of tunnel junctions have been answered. It is necessary to ascertain, in particular, the quantitative contribution made to $\sigma(U)$ by the interference term[16] that is undoubtedly present in the tunnel characteristics. Its influence was apparently found to be noticeable for junctions with bismuth. From the experimental viewpoint the main task is the production of new barrier layers with large values of the coefficient C. This will permit an increase in the amplitude of the observed effects and consequently improve the accuracy of the results.

In conclusion, we thank A. A. Galkin for constant interest and support, V. A. Chubar' for help with the experiment, and A. I. D'yachenko for helpful discussions.

[1)] We consider here only the case of nonresonant tunneling when the electron energy is far from the energy of the impurity levels.

[2)] Experiments[10] aimed at observing the tunnel current between junction electrodes that have different temperatures also yielded for Ca value smaller by an order of magnitude than follows from Eq. (8).

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