TUNNELING OBSERVATION OF PHONON STRUCTURES IN Bi–CONTAINING HIGH TEMPERATURE SUPERCONDUCTORS

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Tunneling investigations were carried out on superconducting $(Bi, Pb)_2Sr_2Ca_2Cu_9O_{10}$ *film and* $Bi_2Sr_2CaCu_2O_8$ *texture. There were reconstructed EPI spectra* $\alpha^2F(\omega)$ *from tunneling data. These spectra were compared with each other and the neutron ones. For a understandingly of the EPI main role for* T_c *change we compare the values of* λ, μ^*, T_c *derived from the reconstructed EPI function* $\alpha^2F(\omega)$ *with the familiar relations. From the obtained facts one can infered an argument for the electron-phonon model of interaction in high-*T_c *superconductors.*

Introduction. A complicated nature of high temperature superconductivity causing superconductive properties of materials is not quite clear and the object of the majority of researches, including tunnel ones, is the elucidation of the mechanism of superconductivity. Either tunnel characteristics fully reveal the densities of different excitations in the investigated superconductors and their dependence on the structures. Therefore, it is interesting to trace a correllation between the results of tunnel investigations and superconducting properties of different compositions. Being combined with the results of other experiments it allows one to reveal the nature of the electron-phonon interactions (EPI) in high temperature superconductors.

Sample parameters. The objects for our tunnel investigation were superconducting $(Bi, Pb)_2Sr_2Ca_2Cu_9O_y$ film and $Bi_2Sr_2CaCu_2O_x$ texture with distinguished crystallographic c axis (by X-ray analysis data).

The film has been evaporated by means of laser sputtering onto a MgO substrate. The thickness of the film was about ~ 1 μm. The film has the superconducting transition finish at a 105 K which has been measured by the standard resistive four probe method. The transition width is about 3–4 K. Electron microscope investigations show granular structure of the film surface.

The texture has been grown by the flux method * and has superconducting transition with the resistance zero at 81.5 K.

Tunnel measurements. The tunnel investigations have been made by the standard modulation technique at the temperature of 20 K. The normal metal-superconductor ($N-S$) contact has been realized by the W needle with the point with the diameter of about 1 μm, as normal metal.

Fig. 1,*a* shows the typical $I-V$ characteristics for our samples at $T = 21$ K. The singularity of this $I(U)$ function indicates that we probably deal with superposition of two current components, i.e. $I(U) = I_n(U) + I_s(U)$, where $I_n(U)$ corresponds to the background tunnel current of normal electrons of $N-I-N$ contact, and $I_s(U)$ corresponds to the tunnel current of quasiparticles. In our opinion the reason of $I_n(U)$ appearance is inhomogenity of a superconducting sample (the

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presence of nonsuperconducting grains coming with superconducting ones in contact with the metal needle).

$I_n(U)$ can be represented as:

$$I_n(U) = (aU + bU^3 + ...) \ ,$$

where a,b are the parameters.

Fig. 1 (b,c) shows the first derivatives of the $I-V$ characteristics which are the reflection of two components of tunnel current. Therefore central peak (at $U = 0$) and nonlineary of $I(U)$ at $|U| > |\Delta|$ of the first derivatives are probably caused by the presence of $I_n(U)$ component.

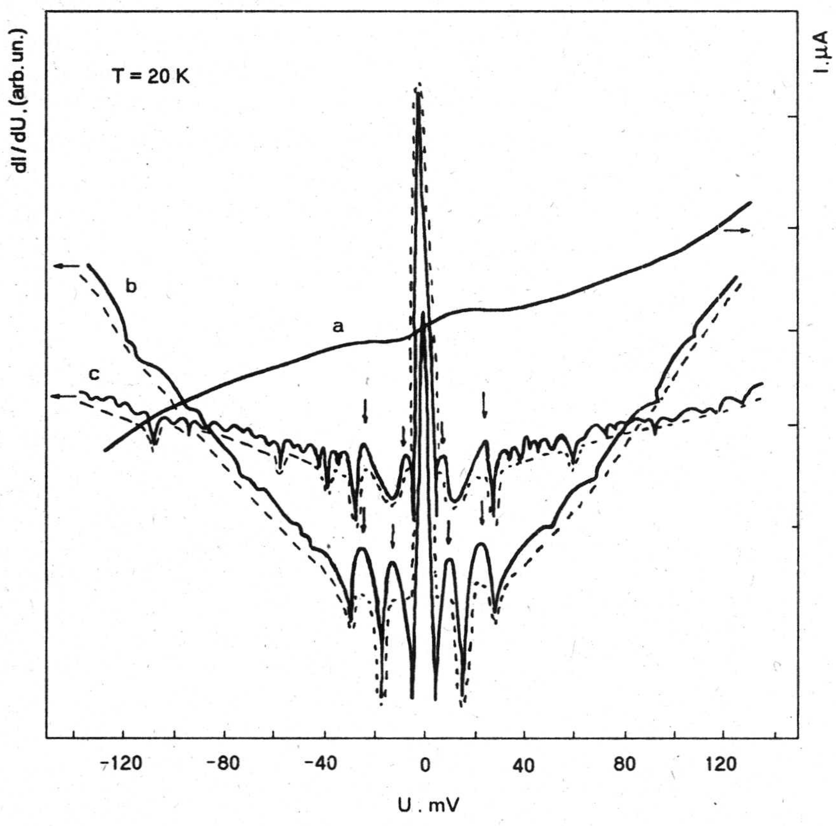

Fig. 1. $I-U$ and $(dI/dU)-U$ data of tunnel junctions of the contacts: a, b — texture; c — film. Dashed lines indicates $\sigma_n(U)$ functions

We have determined the values of superconducting gaps with the maxima of the $I-V$ characteristics presented in Fig. 1 (b,c). These values are $\Delta_{\text{film}} = 26$ meV for the film sample and $\Delta_{1T} = 14$ meV and $\Delta_{2T} = 24$ meV for the texture. This closeness of magnitudes of superconducting gaps Δ_{film} and Δ_{2T} for different critical temperatures T_c is probably linked with the fact that Δ_{film} is the average value $<\Delta_{\text{film}}>$ because of anisotropy [1] and the gap Δ_{2T} for textured sample corresponds to the direction of crystallographic axis c. The negative peaks situated immediately after the gap maxima at the $I-V$ characteristic's derivative

(Fig. 1,*b*,*c*) in our opinion, are caused by the fact that the increase in the tunnel current through the contact is interrupted at the values of voltage U close to the gap value Δ/e because of overheating of weak links between the grains in the contact region. It is reflected in the $I - V$ derivatives as a sudden drop of the differential conductance immediately after the gap singularities.

The reconstruction of the EPI function. The reconstruction of the function of EPI $\alpha^2F(\omega)$ from the $I - V$ characteristics has been made by dispersion method [2] under a program [3]. In addition to the calculation of $\alpha^2F(\omega)$ this program is able to calculate the function of density of states $N(\omega)$, the constant of EPI λ, the Coulomb potential μ^*, the superconducting transition temperature T_c and other parameters. The normalized function of the tunnel contact conductance σ_s/σ_n is used as a starting parameter of the program. The aim of the normalization is to exclude the singularities of non-phonon nature from the curve of the density of states. Proceeding from the above reasons as $\sigma_n(U)$ we used such $dI_n(U)/dU$ function, which tracks the form of $\sigma_s(U)$ without phonon singularities and consists of central and negative peaks of evidently non-phonon nature (see Fig. 1, *b*,*c*). This choice of $\sigma_n(U)$ function probably leads to a certain loss of information on phonon singularities in small region of a negative peak width at the U axis.

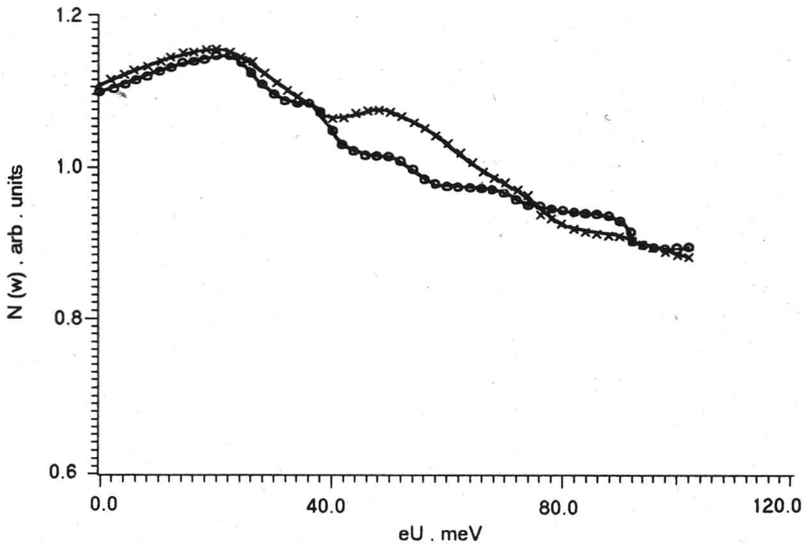

Fig. 2. The corrected tunnel density of states $N(\omega)$: O — texture; × — film

The starting value of the textured sample gap was assumed as Δ_{2T}.

The peculiarities of the EPI function for the superconductors with the phonon mechanism of the Cooper coupling are reflected in the differentials of the $I - V$ characteristics of contacts with direct conductance as a singularities located at the U axis near the phonon characteristic energies [4] seem. These singularities to be well-revealed at the calculated functions of the density of states $N(\omega)$ presented in Fig. 2.

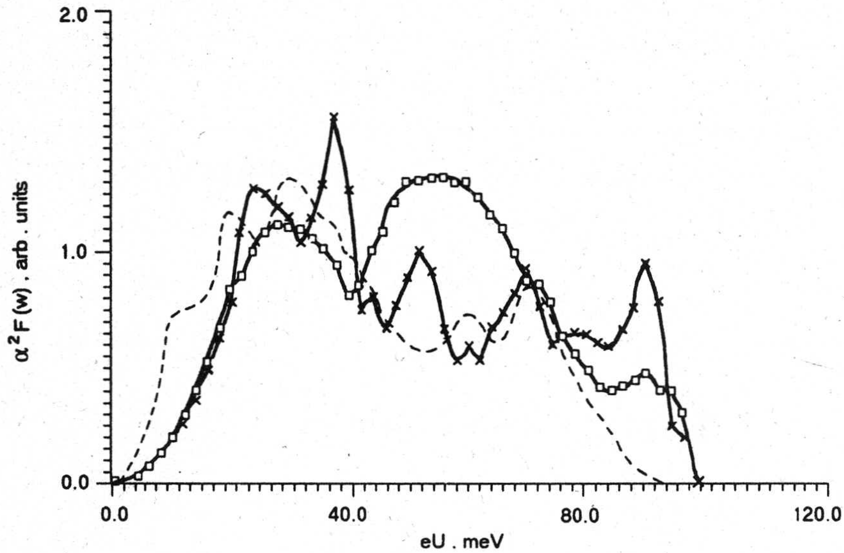

Fig. 3. The EPI function $\alpha^2F(\omega)$: × — texture; □ — film; --- — neutron scattering data

Fig. 3 shows the calculated functions of the EPI for both samples. Good agreement between the results of electron scattering [5] and calculated $\alpha^2F(\omega)$ of textured sample is observed in the general form of the spectrum. However, the calculated functions $\alpha^2F(\omega)$ of our samples are slightly shifted (by ~ 10 meV) to the high-frequency range and the additional peaks are revealed there at 90 meV range. The comparison of the EPI functions of the texture and the film shows that the amplitude of the spectrum peaks for the film decreases at the low and high-frequency range and increases at the mid-frequency range. At this broadening and confluence of the peaks at 52, 60, 70 meV probably occurs. Such spectrum transformation is, probably, linked with either an appearance of new vibration modes because of an increase of CuO planes a number of (from 2 to 3) in the Bi–Pb–Sr–Ca–Cu–O elementary cell or the intrinsic structure of the film.

This broadening and confluence of $\alpha^2F(\omega)$ spectrum had been observed earlier for Pb films with different degrees of disordering [6] and for domestic Al films [7,8].

The critical temperature of superconducting transition. Conclusion. To disclose the EPI main role for T_c change we tried to compare the values of λ , μ^* , T_c derived from the reconstructed EPI function $\alpha^2F(\omega)$ with the following familiar relations:

McMillan relation [9]

$$T_c = \frac{\omega_1}{1.2} \exp\left\{-\frac{1.04(1+\lambda)}{\lambda - \mu^*(1+0.62\lambda)}\right\}, \tag{2.1}$$

where

$$\omega_1 = \frac{2}{\lambda}\int_0^\infty d\omega\, \alpha^2 F(\omega)\,; \tag{2.2}$$

Allen-Dynes [10] (2.1), where $f_1 f_2 \omega_{\log}$ is substituted for ω_1 :

$$\omega_{\log} = \exp\left\{\frac{2}{\lambda}\int_0^\infty \frac{d\omega}{\omega}\alpha^2 F(\omega)\ln\omega\right\} \tag{3.1}$$

$$f_1 = \left[1 + \left(\lambda/2.46(1 + 3.8\mu^*)\right)^{3/2}\right]^{1/3} \tag{3.2}$$

$$f_2 = \left[1 + \frac{(\omega_1/\omega_{\log} - 1)^2}{\lambda^2 + \left[1.82(1 + 6.3\mu^*)(\omega_1/\omega_{\log})\right]^2}\right]^{1/3}\,; \tag{3.3}$$

Wu-Ye [11]:

$$T_c = (1/5.42)\omega_{\log}(1 + 0.53\lambda)\exp\left[-1.25/(\lambda - 0.11)\right]. \tag{4.1}$$

We also substituted an average phonon frequency in the formula (2.1)

$$<\omega> = \frac{\int \omega\, \alpha^2 F(\omega)\, d\omega}{\int \alpha^2 F(\omega)\, d\omega} \quad \text{for } \omega_1\,. \tag{5.1}$$

From the above-mentioned relations values of T_c presented for comparison in Table with the values of experimental $T_{c,\exp}$ and calculated by program of EPI function reconstructed from tunneling data $T_{c,\mathrm{calc}}$ have been calculated. The comparison shows that the results of calculation by formula (5.1) are the most closely spaced to $T_{c,\exp}$ and $T_{c,\mathrm{calc}}$. Besides, the correlation between the rise of T_c and increase of EPI constant value λ has been observed.

A good agreement (difference ~ 12 %) of calculated magnitudes $T_{c,\mathrm{calc}}$ by Eliashberg theory's formula and McMillan's estimation formula (5.1) with the experimental results $T_{c,\exp}$ is a serious argument for the EPI model in high-T_c superconductors. The obtained values of $2\Delta/kT_c$ for the film and texture samples were equal to: $2\Delta_{\mathrm{film}}/kT_c = 5.74$; $2\Delta_{1T}/kT_c = 3.7$; $2\Delta_{2T}/kT_c = 6.8$.

The data presented in this paper could be important for practical applications. The careful investigation of the phonon spectrum of high-T materials, in particular, Table. Comparison of the results of calculations by formulae (2.1)–(5.1), by program of reinserted EPI spectra and experimental data.

	FILM	TEXTURE
$T_{c,exp}$, K	105	81.5
$T_{c,calc}$, K	121.3	95.3
T_c (McMillan), K	86.6	66.9
T_c (Allen–Dynes), K	33.8	23.5
T_c (Wu–Ye), K	50.4	46.8
T_c (5.1), K	93.7	73.9
λ	3.76	3.6
μ^*	0.11	0.23
ω_{log}, meV	11.08	10.75

allows one to calculate theoretically the non-equilibrium states which can appear in high-T_c superconductors at external pumping conditions.

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