THE NORMAL STATE OF HIGH TEMPERATURE SUPERCONDUCTORS: ELECTRON TUNNELING STUDIES

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Original results and literature data on electron tunneling into the normal state of high-T_c oxides are discussed. It is shown that the linearity of the normal tunnel conductance, the most striking feature of these curves, has not obtained a satisfactory explanation yet.

At present there is a quite large number of studies of high-T_c superconductors by the electron tunneling method [1,2,3]. However, nearly without exception main effort in these papers was aimed at measuring the magnitude of the superconducting gap and reconstructing the electron-phonon interaction function $g(\omega)$ [3] while normal state properties are almost undiscussed. In this contribution on the basis of own results and an analysis of data obtained by other experimental groups we are going to show that tunneling into the normal state of metal oxides can perform not only an auxiliary function placing at our disposal curves for normalizing superconductive tunnel characteristics but also play the role of an arbiter between different theoretical models of HTSC.

The normal state tunneling characteristics measured over a wide voltage range can carry the most important and interesting information that is able to change drastically our conception on electron properties of metal oxides. Now there is no doubt that above the superconductive gap voltage where behaviour of tunneling characteristics is determined by the normal-state rather than superconductive properties the curve of the differential conductance $\sigma(V) = dI/dV$ of metal oxide contacts radically differs from corresponding one of conventional metals. Namely, at large voltages it has an unusual shape. For example, we present in Fig. 1 the dependence of $\sigma(V)$ obtained by us [5] from tunnel structure Pb/YBCO. A thin

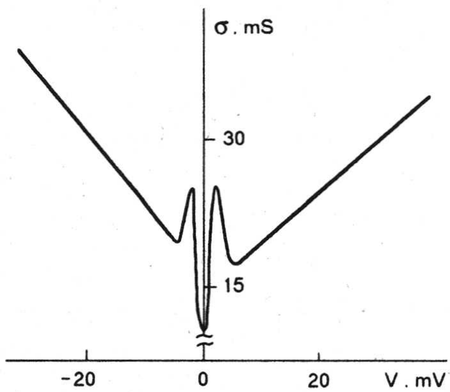

Fig. 1. Differential conductance $\sigma(V) = dI/dV$ of the tunnel contact Pb (thin film)/YBCO (single crystal) at 4.2 K

film lead injector was condensed on a fresh cleaved surface of a superconductive yttrium single crystal. The role of the insulator layer played a nonconducting surface layer that is naturally formed on the sample surface. The presence of a gap like structure in Fig. 1 proves that tunneling is the main mechanism of charge transfer through the insulator layer. The lack of a gap structure of the material under study is caused by the presence of a nonsuperconducting layer that is placed immediately under nonconducting one. The tunneling into this layer completely determines the shape of the tunneling characteristics. In general case the behaviour of the experimental curves $\sigma(V)$ can be described by the formula

$$\sigma(V) = \begin{cases} \sigma_0 + \alpha_1 V & \text{at } V > 0 \\ \sigma_0 - \alpha_2 V & \text{at } V < 0 \end{cases} \quad (1)$$

The presence of a linear term in $\sigma(V)$ by itself is not surprising when it is recalled that such a term in principle can be explained by the change of the barrier transparency with bias voltage. It is the nonanalytical behaviour near zero voltage (i.e. the presence of the $|V|$ term) that is the most striking feature of these tunneling data.

Nowadays the nature of this anomaly is a subject of intense interest and debate. Indeed, this anomaly proves to be intrinsically connected with features of the normal-state quasiparticle excitation spectrum it will be fatal not only to the conventional Bardin–Cooper–Schrieffer theory with the electron-phonon interaction mechanism but also to all theories with the electron-"something on" interaction mechanism, because then the nonanalytical and asymmetrical behaviour of $\sigma(V)$ means that particle-hole symmetry is broken and the time reversal symmetry is lost.

However, first let us discuss more simple approaches to this problem. For example, models based on the Coulomb blockade phenomena: the Zeller–Giaever model [6,7] and the single-electron tunneling [8,9]. In the former one electron tunneling is assumed to occur through conductive droplets placed in the insulating layer of a tunnel junction. In this case there is a threshold bias beginning from which electron transfer across the barrier via intermediate states in grains is possible (V_d is a random variable representing the offset of the highest filled electron level of a grain from the Fermi level of the electrode). Averaging over V_d and C gives formula (1). In spite of its popularity this model has serious difficulties when trying to reach a quantitative agreement between theoretical and experimental data. In order to the linear increasing in $\sigma(V)$ stretches up to voltages of a few hundred of millivolts it is necessary to assume that the capacity of the grains can be extremely small. In its turn this put on a strict restriction on the geometrical size of grains. If the grains are assumed to be spherelike, i.e. its capacity is $C = 4\pi\varepsilon\varepsilon_0 r$, where the dielectric constant ε of an insulating layer can not be less than unity, it follows that the particles of several angstrom diameter must be present in the insulating layer.

Another mechanism, that results in the linearity of $\sigma(V)$ was proposed in [8]. It is based on the effect of the Coulomb blockade caused by the small capacitor of the tunnel junction itself. If $C < 10^{-15}$F, $T = 1$ K the so called process of single electron tunneling is possible at which the electrons tunnel one at a time at a more or less fixed time interval. A feature of the single-electron tunneling is that the static $I-V$ characteristic is quadratic in V at low voltages, and at high voltages tends to a linear asymptote, which is displaced from the origin by $e/2C$. Such effects have been already observed in very small planar film junctions fabricated on the base of conventional superconductors and as shown in [10], in principle, can be realized in the standard point contacts [9]. The point is that the tunneling process and the subsequent redistribution of the charge on the tip is a dynamical process and the stray capacitance of the part far away from the tip does not give any contribution to the effective capacitance $\sim 10^{-8}$ F is quite feasible, and range of the linear behaviour of the tunnel conductance can fulfill over several tens of millivolts.

In connection with the above discussions it was very interesting to study the behaviour of the tunnel conductance at voltage bias much more than 100 mV. Such investigations were carried out on thin film contacts Pb/YBCO [11]. As Fig. 2 illustrates, the symmetrical linear behaviour extends up to 0.5 V that implies a full failure of the discussed models.

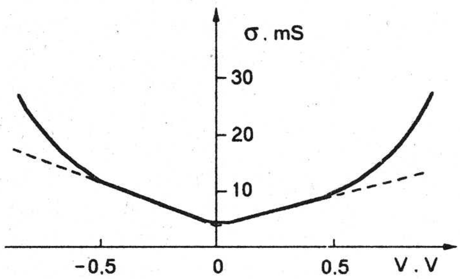

Fig. 2. Differential conductance $\sigma(V)$ of the thin film tunnel contact Pb/YBCO at 112 K

Note that in contrast to Fig. 1 the anomaly of $\sigma(V)$ presented in Fig. 2 is symmetrical respective to $V = 0$, i.e. coefficients α_1 and α_2 are equal and the conductance-voltage dependence is given by $\sigma(V) = \sigma_0 + \alpha|V|$. In this structure tunneling is believed to be realize between two metal oxide grains located away from the contact area of metal and metal oxide films. This assumption is supported by the correlation between the asymmetry of the tunnel characteristics and observation of the superconducting gap of the metal injector. The curves not having any metal injector gap structure were in most part symmetrical while the curves showing such a structure were asymmetrical, sometimes very greatly. It should be emphasized that in agreement to conclusions of [12] the conductance rose more rapidly at positive voltage bias on the metal oxide side.

It is instructive to note once more the unusual character of the above results. If the effect of increasing conductance was caused by changing of transparency of a trapezoidal barrier, the dependence of differential $\sigma(V)$ must be given by the formula

$$\sigma(V) = \sigma_0 + \alpha\Delta\Phi V + \beta V^2 . \qquad (2)$$

In this case the linear term must be present in the odd part of conductance $\sigma^-(V) = [\sigma(V) - \sigma(-V)]/2$. But the fact is the linear behaviour occurs in the even part of conductance $\sigma^+(V) = [\sigma(V) + \sigma(-V)]/2$, while the odd part does not reveal any linear increasing with voltage.

Now we are going to discuss another approach to interpretation of tunneling data. Earlier we automatically supposed that tunneling occurs via an elastic channel, but these features can result from inelastic interaction of the tunneling electron with some excitations in the structure. As was shown in [13] the shape and amplitude of the anomaly in curves $\sigma(V)$ can be understood if spin fluctuations are assumed to play the role of such excitations. These fluctuations are very important for the theory of "spin bag" by J. R. Schrieffer. The very interesting results were obtained in [14] for four copperless compounds $BaPbBiO_3$ ($T_c = 3.5$ K), $BaPb_{0.75}Bi_{0.25}O_3$ ($T_c = 11 \div 12$ K), $Ba_{0.7}K_{0.3}BiO_3$ ($dT_c = 24 \div 30$ K). The tunnel conductance of the contacts metal (Au, In or Ag) — insulator — (copperless) HTSC was found to closely follow a linear dependence on voltage (1). Moreover, a clear correlation between the slope of the conductance curve and T_c was found: the higher T_c the greater coefficient α_i. The authors of [14] believe that this fact is due to strong renormalization of spectral characteristics of charge carriers caused by many particles effects and the slope of the conductance curve is a measure of the strength of the coupling in a mechanism that is responsible for occurrence of high-T_c superconductivity. On the other hand, the materials under study are three-dimensional objects, and it is suspected that the two-dimensional theories (including the RVB theory by Anderson) are justified in this class of materials. Besides, these materials do not contain any magnetic moments therefore it is very doubtful that the theory of "spin bag" is useful in this case. Maybe we must not spurn the usual BCS theory but look for a mechanism that will be able to explain the results of tunneling experiments (in [15] it was argued that the linear anomaly in $\sigma(V)$ can be understood in terms of a model of two narrow bonds located on a short distance above and bellow the Fermi level against a background of one wide bond).

Now it is only clear that solution of this problem can give insight on the nature of the high-T_c superconductivity.

1. *Kirtley J. R.*, Int. J. Modern Phys. B4, 201 (1990).
2. *Hasegawa T., Ikuta H., Kitazawa K.*, Preprint, 96 p. (1992).
3. *Свистунов В. М., Белоголовский М. А., Хачатуров А. И.*, Препринт АН УССР, ДонФТИ, № 14, 40 с. (1990).
4. *Свистунов В. М., Белоголовский М. А., Хачатуров А. И.*, Препринт АН УССР, ДонФТИ, № 1, 48 с. (1992).
5. *Свистунов В. М., Белоголовский М. А., Хачатуров А. И.*, Тезисы докладов II Всесоюзной конференции по ВТСП, Киев, 1989, т. 2, с. 201—202.
6. *Zeller H. R., Giaever I.*, Phys. Rev. 181, 789 (1969).
7. *Kirtley J. R, Tsuei C. C., Park S.I. et al.*, Phys. Rev. B35, 7216 (1987).
8. *Averin D. V., Likharev K. K.*, J. Low. Temp. Phys. 62, 345 (1986).
9. *Van Bentum P. J. M., van de Leemput H., van de Leemput L. E. C., Teunissen P. A. A.*, Phys. Rev. Lett. 60, 369 (1988).
10. *Fulton T. A., Dolen G. J.*, Phys. Rev. Lett. 59, 109 (1987).
11. *Svistunov V. M., Khachaturov A. I., Belogolovskii M. A. et al.*, Modern. Phys. Lett. B4, 111 (1990).
12. *Flensberg K., Hedegard P., Brix M.*, Phys. Rev. B38, 841 (1988).
13. *Kirtley J. R., Washburg S., Scalapino D. J.*, ФНТ 18, 556 (1992).
14. *Dynes R. C.*, J. Phys. Chem. Solids 52, 1477 (1991).
15. *Пашицкий Э. А., Малозовский Ю. М., Семенов А. В.*, ЖЭТФ 100, 465 (1991).