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Tunneling spectroscopy of Bi(Pb)-Sr-Ca-Cu-O superconductors

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Abstract

The tunneling characteristics for break junctions in polycrystalline $Bi_{1.7}Pb_{0.4}Sr_{2-X}Ca_{2+Y}Cu_{3+Z}O_{10+\delta}$ samples fabricated by direct mixing of oxides-carbonates (1) and via Bi(Pb)-Ca - O + Sr-Ca-Cu-O precursors (2) have been investigated. Long time annealing of the samples (1) causes decomposition in the form of the intergrowth faults (2212 - in 2223 - phase), which leads to the formation of the natural superlattice of the type S_1-S_2-S_1-S_2-.. and to an emergence of a reproducible vertical rise of current in the I-V characteristics for break junctions at voltages $V \cong \pm 2\Delta/e$. A record value of the characteristic voltage $V_c = I_cR_n = (31 \pm 4)$ m V at T=4.2K has been detected. Evidence for an important role of the proximity effect in the samples (1) has been obtained. For the samples (2) the tunneling characteristics were strongly dependent on X,Y and Z . The samples with X=0.2, Y=Z=0 consist of an almost pure 2223-phase with a large gap parameter $\Delta=(31 \pm 1)$meV (T=4.2K). For these samples the subharmonic structure in the I-V characteristics , caused by the self-detection of Josephson radiation was observed. From I-V and dI/dV - V characteristics the tunneling density of states has been calculated. The advantage of the method of precursor synthesis for the effective modification of superconducting properties of Bi(Pb)-Sr-Ca-Cu-O has been demonstrated.

1. Introduction

Preparation conditions of BSCCO superconductors have a profound effect on their chemical, physical and superconducting properties. This provides a way for their modification. Long time annealing of the BSCCO samples, for example, causes decomposition in the form of intergrowth faults, which often leads to the formation of a natural superlattice of the type S_1-S_2-S_1-S_2.. . Up to now little is known about the physical properties of such structures, though recently a strong manifestation of the proximity effect has been reported [1].

The temperature dependence of the gap parameter $\Delta(T)$ and of the lifetime of quasiparticles $\tau(T)$, the energy dependence of the density of states of quasiparticle exitations at different temperatures and many other important characteristics can be determined quite accurately from tunneling experiments. In this communication we report break junction tunneling measurements on $Bi_{1.7}Pb_{0.4}Sr_{2-X}Ca_{2+Y}Cu_{3+Z}O_{10+\delta}$ samples, where X, Y, Z values were varied through a range from 0 to 0.4. Experimental results illustrating high local quality of BSCCO samples are presented.

2. Experiment

Polycrystalline samples have been fabricated by direct mixing of oxides-carbonates (1) and via Bi(Pb)-Ca-O + Sr-Ca-Cu-O precursors (2). The precursor preparation technique as well as the sample properties have been reported in our earlier papers [2-3]. The precursors were mixed in the required stoichiometric amounts, ground, pelletised and annealed in an air-argon mixture at 850°C for 120 - 400 hours. The break junctions [4] have been prepared at helium temperatures. The tunnel structure was formed as the

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result of a mechanical contact of two cryogenic fracture surfaces, which offer the best surface quality presently available. In this case one makes use of a natural surface barrier, which according to the results of many studies is a Shottky type barrier . Due to the fact that the BiSrCaCuO crystals split easily along the ab-planes under stress, the most probable direction of the tunneling current in the fractured grains is the c-axis direction. A proper adjustment of a beak junction with a micrometer makes it possible to finally reach a tunneling current in a single fractured grain . This method of contact preparation provides I - V characteristics with high values of the characteristic voltage $V_c = I_cR_n$ (I_c - critical current, R_n - resistance in the normal state) [5] and with a well defined gap structure [1,6].

3. Results and discussion

The I-V characteristic for a break junction in a sample from group (1) (direct mixing , X=0.4, Y=Z=0, annealing time - 375 hours) at T=4.2K is shown in Fig.1. The hysteretic behaviour of the I-V curve (Fig.1) is typical for a Josephson S-I-S junction with a large capacitance C [5,7] (for our junction C ≅ 0.01 pF). The quantum nature of the contact was confirmed by a Fraunhofer-like magnetic field dependence of the critical current I_c. From the period of the oscillations of $I_c(H)$ the effective width of the contact w ≅ 0.4 μm has been calculated. At helium temperature the critical current density j_c and the McCumber parameter $\beta=2eI_cR_n^2C/\hbar$ were estimated to be $j_c \cong 4.4\cdot10^5$ A/cm² and $\beta \cong 30$.

There are three important characteristic features of the I-V curve presented in Fig.1 : a) a steep rise of the quasiparticle current at the "gap" voltage $V_g = \pm2\Delta/e$, which makes it possible to estimate the gap parameter Δ(4.2K) = 19 meV with sufficient accuracy, b) a high characteristic voltage $V_c = I_cR_n = (31 \pm 4)$ mV, coinciding within the error limits with the value, given by the Ambegaokar-Baratoff's formula [8] : $V_c = (\pi/2e)\Delta(T)\tanh(\Delta(T)/2kT)$ = 29.8 mV (T=4.2K), c) a "knee"-like feature at the "gap" voltage V_g , which complicates the task of determining the normal state resistance R_n (R_n(4.2K) = (41 ±4) Ohm) and which could be caused either by a complicated structure of the contact (S_1-S_2-I-S_2-S_1 or S-N-I-N-S- types [9]) or by a deviation of the bulk density of states (DOS) from a standard form [10,11]. It should be noted that the X-ray studies of the group (1) samples have shown the presence of the intergrowths of the phases 2:2:1:2 and 2:2:2:3, which makes the formation of the S_1-S_2-I-S_2-S_1-structure highly probable. In any case a steep rise of current in the vicinity of the "gap" voltage V_g indicates that the DOS-function has a sharp peak at the gap edge. This conclusion is possibly confirmed by recent results published by Martens at al.[7].

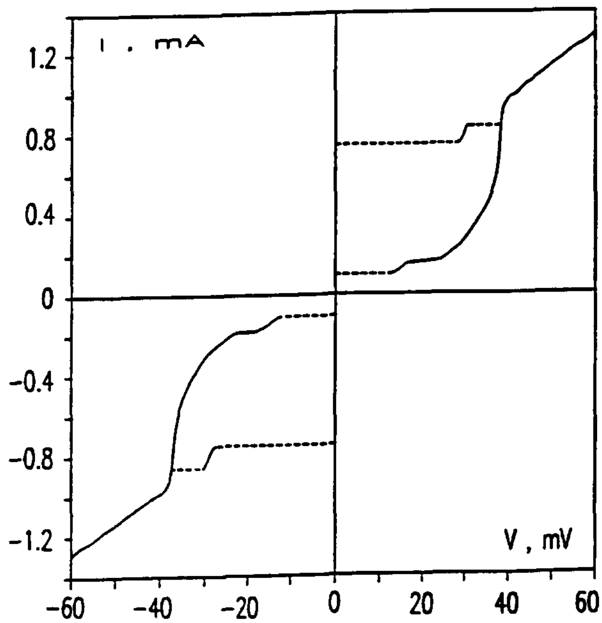

Figure 1: I-V characteristic for a Josephson break junction in BSCCO sample at T = 4.2 K ($\Delta(0)$ = 19 meV, V_c = 31 mV).

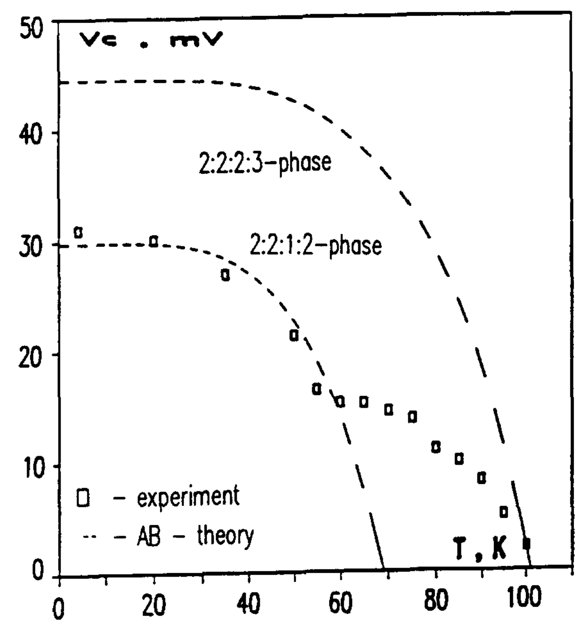

Figure 2: Temperature dependence of the characteristic voltage $V_c = I_cR_n$ for a break junction in a BSCCO sample (2:2:1:2 + 2:2:2:3 phases) (open squares).

A junction of the type discussed above presents a unique possibility to study temperature dependences of the characteristic voltage $V_c(T)$ and the gap $\Delta(T)$ simultaneously. Earlier only the $\Delta(T)$-dependences have been studied for the break junctions in the group (1) samples, which contained an of the 2:2:1:2 and 2:2:2:3 phases in the form of a natural superlattice with a period of about 20 in the c-direction [1]. It was proposed that the specific $\Delta(T)$-dependences, similar to those obtained for of the classical superconductors with differing T_c [12], could be explained by a strong influence of the proximity effect on the physical properties of the S_1-S_2-I-S_2-S_1 type structures, where S_1 is a massive 2:2:2:3 phase and S_2 is a thin layer of 2:2:1:2 phase (the crack is supposed to be invoked in the S_2-region of the superlattice). A theoretical confirmation of the observed effect can be found in a recent publication of Buzdin et al.[13].

The temperature dependence of the characteristic voltage V_c for the junction under investigation is shown in Fig. 2 (open squares). The dashed curves present the results of the calculations of $V_c(T)$ using the Ambegaokar-Baratoff's formula for a 2:2:1:2-phase sample with $\Delta(0)$ = 19 meV and for a 2:2:2:3- phase sample with T_c = 101 K. If we assume that our junction has a S_1-S_2-I-S_2-S_1 type structure discussed above, the explanation of a step-like temperature

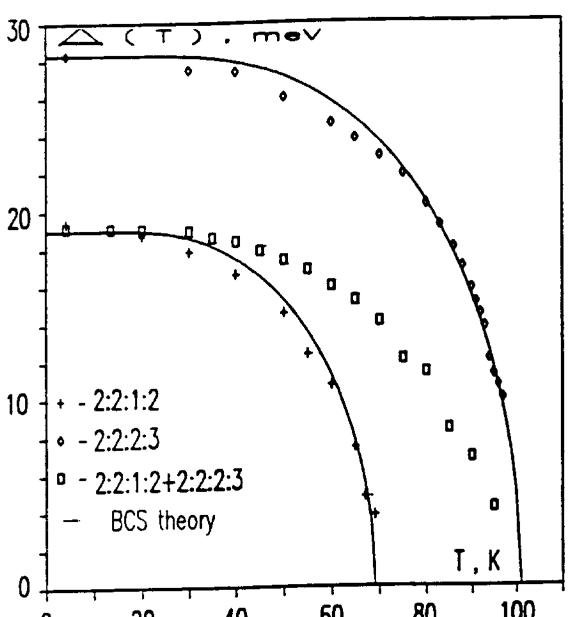

Figure 3: Temperature dependence of the gap for the break junctions in BSCCO samples (open squares-intergrowths of the 2:2:1:2 and 2:2:2:3 phases, crosses - 2:2:1:2 phase, open rhombs - 2:2:2:3 phase).

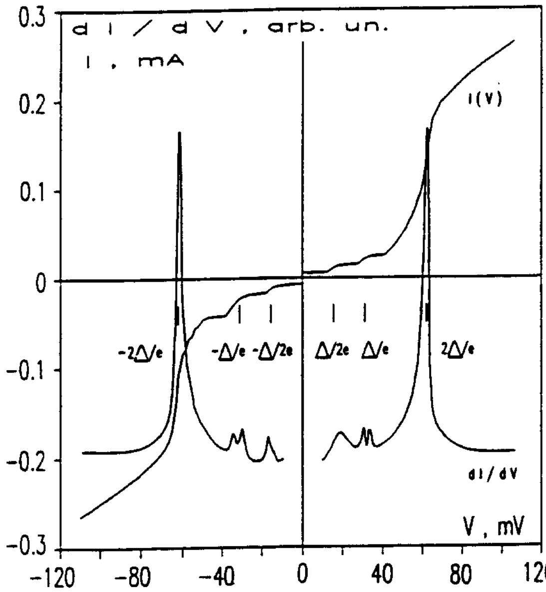

Figure 4: I-V and dI/dV-V characteristics for a Josephson break junction in a BSCCO sample at T=4.2K ($\Delta(0)$=31 meV, T_c=106 K). The subharmonic structure due to the self-detection of the Josephson radiation is indicated.

dependence of V_c (Fig. 2) could be done on the basis of the proximity effect [14]. At sufficiently low temperatures ($T << T_{c2}$) the coherence length ξ_2 is smaller than the thickness d_2 of the S_2-layer (2:2:1:2). As a result the proximity effect is insignificant and the $V_c(T)$- dependence follows the Ambegaokar-Baratoff's law for the 2:2:1:2- phase (Fig.2). In the vicinity of T_{c2} due to the divergence of $\xi_2 \propto (T_{c2} - T)^{-1/2}$ ($T \le T_{c2}$) and of the decay length $K_2^{-1} \propto (T - T_{c2})^{-1/2}$ ($T \ge T_{c2}$) the influence of the 2:2:2:3-phase S_1-layer on the S_2-layer (2:2:1:2) via the proximity effect becomes important . This causes a substantial increase in V_c and finally initiates a step- like temperature dependence of this parameter (Fig. 2). The same type of behaviour for $I_c(T)$ has been observed recently for YBCO SNS heterostructures with a current in the a-b plane [15]. The temperature dependence of the gap parameter Δ for the junction discussed above is presented in Fig. 3 (open squares). For comparison the temperature dependences of the gap in the 2:2:1:2- phase single crystal (crosses, $\Delta(0)$ = 19.2 meV) and in the 2:2:2:3-phase polycrystalline sample (open rhombs, T_c = 101 K) are also shown (solid curves present the results of calculations using the Thouless formula: $\Delta(T) = \Delta(0)\tanh[\Delta(T)T_c/\Delta(0)T]$). For both of the latter cases $2\Delta(0)/kT_c \cong 6.5$. For the junctions under

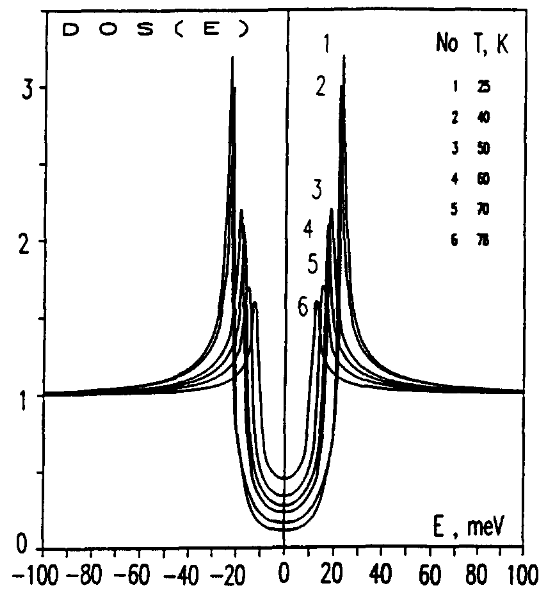

Figure 5: The tunneling density of states at various temperatures derived from the I-V and dI/dV-V characteristics for a break junction in BSCCO sample.

investigation with assumed S_1-S_2-I-S_2-S_1 structure this ratio is significantly smaller: $2\Delta(0)/kT_c = 4.4$. This may be considered to be an important manifestation of the proximity effect [1].

The ceramic samples of the precursor series (2) which were obtained after annealing for 100-120 hours are characterized by large microcrystals of the size $\approx$ 2x20x40 μm^3. The physical properties of these samples depend on X, Y and Z values. It was found that the maximal 2:2:2:3-phase content in the synthesized samples does not correspond to the stoichiometric 2:2:2:3 composition. From the resistivity measurement it was also found that the highest $T_c=110$ K (R=0) corresponds to the composition with a small Sr deficit.

The group (2) samples with X=0.2, Y=Z=0 ($T_c=(106 \pm 2)$ K) consist of a practically pure 2:2:2:3 phase with a large gap parameter $\Delta = (31 \pm 1)$ meV at T=4.2 K. These samples have shown an additional significant evidence for the existence of a sharp peak of the density of states at the gap edge of the superconducting material : 1) a well defined subharmonic structure in the I-V curves for the Josephson junctions has been observed due to the self-detection of the Josephson radiation (Fig. 4), 2) the Dayem-Martin steps in the I-V characteristics of slightly asymmetric junctions have been detected in presence of the external microwave field due to the photon-assisted tunneling of thermally activated quasiparticles.

Good reproducibility of the main characteristic features of the I-V curves encouraged us to perform the calculations of the tunneling density of states (DOS) from the experimental data. The results of the calculations for a group (1) sample are presented in Fig.5. The DOS-function deviates significantly from the simple BCS-type behaviour inside the gap region and in the vicinity of the gap edge (Fig.5): relatively sharp peaks at the gap edges coexist with a substantial smearing at the subgap energies. In addition, as the temperature approaches T_c the density of states at the Fermi level quickly increases. It should be noted that this type of behaviour has been predicted for HTSC in [10,11] on the hypothesis that the strong electron-phonon interaction is of considerable importance in these materials.

4. Conclusion

A profound effect of preparation conditions of BSCCO superconductors on the characteristics for BSCCO Josephson break junctions has been observed. A strong evidence for the existence of a sharp peak of the density of states at the gap edge of the HTSC material has been obtained.

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