Influence of proximity effect on the current-voltage characteristics of Bi–Sr–Ca–Cu–O:Pb break junctions

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A study has been made of the current-voltage characteristics of break junctions in BiSrCaCuO–Pb samples containing 2-2-1-2 and 2-2-2-3 phase intergrowths. The current-voltage characteristics of these break junctions have a region in which the current rises vertically, at $V_g = \pm 2\Delta/e$. They also have the knee typical of S_1–S_2–I–S_2–S_1 tunnel structures. The temperature dependence of the gap parameter Δ of these samples indicates a strong proximity effect.

One-particle tunneling in S–I–S structures makes it possible to determine the temperature dependence of the gap parameter, $\Delta(T)$, in the superconductor quite accurately over a broad temperature range, up to the transition temperature T_c (Ref. 1). In the present study, $\Delta(T)$ was determined for BiSrCaCuO–Pb (2-2-2-3 and 2-2-1-2 phases) from the current-voltage characteristics of break junctions[2] in single-crystal and polycrystalline samples. The microscopic crack was produced in the sample by bending the substrate, along with the sample, at liquid-helium temperature.

According to x-ray analysis, the single-crystal BiSrCaCuO–Pb samples (in this study, the *LIL* lot) had the structure of the 2-2-1-2 phase. The transition temperature taken as the temperature at which the gap structure disappeared from the I-V characteristic, was in the interval 63 K$\leqslant T_c \leqslant$75 K for the *LIL* samples. The value of the gap parameter, $\Delta(T)$, was found from the distance $V^* = 4\Delta/e$ between the dynamic-conductance peaks on the $dI(V)/dV$ characteristic.

For most of the *LIL* samples which we studied, the ratio $2\Delta(0)/kT_c$ is in the interval 5.8–6.8, and the temperature dependence of the gap, $\Delta(T)$, can be described well in reduced coordinates by the Thouless formula.[3] Calculations from that formula yield results that are essentially identical to those predicted by the formal BCS theory. We obtained a corresponding result for polycrystalline samples with the structure of the 2-2-2-3 phase (the *VS* lot), with a transition temperature 98 K$\leqslant T_c \leqslant$104 K. The gap structure on the I-V characteristics of the break junctions in the single-crystal samples of the *LIL* lot and in the polycrystalline samples of the *VS* lot was smeared to some extent, so the vertical rise of the current at a bias voltage $V_g = \pm 2\Delta/e$, which is characteristic of classic S–I–S junctions, was observed only in extremely rare cases. It was accompanied by a pronounced hysteresis, whose origin has not been identified.

We observed a region of a vertical current rise, reproducible quite well, in the region of "gap" bias voltages at $T = 4.2$ K on the I-V characteristics of break junctions in polycrystalline BiSrCaCuO–Pb samples of the *BUSH* lot and the *OS* lot (104 K $\leqslant T_c \leqslant$108 K) (Fig. 1).

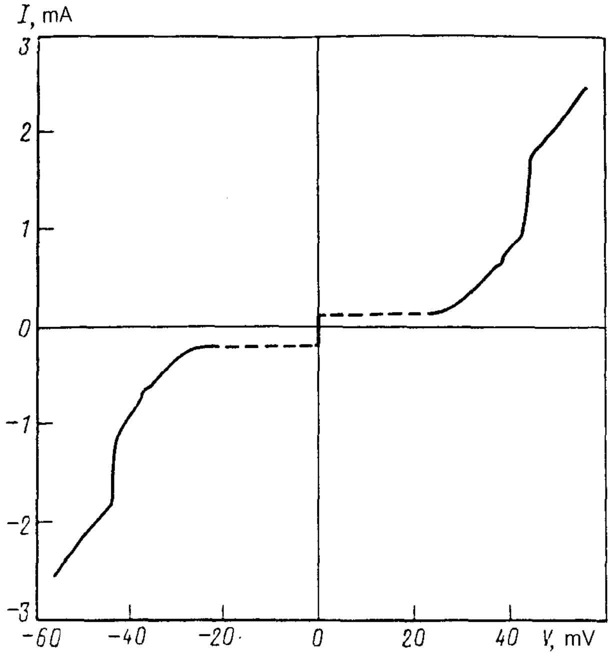

FIG. 1. Current-voltage characteristic of a break junction in a polycrystalline BiSrCaCuO–Pb sample containing intergrowths of the 2-2-2-3 and 2-2-1-2 phases, at $T = 4.2$ K (sample *OS*-4).

An x-ray study of the samples of the *BUSH* lot revealed that the samples had a ~90% concentration of the 2-2-2-3 phase and a ~5% concentration of each of the 2-2-0-1 and 2-2-1-2 phases. Some x-ray powder patterns revealed reflections indicating the presence of phases of an ordered intergrowth in these samples. These phases were similar to those observed in Refs. 4 and 5. These phases have the structure of an ordered alternation, along the *c* axis, of layers of the 2-2-0-1, 2-2-1-2, and 2-2-2-3 phases.

In addition to a vertical current rise, the characteristic feature of the *I-V* characteristics which we found (of the type shown in Fig. 1) include a clearly defined knee in the gap–voltage region ($V \gtrsim 2\Delta/e$) and a significant excess current at subgap voltages. Qualitatively, the *I-V* characteristic in Fig. 1 is very similar to the characteristics of niobium junctions, in which the niobium surface is "poisoned" by oxygen[6,7] and which are usually classified as being of the *S–I–N–S* or *S–N–I–N–S* type.[8,9] Note that a knee on the *I-V* characteristics is also a characteristic feature of $S'–I–S_2–S_1$ and $S_1–S_2–I–S_2–S_1$ tunnel structures. A proximity effect plays a role[10,11] in shaping the properties of these structures—a role as large as that which it plays in shaping the properties of *S–N–I–N–S* structures. We have grounds for suggesting that symmetric tunnel structures, of either the *S–N–I–N–S* type or the $S_1–S_2–I–S_2–S_1$ type, and formed in these break junctions in the *OS* and *BUSH* samples. As the temperature is raised, the dynamic-conductance peaks on the dI/dV curves corresponding to a bias voltage

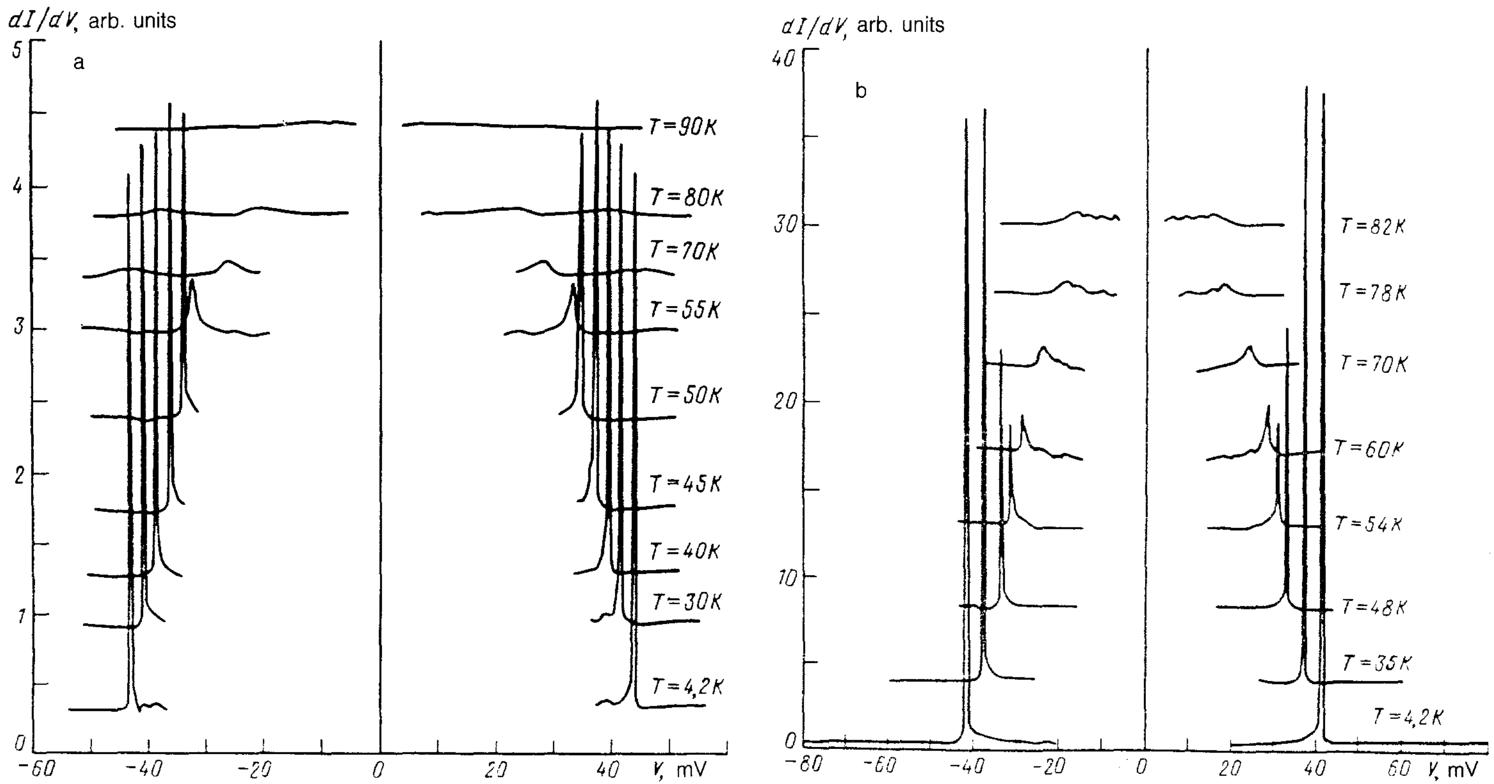

FIG. 2. dI/dV characteristics of break junctions at various temperatures. a—In sample *OS*-4; b—in a BiSrCaCuO–Pb sample containing intergrowths of the 2-2-2-3 and 2-2-1-2 phases (sample *BUSH-X*).

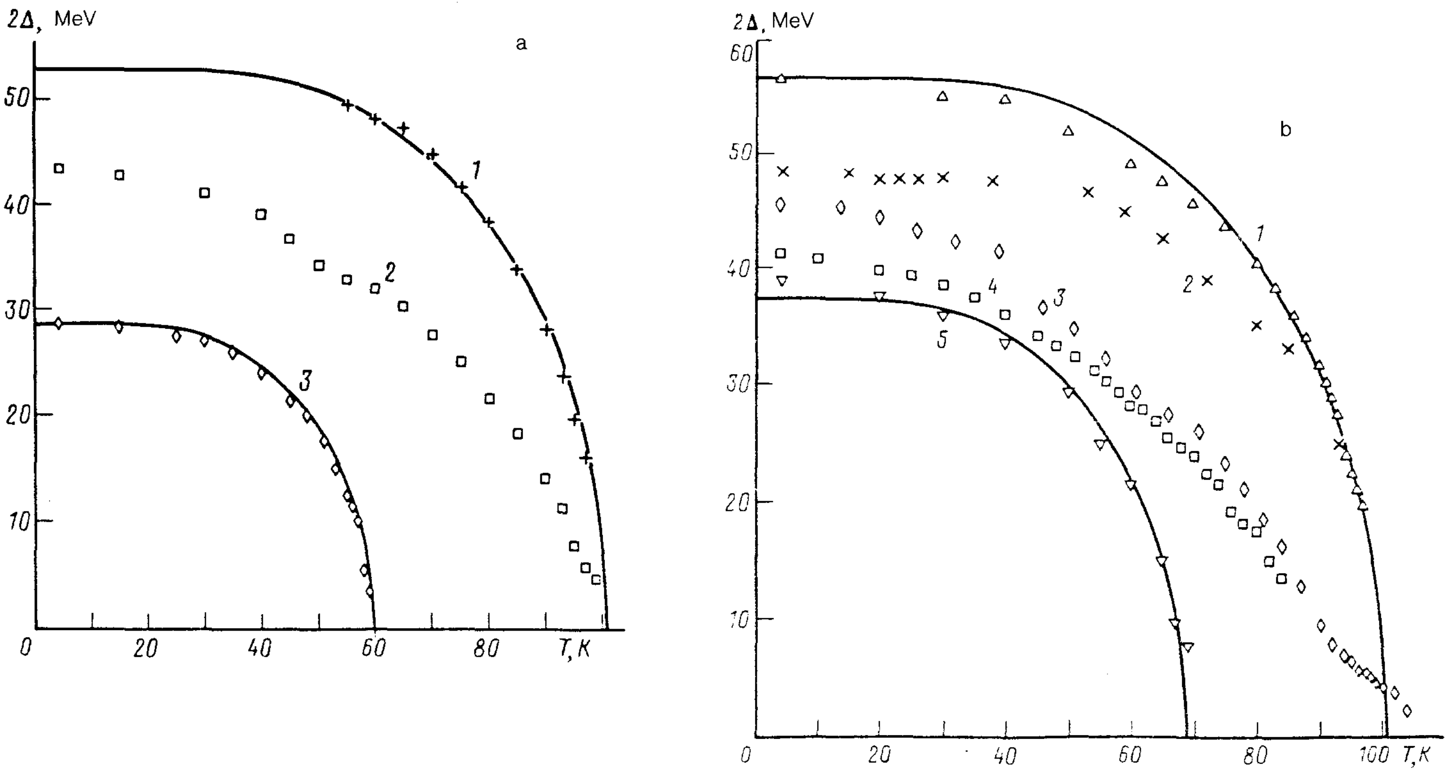

FIG. 3. Temperature dependence of 2Δ of BiSrCaCuO–Pb samples. a: 1,2,—Sample *OS*-4, containing intergrowths of the 2-2-2-3 and 2-2-1-2 phases; 3—sample *BUSH*-3 (the 2-2-1-2 phase). b: 1—Sample *VS*-1 (the 2-2-2-3 phase); 2–4—samples of the *BUSH* lot (the 2-2-1-2 + 2-2-2-3 phases); 5—sample *LIL*-2 (the 2-2-1-2 phase). The solid lines were calculated from the Thouless formula.

$V_g = \pm 2\Delta/e$ shift toward a lower bias voltage, for both the *OS* samples (Fig. 2a) and the BUSH samples (Fig. 2b). The reason for this shift is a decrease in the gap parameter Δ. Note the very nonmonotonic way in which the heights of the dynamic-conductance peaks decrease with the temperature: The sharpest decrease in peak height is observed in the narrow temperature interval 45 K–55 K (Fig. 2, a and b). This temperature interval is in the immediate vicinity of the region in which the transition temperatures T_c of the various samples of the 2-2-1-2 phase are bunched. The latter result is evidence of the existence of an S_1–S_2–I–S_2–S_1 structure in the junction region, where S_1 is a 2-2-2-3 superconducting phase, and S_2 is a thin layer of a 2-2-1-2 superconducting phase.

The temperature dependence of the quantity 2Δ found from the positions of the dynamic-conductance peaks on the dI/dV characteristics of sample *OS*-4 (Fig. 2a) is shown by branch 2 in Fig. 3a. At $T \geqslant 60$ K an additional gap structure, smaller in amplitude, was detected on the *I-V* characteristic of sample *OS*-4 (Fig. 2a). This structure led to the second branch, $2\Delta(T)$, in Fig. 3a (branch 1), which agrees well with the theoretical result calculated from the Thouless formula[3] (the solid line in Fig. 3a). We believe that it corresponds to the pure 2-2-2-3 phase. Branch 2 in Fig. 3a corresponds to the basic gap feature on the *I-V* characteristics of sample *OS*-4 (Figs. 1 and 2a). This branch can be attributed to a thin layer (possibly a monolayer) of the 2-2-1-2 phase, in which the gap parameter is substantially increased by a proximity effect in the S_1–S_2–I–S_2–S_2 structure.

Branch 3 in Fig. 3a was found for the pure 2-2-1-2 phase (polycrystalline sample *BUSH*-3). Note the nonmonotonic $2\Delta(T)$ curve (branch 2), in the sample temperature region as that in which the gap in the pure 2-2-1-2 phase decreases rapidly (branch 3).

Figure 3b shows curves of $2\Delta(T)$ in the pure 2-2-2-3 phase (branch 1, polycrystalline sample *VS*-1), in the pure 2-2-1-2 phase (branch 5, single-crystal sample *LIL*-2), and also in polycrystalline samples of the *BUSH* lot (branches 2–4), which contain phase intergrowths as mentioned above. These intergrowth apparently lead to the appearance of an S_1–S_2–I–S_2–S_1 structure (where S_1 is the 2-2-2-3 phase, and S_2 is the 2-2-1-2 phase) upon the generation of a microscopic crack in the samples, and they lead to $2\Delta(T)$ curves (branches 2–4) typical of bilayers of superconductors differing in transition temperature.[10,12] A proximity effect plays an important role in such structures. We do not rule out the possibility that in our case a "strong" superconductor (2-2-2-3) has a "healing" effect on the thin layer of the "weak" (2-2-1-2) superconductor, smoothing out the fluctuations in the gap parameter in the plane of the layer. The latter should lead to an increase in the lifetime τ of the quasiparticle excitations and to a decrease in the spreading of the peak in the density of states. This effect may also cause the vertical current rise on the *I-V* characteristics of the junction (Fig. 1).

A question which remains unclear is how to reconcile the features on the current-voltage characteristics of break junctions which point to a strong proximity effect, on the one hand, with the short coherence length ζ, on the other, in the high-T_c superconductors.[13]

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[1] L. Solymar, *Superconductive Tunneling and Applications*, Halstead, New York, 1972.
[2] J. Moreland and J. W. Erkin, J. Appl. Phys. **58**, 3888 (1985).
[3] D. J. Thouless, Phys. Rev. **117**, 1256 (1960).
[4] A. A. Bush, Sverkhprovodimost' (KIAE) **3** (9), 2026 (1990) [Superconductivity **3**, 1475 (1990)].
[5] J. S. Luo *et al.*, J. Solid State Chem. **89**, 94 (1990).
[6] L. Y. L. Shen, in *Superconductivity in d- and f-Band Metals* (ed. D. M. Douglass), AIP Conf. Proc. No. 4, American Institute of Physics, New York, 1972.
[7] R. F. Broom, S. I. Raider, and A. Oosenberg, IEEE Trans. Electron. Dev. **ED27**, 1998 (1980).
[8] A. A. Golubov and M. Yu. Kupriyanov, J. Low Temp. Phys. **70**, 83 (1988).
[9] A. A. Golubov and M. Yu. Kupriyanov, Zy. Eksp. Teor. Fiz. **96**, 1420 (1989) [Sov. Phys. JETP **69**, 805 (1989)].
[10] A. Gilabert, J. P. Romaganan, and E. Guyon, Solid State Commun. **9**, 1295 (1971).
[11] W. L. McMillan, Phys. Rev. **175**, 537 (1968).
[12] J. Vrba and S. B. Woods, Phys. Rev. B **3**, 2243 (1971).
[13] D. M. Ginzberg (editor), *Physical Properties of the High-Temperature Superconductors*, Mir, Moscow, 1990.

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