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Physica C 314 (1999) 51–54

PHYSICA C

Applicability of the theory based on Andreev reflection to the description of experimental current–voltage characteristics of polycrystalline HTSC + normal metal composites

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Received 23 November 1998; accepted 22 January 1999

Abstract

Measurements of current–voltage characteristics (CVC) of $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + BaPbO_3$ and $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7 + BaPb_{0.9}Sn_{0.1}O_3$ composites modelling network of superconducting–normal metal–superconducting (S–N–S) junctions in effectively ‘clean’ and ‘dirty’ limits, respectively, have been performed. Essential difference of CVCs for these composites is observed in spite of the identical preparation technique and experimental conditions. It is shown that the theory for S–N–S junctions [R. Kummel, U. Gunsenheimer, R. Nicolsky, Phys. Rev. B, 42 (1990) 3932] well describes the experimental CVCs of the composites in both cases. © 1999 Published by Elsevier Science B.V. All rights reserved.

PACS: 74.50.+r; 74.70.Mg; 74.70.Vy

Keywords: YBaCuO + $BaPbO_3$ composites; Network of weak S–N–S links; Current–voltage characteristic

1. Introduction

In some cases, current–voltage characteristics (CVC) of Josephson weak links based both on low- and high-temperature superconductors have regions with negative differential resistance (NDR). This phenomenon revealed experimentally in hysteresis peculiarity (at fixed current condition) has been reported to register on single junctions, based on low [1–4] and high temperature superconductors (HTSC) [5,6], and polycrystalline HTSC [7–9].

Several theories, such as the resistively shunted junction (RSJ) model, including its modifications [1,3,10], self-heating effect [3,11], and recent Kümmel–Nicolsky (K–N) theory [12,13], based on Andreev reflection of carriers, developed for superconducting–normal metal–superconducting (S–N–S) junctions predict the existence of NDR. This Letter is devoted to the testing of applicability of the K–N theory to the description of experimental CVC of HTSC-based composites.

2. Discussion

The absence of chemical interaction of HTSC with 1-2-3 structure and $BaPbO_3$ during common

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PII: S0921-4534(99)00151-3

backing [14] allowed us to prepare composites with edge interfaces between granules of the ingredients. Composites HTSC + $BaPbO_3$ have been shown to be a model of network of weak S–N–S links in the 'clean' limit (mean free path l is larger than coherence length ξ_0, i.e., $l > \xi_0$ [3]) [14]. Substitution tin for lead in $BaPbO_3$ leads to increasing of electron–phonon interaction due to the local lattice distortion and to decreasing of the mean free path [15]. So realization of the effectively 'dirty' limit ($l \ll \xi_0$ [3]) in composites HTSC + $BaPb_{1-x}Sn_xO_3$ is expected.

Composites were prepared according to the following scheme. $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ was obtained by the standard solid state reaction technique. Non-superconducting ingredients $BaPb_{1-x}Sn_xO_3$ ($x = 0$, 0.1) were synthesized from the oxides BaO_2, PbO and SnO_2 at 880°C for 20 h. X-ray diffraction pattern of $BaPb_{0.9}Sn_{0.1}O_3$ shows the same perovskite structure as pure $BaPbO_3$ with the same lattice constant without any additional reflections. The Mössbauer spectrum of $BaPb_{0.9}Sn_{0.1}O_3$ manifests the absence of doublet which is characteristic of SnO_2 [16]. Absolute values of the resistance at 4.2 K are ≈ 20 mΩ cm for $BaPb_{0.9}Sn_{0.1}O_3$ and ≈ 0.55 mΩ cm for $BaPbO_3$. The reported facts show that ions of tin play the role of additional scattering centers for current carriers.

The composite samples containing 92.5 vol.% $Y_{3/4}Lu_{1/4}Ba_2Cu_3O_7$ and 7.5 vol.% $BaPb_{1-x}Sn_xO_3$ with $x = 0$, 0.1 were prepared by the method of fast sintering (5 min at 950°C and then 6 h at 400°C) [14]. Hereafter, we denote samples as S + 7.5 N for composite with $BaPbO_3$ and S + 7.5 N(Sn) for composite with $BaPb_{0.9}Sn_{0.1}O_3$.

X-ray diffraction patterns of composite samples show 1-2-3 and perovskite phases only. Both composites have the same critical temperatures determined by magnetic and resistance (onset of the resistive transition) measurements (93.5 K). In this communication, we pay attention to CVC of composites only. Details of resistive and magnetic properties will be published elsewhere [16].

Measurements of the CVC of the composites have been performed by the standard four-probe technique under the fixed current conditions. The current contact pads were coated with a layer of In–Ga eutectics. The area of contact pads was about two orders of magnitude larger than the area of the transverse cross section on the 'working' part of the sample (1×0.2 mm^2), see Fig. 1 in Ref. [7]. The sample was glued onto a sapphire substrate attached on a silver rod and put into a liquid helium bath in order to lower the self-heating effects.

Fig. 1 shows experimental CVCs of the composites (squares). CVCs are fully reproducible at any current scanning velocity. CVC for the sample S + 7.5 N(Sn) is smoothly increasing voltage drop. Extrapolation of the linear region to zero voltage manifests the excess current J_{ex} typical for S–N–S junctions [17]. The CVC of the sample S + 7.5 N is characterized by hysteresis peculiarity and has J_{ex} also. This hysteresis reflects the NDR. The form of NDR is possible to observe only in the case of measurements under fixed voltage conditions.

Two theories can be chosen for description of NDR: RSJ model with self-heating [3] and recent K–N theory [12,13]. A complete description of CVC including existence of J_{ex}, absence or presence of hysteresis is difficult in the former theory and possible in the latter one. Moreover, the K–N theory has attractive physical sense [18] in contrast to the former one.

Let us consider a simplified model of the K–N theory [12,13] for S–N–S junction proposed by Pereira and Nicolsky [18]. According to Ref. [18], the form of the expression for CVC is:

$$j = C \sum_n \exp[-(2n-1)a/l]\, J_0$$

with

$$J_0 = \int_{neV - eV/2 - \Delta}^{\Delta + eV/2} E^2 \tanh\left[\frac{E}{2k_B T}\right] \mathrm{d}E, \qquad (1)$$

where C is a constant defined in Ref. [18], n = number of Andreev reflections, Δ = energy gap, E = quasiparticle energy, $2a$ = the length of normal region in S–N–S junction. Solid lines in Fig. 1 calculated from Eq. (1) are fittings to experimental CVCs of samples S + 7.5 N(Sn) (left) and S + 7.5N (right). Using a/l as a fitting parameter, we tried to achieve coincidence of forms of experimental and theoretical curves. As can be seen, both 'clean' and 'dirty' cases are well described by the model [18].

Note some quantitative discrepancy. Values $l = (7.5 \pm 0.7)a$ and $l = (35 \pm 2)a$ are obtained from

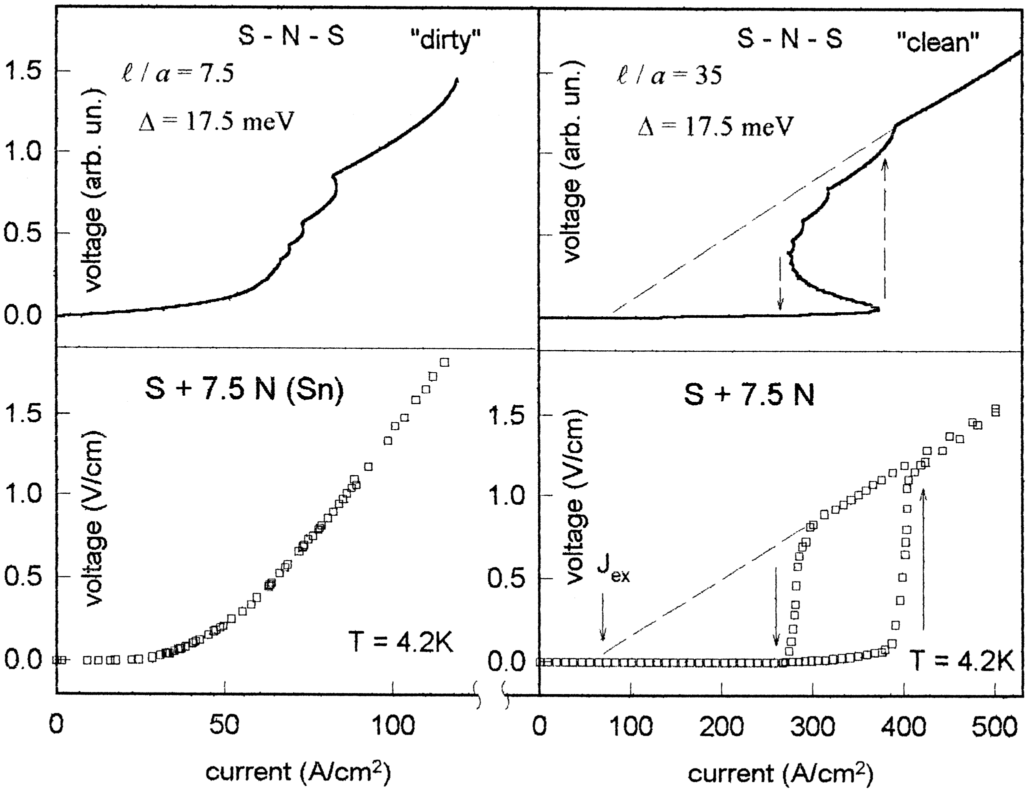

Fig. 1. Experimental CVC of composites S + 7.5 S(Sn) (left) and S + 7.5 S (right) at 4.2 K – squares. Solid lines are fits by the simplified model for CVC of S–N–S junction [18] using Eq. (1).

fitting for samples S + 7.5N(Sn) and S + 7.5N, respectively. It is natural to assume that effective thickness on N-layers in the composites $2a$ is the same (in geometrical sense) because they contain the same volume contents of nonsuperconducting components. So the mean free path in $BaPb_{0.9}Sn_{0.1}O_3$ layers decreases ~ 5 times compared to $BaPbO_3$ ones. On the other hand, based on resistivity data (see above), the value l for $BaPbO_3$ divided by l for $BaPb_{0.9}Sn_{0.1}O_3$ equals ~ 35 (l for single crystal $BaPbO_3$ is 220 Å [19]). This non-dramatic discrepancy can result from the following causes. (i) Simplified model [18] takes into consideration the Andreev reflection as the only mechanism of Cooper pair transfer in S–N–S junction. Proximity effect increases the N-boundary longitude (in electric sense) in more degree for 'clean' metal cases than for 'dirty' ones. On this reason taking into account the proximity effect should improve quantitative agreement. (ii) At a current higher than its critical value, the distribution function of N-metal boundaries thicknesses begins to play the role in CVC formation. Despite the identity of distribution functions (in geometrical sense) for both composites due to the same technology of preparation, the role of distribution function may be different for 'clean' and 'dirty' cases. These two factors mentioned above will be analyzed later. On our opinion at this stage, they do not change significantly the physical picture.

Thus, the K–N theory [12,13], even in its simplified form [18], is shown to be adequate for the explanation of experimental CVCs of composite HTSC. This supports the arguments to the Andreev reflection playing the important role for the interpretation of resistive properties of S–N–S junctions.

On the other hand, the authors should emphasize the possible practical aspects of the application of such kind of material in fault current limiter devices.

In reality, a material having CVC with hysteresis peculiarity is close to an ideal limiter because it has the jump-wise transition from low to high resistivity.

Acknowledgements

One of the authors, D.A.B., is thankful to Prof. R. Nicolsky (Instituto de Fisica, Univ. Fed. do Rio de Janeiro) for the fruitful discussion on the problem of hysteresis on S–N–S junctions CVC. We are grateful to Prof. R. Kümmel (Univ. of Wurzburg, Germany) for interest in this work. We acknowledge O.A. Bayukov for Mössbauer measurements and A.D. Vasilyev for carrying out the X-ray diffraction analyses. This work was partially supported by grant for young scientists of Siberian Branch of Russian Academy of Sciences.

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