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Physica C 408–410 (2004) 620–622
PHYSICA C
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Andreev reflections and experimental current–voltage characteristics of break junctions of polycrystalline HTSC

M.I. Petrov [a,*], D.M. Gokhfeld [a,b,c], D.A. Balaev [a], K.A. Shaihutdinov [a], R. Kümmel [c]

[a] *Kirensky Intitute of Physics, Akademgorodok, 660036 Krasnoyarsk, Russia*
[b] *Reshetnev Siberian State Aerospace University, 660014 Krasnoyarsk, Russia*
[c] *Institut für Theoretische Physik und Astrophysik der Universität Würzburg, D-97074 Würzburg, Germany*

Abstract

The temperature evolution of current–voltage characteristics (CVCs) of break junctions made from polycrystalline $Y_{0.75}Lu_{0.25}Ba_2Cu_3O_7$ and $La_{1.85}Sr_{0.15}CuO_4$ is investigated. The experimental CVCs have hysteretic features that reflect a part of a curve with negative differential resistance. The temperature evolution of the CVCs is discussed within the framework of the Kümmel–Gunsenheimer–Nicolsky theory for superconductor/normal-metal/superconductor junctions considering multiple Andreev reflections. It is shown that the shape of the CVCs of break junctions is determined by the ratio of the number of "short" and "long" intergrain normal regions in the polycrystalline HTSC under investigation.

Keywords: Andreev reflections; Break junction; Current–voltage characteristics

1. Break junctions in HTSC

The break junction technique allows to investigate quantum phenomena in bulk HTSCs. The formation of a microcrack in a bulk sample leads to a significant reduction of the effective cross section for charge transport, A. In the non-tunneling case two massive polycrystalline banks are connected by weak links which constitute narrow bottlenecks. The critical current and the current–voltage characteristics (CVCs) of the whole sample are determined by the cross section A. For this reason we can measure CVCs at bias currents that are much smaller than the critical current of the bulk samples, and self-heating effects and vortex motion should not matter.

$La_{1.85}Sr_{0.15}CuO_4$ (LSCO) and $Y_{0.75}Lu_{0.25}Ba_2Cu_3O_7$ (YBCO) were sintered by standard ceramic technology. The T_c values of LSCO and YBCO are 38 and 92 K respectively. Details of the break junction technique are described in [1]. Comparison of sample resistances before the creation of the microcracks and after (typical resistance after: <10 Ω) shows that the value of A decreased by factors between approximately 30 and 100. The CVCs were measured by four probe technique under bias current.

2. Current–voltage characteristics

A typical CVC of an YBCO break junction is shown in Fig. 1. The hysteretic peculiarity reflects a part of a current (I) versus voltage (U) curve with negative differential resistance which one would be able to observe under voltage bias. The temperature evolution of the CVC of a LSCO break junction is shown in Fig. 2a.

* Corresponding author. Tel.: +7-3912-494600; fax: +7-3912-438923.
E-mail address: smp@iph.krasn.ru (M.I. Petrov).

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doi:10.1016/j.physc.2004.03.085

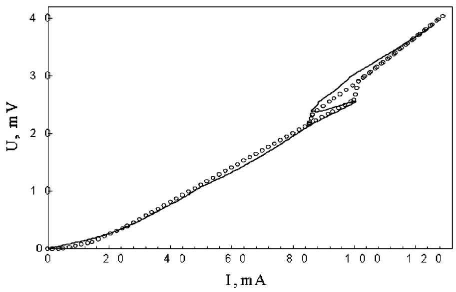

Fig. 1. Experimental CVC of YBCO break junction at 5 K (circles) and fitting curve (solid line).

Again the CVCs exhibit the hysteretic peculiarity and, in addition, an arch-like structure.

Among the theories developed for SNS structures we use the KGN theory [2] to describe the experiment. This theory considers multiple Andreev reflections of quasiparticles. According to [2] the expression for the CVC is given by:

$$
\begin{aligned}
I = & -\frac{1}{2a}\frac{e}{m^*}\sum_k \sum_{n=1}^{\infty} P_N(E_k) \\
& \times [f(E_k)k_e - (1 - f(E_k))k_h] \\
& \times \exp(-n2a/\ell)(|A_n^+(E_k + eU/2)|^2 \\
& - |A_n^-(E_k - eU/2)|^2) + I_{\mathrm{Sh}}, \qquad (1)
\end{aligned}
$$

where we use the same notations as in Ref. [2]: $f_0(E_k)$—Fermi distribution function; P_N, from Eq. (2.19) of [2], is the probability of finding the quasiparticles in the N region of thickness $2a$ and with inelastic mean free path ℓ; e—charge and m^*—effective mass of electron; n—number of Andreev reflections which a quasiparticle that starts its motion from an Andreev level characterized by the quantum-number set k undergoes before it moves out of the pair potential well; $A_n^-(E_k - eU/2)$, $A_n^+(E_k + eU/2)$ from Eqs. (A.32) and (A.33) of [2] are the probability amplitudes of n Andreev reflections of quasiparticles with directions of propagation parallel (+) or antiparallel (−) to the electric field; $I_{\mathrm{Sh}} \sim U$ is the Sharvin current, see Eq. (3.22) of [2].

The resistive state of a break junction is determined by a finite number of intergrain normal regions. For this reason the experimental CVC in Fig. 1 has a complicated form that cannot be reproduced by Eq. (1). The experimental CVCs are described using a heuristic formula for a series of weak links:

$$
U(I,T) = \sum V_i U_i(I,T,a_i), \qquad (2)
$$

where the sum is over all weak links; $U_i(I,T,a_i)$ are the I–U characteristics of SNS junctions defined by Eq. (1); V_i is a weight factor indicating the effect of a junction of thickness $2a_i$. We find that Eq. (2) correctly describes the experimental data for YBCO when the sum contains at least two terms. The best agreement has been reached for values $2a_1/\ell = 0.15$, $V_1 = 0.34$ and $2a_2/\ell = 0.5$, $V_2 = 0.66$. The solid curve in Fig. 1 shows this superposition of the theoretical I–U characteristics. The temperature evolution of the experimental CVC has been successfully described in a range from 5 K to T_c. For LSCO a good fit of $U(I,T)$ of Eq. (2) to the experimental CVC has been obtained for two terms in the sum with parameters $2a_1/\ell = 0.2$, $V_1 = 0.93$ and $2a_2/\ell = 0.6$, $V_2 = 0.07$, see Fig. 2. As the simulation curves demonstrate (Fig. 2b), the arch in the experimental CVC of LSCO is the last arch of the subgarmonic gap structure that is due to multiple Andreev reflections. The temperature dependence of the two ends U_{SGS1} and U_{SGS2} of this arch in Fig. 2a is close to the BCS gap dependence.

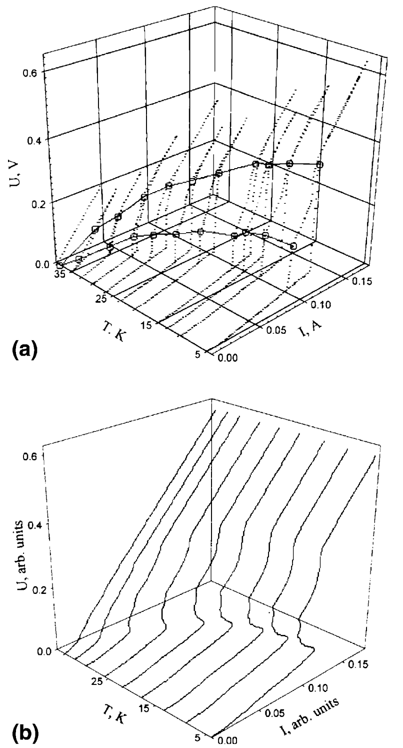

Fig. 2. Temperature evolution of CVC of one break junction of $La_{1.85}Sr_{0.15}CuO_4$: (a) experiment, (b) simulation.

Although the simulated and the experimental CVCs in Figs. 1 and 2 agree quite well, a precautionary note should be added. Eq. (1) has been derived from wave packets that travel ballistically in a normal layer between conventional superconductors without elastic scattering from, e.g., lattice defects. Its applicability to break junctions from HTSCs should be substantiated by further investigations involving elastic scattering and time-dependent density functional theory for superconductors [3].

Acknowledgements

This work was supported in part by grant for Young Scientist Group of SB of Russian Academy of Sciences and by joint RFBR and KSF program Enisey, grant no. 2-02-97711.

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