Physics of the Solid State, Vol. 44, No. 7, 2002, pp. 1229–1234. Translated from Fizika Tverdogo Tela, Vol. 44, No. 7, 2002, pp. 1179–1184.

METALS AND SUPERCONDUCTORS

Temperature Evolution of the Hysteresis in the Current–Voltage Characteristic of a Polycrystalline High-Temperature Superconductor with 1-2-3 Structure

M. I. Petrov[1], D. A. Balaev[1], D. M. Gokhfel'd[1, 2], K. A. Shaĭkhutdinov[1], and K. S. Aleksandrov[1]

[1] *Kirensky Institute of Physics, Siberian Division, Russian Academy of Sciences, Akademgorodok, Krasnoyarsk, 660036 Russia*

[2] *Reshetnev Siberian State Aerospace University, Krasnoyarsk, 660014 Russia*

e-mail: smp@iph.krasnoyarsk.su

Received July 20, 2001; in final form, November 1, 2001

Abstract—The temperature evolution of the current–voltage (*I*–*U*) characteristic of a contact of the break-junction type with direct conduction is investigated on a polycrystalline HTSC of the Y–Ba–Cu–O system. The experimental *I*–*U* characteristics possessing a hysteresis are correctly described in the framework of the Kümmel–Nicolsky theory for an *S*–*N*–*S* contact (*S* stands for a superconductor; *N*, for a normal metal) in which the Andreev reflection of quasiparticles from the *N*–*S* interface is considered. It is shown that the shape of the *I*–*U* curve, as well as the existence of a hysteresis, is determined by the ratio of the number of "long" and "short" intergranular boundaries in the polycrystal under investigation. The coincidence of the calculated and experimental *I*–*U* curves made it possible to estimate the effective length of "natural" intergranular boundaries in polycrystalline HTSC materials. The estimate is obtained from the experimental temperature dependence of the critical current in the sample under investigation. *© 2002 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

Bulk HTSC polycrystals possess much lower current-carrying capacity than single crystals and thin films. It is well known that the main limiting factor is the intergranular boundaries, whose presence results in the formation of a random network of weak links *S*–*N*–*S* (*S* is a superconductor and *N* is a normal metal) in a polycrystal. The distribution of geometrical parameters of individual weak links in such a network is described by a certain distribution function determined by the technology of the synthesis of polycrystals.

Junctions at microcracks (break junctions) were actively studied during the first years following the discovery of HTSC materials. However, break junctions continue to be attractive objects of investigation [1], since they make it possible to study both tunnel junctions and contacts with direct (metallic-type) conduction. The formation of a microcrack in a bulk HTSC sample in the case of a direct-conduction contact leads to a decrease in the effective cross-sectional area. The current density in the breaking region is much higher than the current density in the sample volume; consequently, weak links in the breaking region are the first to pass to the resistive state and determine the critical current and the current–voltage (*I*–*U*) characteristic of the sample until degradation of the superconductivity begins in the bulk of the sample. Consequently, the resistive state of a contact of the break-junction type is determined by the superposition of a finite number of weak links. It becomes possible to measure the *I*–*U* characteristics of junctions at natural intergranular boundaries over a wide temperature range in the region of current densities much higher than the critical value; this almost entirely eliminates the effect of self-heating, which is difficult to achieve in bulk HTSC samples.

In order to describe the experimentally observed *I*–*U* curves for *S*–*N*–*S* junctions of the Josephson type, the resistive shunted junction (RSJ) model [2] or its modifications [3, 4] are often used. However, this model is only an equivalent electric circuit and does not reflect the quantum physical processes of charge carrier transport in an *S*–*N*–*S* junction [2, 5, 6].

The charge carrier transport in an *S*–*N*–*S* junction is determined by physical processes such as tunneling, the proximity effect, and Andreev reflection [7]. Starting from the publications by Artemenko, Volkov, and Zaĭtsev [8, 9], several models have been developed in which the major role in the formation of *I*–*U* characteristics is assigned to Andreev reflection. In the pioneering works [8, 9], the *I*–*U* curves for microbridges were calculated only for the limiting cases, namely, near T_c and at voltages across a junction much larger than the energy gap in the superconductor. Blonder *et al.* [10] described the *I*–*U* curves of an *S*–*N* point contact and of a microconstriction; in this case, the shape of the *I*–*U* curve is determined by the barrier transparency. The theory describes the excess current and arc-shaped features in *I*–*U* curves (subharmonic gap structure) but fails to describe the negative differential resistance (NDR). In experiments, the NDR is manifested in the fixed stable current mode as a hysteresis loop on the *I*–*U* curves [11]. Some authors analyze the *I*–*U* curves of *S*–*N*–*S* junctions in various approximations (see, for example, [12–14]); however, *I*–*U* curves calculated on the basis of these models do not contain segments corresponding to NDR.

In our opinion, the most attractive theory capable of describing *I*–*U* curves of *S*–*N*–*S* structures in wide ranges of the mean free paths (l) of carriers in the *N* layer and geometrical thicknesses of the *N* layer ($2a$) is the Kümmel–Nicolsky theory [15]. This theory takes into account the contribution from Andreev reflections in the *S*–*N*–*S* to the current junction and predicts the existence of NDR in pure ($l > 2a$ [11]) *S*–*N*–*S* structures. This theory also describes the excess current and gap singularities at voltages that are multiples of the energy gap Δ. The theory developed in [15] was successfully used to describe some results obtained on *S*–*N*–*S* contacts with low-temperature superconductors [6]. The authors of [15–17] pointed out that the hysteresis observed on *I*–*U* curves of a weakly linked HTSC can be interpreted in the framework of this theory.

It has been proved [18] that a simplified version of the Kümmel–Nicolsky theory [5] satisfactorily describes the experimental *I*–*U* curves for composites $Y_{0.75}Lu_{0.25}Ba_2Cu_3O_7 + BaPb_{1-x}Sn_xO_3$ ($x = 0, 0.1$) measured at 4.2 K. In these composites, the normal metal $BaPb_{1-x}Sn_xO_3$ forms artificial metal boundaries between HTSC crystallites. For $x = 0$, the “clean” limit is realized in composites, while for $x = 0.1$, an effectively dirty limit ($l < 2a$ [11]) exists.

The aim of the present work is to demonstrate the applicability of the theory [15] not only to a network of weak links with artificially created metallic intergranular boundaries [18] but also to *I*–*U* characteristics of polycrystallites with natural intergranular boundaries in HTSC materials.

We measured *I*–*U* curves with a hysteresis loop of break-junction-type contacts with direct conduction in the temperature range 4.2–95 K. The results obtained are described satisfactorily in the framework of the theory [15] under the assumption that junctions of various geometric length are connected in series.

2. EXPERIMENT

We used the standard ceramic technology of fabrication of HTSC $Y_{0.75}Lu_{0.25}Ba_2Cu_3O_7$. The time of final firing was 40 h at 910°C. The Debye powder pattern displays only reflections corresponding to the 1-2-3 structure. The superconducting-transition temperature T_c as determined from magnetic measurements coincides with the temperature corresponding to the beginning of the resistive transition and amounts to 93.5 K.

Samples with a typical size of $2 \times 2 \times 10$ mm were sawed out from synthesized pellets. The sample was glued to a sapphire substrate. The central part of the sample was polished down to obtain a cross-sectional area $S \sim 0.2 \times 1$ mm. For such a value of S, the critical current at 4.2 K was ~2 A (current density 1000 A/cm^2). Further controllable decrease in the area S under inevitable mechanical stresses at current and potential contacts is very difficult. In order to obtain a contact of the break-junction type, the sample with the above value of S was bent together with the substrate with the help of screws of spring-loaded current contacts, which led to the emergence of a microcrack in the part of the sample between the potential contacts. As a result, either a tunneling contact (with resistance $R > 10\ \Omega$) or a direct-conduction contact ($R < 10\ \Omega$) was formed. For $R \sim 1$–$2\ \Omega$, the samples possess a critical current $J_c \sim 1$–10 mA at 4.2 K, which corresponds to a decrease in the value of S by a factor of ~10^2–10^3. It should be noted that the shape of the *I*–*U* curves for the samples was completely preserved after thermocycling from 4.2 to 100 K, but thermocycling to room temperature increased the value of R and the contact was converted into a tunneling contact.

During measurements, the samples were held in a helium heat-exchange atmosphere. The *I*–*U*-curve measurements were made under steady-state conditions in the fixed current mode. Relatively low values of the transport current (up to 150 mA) and of the voltage drop across the sample (up to ~100 mV) made it possible to eliminate the effect of self-heating [19]. The critical current was determined from the *I*–*U* curve using the 1-μV criterion [20].

3. RESULTS AND DISCUSSION

Figures 1 and 2a show typical examples of experimental *I*–*U* curves recorded at 4.2 K. The curves display the presence of a critical current and a segment with a nonlinear $U(I)$ dependence followed by a jumpwise (repeated in some cases) increase in the value of U accompanied by a hysteresis. In the region of large values of I and U, the $U(I)$ dependence is close to linear, and its extrapolation to the value $U = 0$ gives an excess current I_{ex} whose existence confirms the metallic type of conduction of the junctions formed [10].

The current due to Andreev reflections in an *S*–*N*–*S* contact, according to theory [15], has the form (in the notation used in [15])

$$j = C\sum_k \sum_{n=1}^{\infty} P_N(E_k)\{[f(E_k)k_e - (1 - f(E_k))k_h] \times \exp(-(2na - a + b)/l)(|A_n^-|^2 - |A_n^+|^2)\}. \quad (1)$$

Here, $f(E_k)$ is the Fermi energy distribution function for quasiparticles, P_N is the probability of finding a quasiparticle in the N region, $A_n^+(E)$ and $A_n^-(E)$ are the probabilities of the nth Andreev reflection for holes (+) and electrons (–), b is the starting position from which quasiparticles begin their motion when an electric field

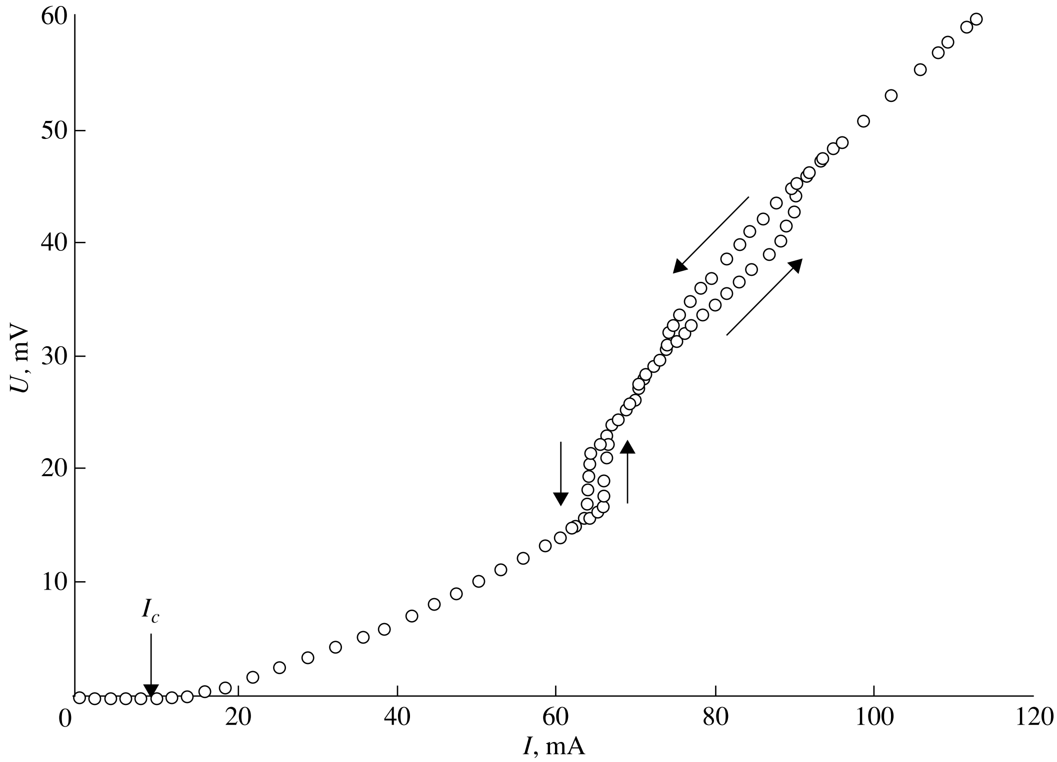

Fig. 1. Experimental *I–U* curve recorded for a sample at $T = 4.2$ K.

starts acting in the *N* layer, *n* is the number of Andreev reflections, and *C* is the constant defined in [15]. In our calculations, we used the density of states for charge carriers in an HTSC material [21].

The theory describes the *I–U* curves for *S–N–S* contacts with the above characteristic features excluding the region near $U \approx 0$, since the calculation of the critical current is a separate problem [7].

An example of a theoretical *I–U* curve is given in Fig. 2b. It can be seen that such a theoretical dependence cannot describe the experimental *I–U* curves shown in Figs. 1 and 2a, in which the hysteresis is observed for larger values of *U*. On the other hand, the multiple hysteresis loops observed on some *I–U* curves (Fig. 1) indicate that the *U*(*I*) dependence is formed by a superposition of *I–U* curves for several contacts with different parameters. A similar conclusion was drawn for a point HTSC contact from an analysis of the effect of radiation on the shape of *I–U* curves [22].

We processed the experimental curve shown in Fig. 2a by using the formula

$$U(I) = \sum_i V_i U_i(I, 2a_i), \quad (2)$$

where $U_i(I, 2a_i)$ are the *I–U* characteristics of *S–N–S* junctions with various values of $2a$ defined by Eq. (1) and V_i are the weight factors indicating the effect of a contact with a given value of $2a$ on the resultant (superposition) *I–U* curve (with the obvious normalization $\sum_i V_i = 1$).

It was found that Eq. (2) correctly describes the experimental data even when the sum in this formula contains only two terms. The best agreement was attained for values of $2a_1/l = 0.15$, $V_1 = 0.34$, $2a_2/l = 0.5$, and $V_2 = 0.66$. Figure 2b shows the theoretical *I–U* curves for each of these two junctions, while Fig. 2a shows their superposition. It can be seen that the theoretical dependence obtained as a result of superposition coincides with the experimental *I–U* curve, including in the region with hysteresis, but the segment of the experimental *U*(*I*) dependence corresponding to values of *U* close to zero cannot be described by the theory from [15] (see above).

Figure 3a shows the experimental *I–U* curves for one of the samples (the same as in Fig. 2a) in the coordinates (*T*, *I*, *U*). Figure 3b presents the temperature evolution of the superposition *I–U* curve shown in Fig. 2b in the same coordinates. The only variable parameter was the temperature-dependent energy gap given by the BCS theory. The theory [15] correctly describes the decreases in the area of the hysteresis loop and its vanishing upon an increase in temperature. At temperatures above 4.2 K, the discrepancy between the theoretical and experimental *U*(*I*) dependences becomes more pronounced, but the difference between these dependences does not exceed 9%. It is important

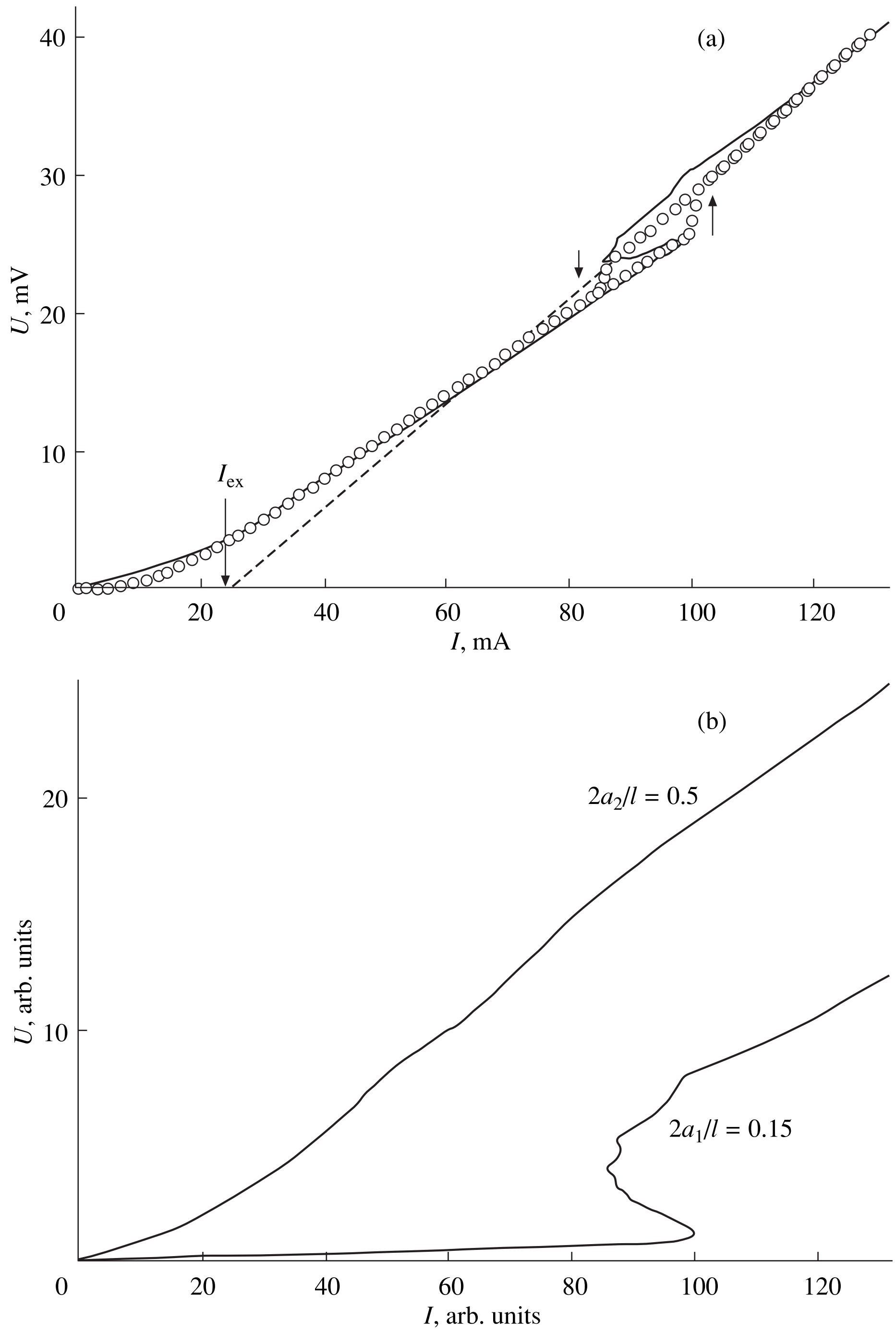

Fig. 2. Experimental *I–U* curve recorded for a sample at $T = 4.2$ K (circles). Solid curves are (a) the resultant superposition curve calculated on the basis of Eq. (2) for $V_1 = 0.34$ and $V_2 = 0.66$ and (b) the theoretical *I–U* curves for *S–N–S* junctions with parameters $2a_1/l = 0.15$ and $2a_2/l = 0.5$ calculated using Eq. (1).

to note that the experimental points corresponding to the jumpwise change in voltage are described by the theory quite successfully. A similar satisfactory agreement was also attained for other samples under investigation over a wide temperature range.

Knowing the mean free path of charge carriers, the lengths of intergranular boundaries in the HTSC material under investigation can be estimated by fitting to the experimental *I–U* curves. If we take for *l* the value ~20 Å given in [23] for a Y–Ba–Cu–O system, we obtain $2a_1 = 3$ Å and $2a_2 = 10$ Å. These values agree with the results obtained for natural intergranular boundaries in polycrystalline Y–Ba–Cu–O [24] and in a bicrystal [25]. The obtained values of coefficients

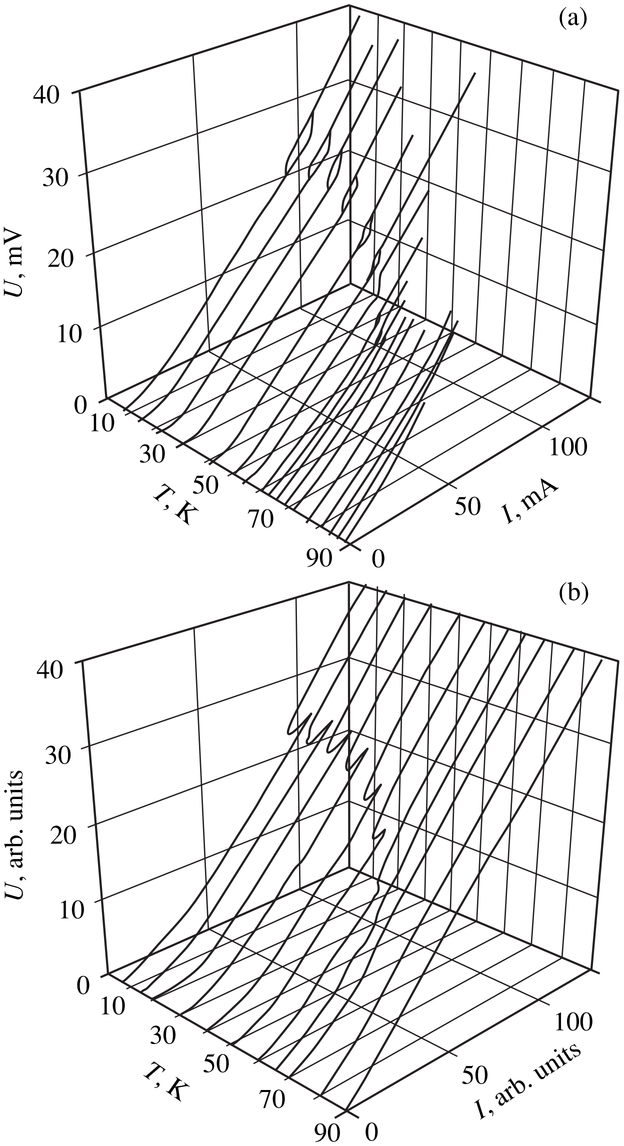

Fig. 3. Temperature evolution of I–U curves presented in Fig. 2: (a) experiment and (b) theory.

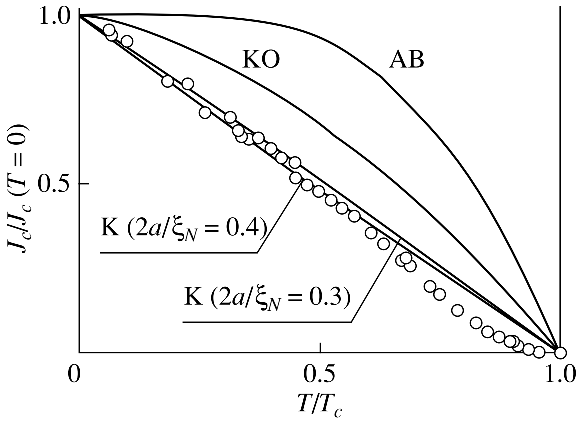

Fig. 4. Temperature dependence of normalized critical current $J_c(T)/J_c(0)$. Circles correspond to experimental data, and solid curves are theoretical calculations: the Ambegaokar–Baratoff (AB) dependence [31], the Kulik–Omel'yanchuk (KO) dependence [30], and the Kupriyanov (K) dependence [28].

$V_1 = 0.34$ and $V_2 = 0.66$ can be interpreted as follows: the I–U characteristic is defined by at least three series-connected contacts, one of which is 3 Å long and the other is 10 Å.

The length of intergranular boundaries can also be estimated from the experimental temperature dependence of critical current [24–27]. The experimental $J_c(T)$ dependence of the sample under investigation is shown in Fig. 4. In some theoretical works [7, 28, 29], the dependence of the critical current of a weak link with direct conduction on the temperature and thickness of the metallic layer was investigated. The theoretical curves from [7, 28], which describe similar results, are in good agreement with our experimental data. In the present work, we describe $J_c(T)$ on the basis of an earlier and simpler theory [28]. Figure 4 shows the theoretical curves from [28]. In a wide temperature range, good agreement is observed between the experimental $J_c(T)$ curve and the theoretical dependences for a weak link having a thickness of the N layer of $2a = (0.3–0.4\xi_N)$, where ξ_N is the coherence length in the normal metal for $T = T_c$ [28]. Figure 4 also shows the $J_c(T)$ dependence predicted by the theory [28] for $2a = 0$, which coincides with the Kulik–Omel'yanchuk (KO) temperature dependence for clean short microbridges [30] and with the dependence obtained in [7] for clean short S–N–S junctions, as well as the Ambegaokar–Baratoff (AB) $J_c(T)$ dependence for tunneling contacts [31]. The cardinal difference (even in the sign of curvature) of the experimental $J_c(T)$ dependence from the AB dependence is an extra argument confirming that a direct-conduction contact is formed in the sample under investigation. In [32], the value $\xi_N \sim 50$ Å is given for intergranular boundaries in Y–Ba–Cu–O. Using this value, we estimate the length of the intergranular boundary to be ~15–20 Å. This estimate is close to the value $2a_2 = 10$ Å obtained from the processing of the I–U curve (clearly, the critical current in series-connected junctions is determined by the worst of these junctions, i.e., by the longer one, since $J_c \sim \exp(-2a)$ in most of the theories from [7, 11, 20, 28, 29]). It should be noted that near T_c, the experimental and theoretical results differ noticeably; the experimental temperature dependence of the critical current becomes quadratic: $J_c \sim (1 - T/T_c)^2$. Such a behavior of the critical current near T_c has been observed by many authors for HTSC film structures [25, 27, 32], HTSC point contacts [33], and in bulk HTSC polycrystals [24, 26] and has been discussed more than once. We can indicate at least two reasons for such a behavior. A small coherence length in HTSC materials reduces the pair potential at the S–N

interface; as a result, the function $J_c(T)$ becomes quadratic and not linear, proportional to $(1 - T/T_c)$ [34]. Thermal fluctuations near T_c also affect the $J_c(T)$ dependence [35, 36].

4. CONCLUSION

Thus, we have proved that the theory [15] based on Andreev reflections can be used to obtain a satisfactory description of the temperature evolution of *I–U* curves with a hysteretic behavior at junctions formed by natural boundaries in HTSC polycrystals. Such a description is found to be possible in the framework of a model with metal-type series-connected contacts with different effective lengths. The existence of a hysteresis loop and its shape are determined by the ratio of long and short intergranular boundaries in the HTSC polycrystals under investigation.

It should be noted that materials characterized by *I–U* curves with a sharp transition from a low to a high differential resistance (i.e., possessing a clearly manifested broad hysteresis loop) can be used in short-circuit current limiters [37, 38].

ACKNOWLEDGMENTS

This work was supported by the Sixth Competition of Evaluation of Youth Projects, Russian Academy of Sciences, 1999 (grant no. 55), and was partly supported by the Krasnoyarsk Regional Science Foundation (grant no. 10F162M).

REFERENCES

1. V. M. Svistunov, V. Yu. Tarenkov, A. I. D'yachenko, and E. Hatta, Pis'ma Zh. Éksp. Teor. Fiz. **71** (7), 418 (2000) [JETP Lett. **71**, 289 (2000)].
2. D. E. McCumber, J. Appl. Phys. **39** (7), 3113 (1968).
3. R. G. Seed, C. Vittoria, and A. Widom, J. Appl. Phys. **75** (12), 8195 (1994).
4. K. Saitoh, I. Ishimaru, H. Fuke, and Y. Enomoto, Jpn. J. Appl. Phys. **36** (3A), L272 (1997).
5. L. A. A. Pereira and R. Nicolsky, Physica C (Amsterdam) **282–287**, 2411 (1997).
6. L. A. A. Pereira, A. M. Luiz, and R. Nicolsky, Physica C (Amsterdam) **282–287**, 1529 (1997).
7. U. Gunsenheimer, U. Schüssler, and R. Kümmel, Phys. Rev. B **49** (9), 6111 (1994).
8. S. N. Artemenko, A. F. Volkov, and A. V. Zaĭtsev, Zh. Éksp. Teor. Fiz. **76** (5), 1816 (1979) [Sov. Phys. JETP **49**, 924 (1979)].
9. A. V. Zaĭtsev, Zh. Éksp. Teor. Fiz. **78** (1), 221 (1980) [Sov. Phys. JETP **51**, 111 (1980)].
10. G. E. Blonder, M. Tinkham, and T. M. K. Klapwijk, Phys. Rev. B **25** (7), 4515 (1982).
11. K. K. Likharev, Rev. Mod. Phys. **51** (1), 101 (1979).
12. A. F. Volkov and T. M. Klapwijk, Phys. Lett. A **168**, 217 (1992).
13. U. Gunsenheimer and A. D. Zaikin, Phys. Rev. B **50** (9), 6317 (1994).
14. E. V. Bezuglyi, E. N. Bratus', V. S. Shumeiko, *et al.*, Phys. Rev. B **62** (21), 14439 (2000).
15. R. Kümmel, U. Gunsenheimer, and R. Nicolsky, Phys. Rev. B **42** (7), 3992 (1990).
16. R. Nicolsky, Cryogenics **29** (3), 388 (1989).
17. T. P. Devereaux and P. Fulde, Phys. Rev. B **47** (21), 14638 (1993).
18. M. I. Petrov, D. A. Balaev, D. M. Gohfeld, *et al.*, Physica C (Amsterdam) **314**, 51 (1999).
19. W. Scocpol, M. R. Beasley, and M. Tinkham, J. Appl. Phys. **45** (9), 4054 (1974).
20. A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect* (Wiley, New York, 1982; Mir, Moscow, 1984).
21. H. Plehn, Q.-J. Wacker, and R. Kümmel, Phys. Rev. B **49** (17), 12140 (1994).
22. A. A. Verevkin, V. A. Il'in, and V. S. Étkin, Sverkhprovodimost: Fiz., Khim., Tekh. **2** (7), 128 (1989).
23. L. P. Gor'kov and N. B. Kopnin, Usp. Fiz. Nauk **156** (1), 117 (1988) [Sov. Phys. Usp. **31**, 850 (1988)].
24. M. I. Petrov, D. A. Balaev, B. P. Khrustalev, and K. S. Aleksandrov, Physica C (Amsterdam) **235–240**, 3043 (1994).
25. J. Manhart, P. Chaudhary, D. Dimos, *et al.*, Phys. Rev. Lett. **61** (21), 2476 (1988).
26. M. I. Petrov, D. A. Balaev, S. V. Ospishchev, *et al.*, Phys. Lett. A **237**, 85 (1997).
27. S. Benacka, V. Strbik, S. Chromik, *et al.*, Fiz. Nizk. Temp. **24** (7), 621 (1998) [Low Temp. Phys. **24**, 468 (1998)].
28. M. Yu. Kupriyanov, Fiz. Nizk. Temp. **7** (6), 700 (1981) [Sov. J. Low Temp. Phys. **7**, 342 (1981)].
29. A. Furusaki and M. Tsukada, Phys. Rev. B **43** (13), 10164 (1991).
30. I. O. Kulik and A. N. Omel'yanuk, Fiz. Nizk. Temp. **3** (7), 945 (1977) [Sov. J. Low Temp. Phys. **3**, 459 (1977)].
31. V. Ambegaokar and A. Baratoff, Phys. Rev. Lett. **10** (11), 486 (1963).
32. J. W. C. De Vries, G. M. Stolmann, and M. A. M. Gijs, Physica C (Amsterdam) **157**, 406 (1989).
33. B. A. Aminov, N. B. Brandt, N. M. Tkhu, *et al.*, Sverkhprovodimost: Fiz., Khim., Tekh. **2** (1), 93 (1989).
34. D. Deutscher and K. A. Müller, Phys. Rev. Lett. **59** (15), 1745 (1987).
35. V. Ambegaokar and B. J. Galperin, Phys. Rev. Lett. **22** (25), 1364 (1969).
36. M. I. Petrov, D. A. Balaev, K. A. Shaĭkhutdinov, and K. S. Aleksandrov, Fiz. Tverd. Tela (St. Petersburg) **41** (6), 969 (1999) [Phys. Solid State **41**, 881 (1999)].
37. M. I. Petrov, D. A. Balaev, V. I. Kirko, and S. G. Ovchinnikov, Zh. Tekh. Fiz. **68** (10), 129 (1998) [Tech. Phys. **43**, 1255 (1998)].
38. M. I. Petrov, S. N. Krivomazov, B. P. Khrustalev, and K. S. Aleksandrov, Solid State Commun. **82** (6), 453 (1992).

Translated by N. Wadhwa