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Depairing critical currents and self-magnetic field effects in submicron $YBa_2Cu_3O_{7-\delta}$ microbridges and bicrystal junctions

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We report on depairing critical currents in submicron $YBa_2Cu_3O_{7-\delta}$ microbridges. A small-angle bicrystal grain boundary junction is used as a tool to study the entrance of vortices induced by a transport current and their influence on the $I-V$ curves. The interplay between the depairing and the vortex motion determines a crossover in the temperature dependence of the critical current. The high entrance field of vortices in very narrow superconducting channels creates the possibility of carrying a critical current close to the depairing limit determined by the $S-S'-S$ nature of the small-angle grain boundary junction.

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1. Introduction

An understanding of the limitations of supercurrent transport in high-T_c superconductors (HTS) is important from fundamental and applied points of view. The upper limit for the critical current density, j_{cp}, in the superconductors is determined by the mechanism of Cooper pair breaking. High nondissipative currents of the order of j_{cp}, however, can only be attained in some special cases. One of the main mechanisms responsible for the observed reduced values is the motion of vortices, which leads to energy dissipation. The critical current density, j_c, in such a case is determined by vortex pinning. Pinning in an HTS is weak because of the small coherence length, ξ, and to hinder the vortex motion a special approach is needed. This may be achieved by employing narrow superconducting channels. In such a channel the penetration of magnetic field and the vortex motion can be blocked by a surface barrier, which may be an effective additional pinning source in the case of a large surface-to-volume ratio. Experiments on narrow

$YBa_2Cu_3O_{7-\delta}$ (YBCO) microbridges with widths W of 2–13 μm showed a tendency to increase j_c while decreasing W [1]. It was suggested that in the limit of very narrow microbridges with $W < \lambda_{\text{eff}}$ the j_{cp} may be attained due to the increasing role of the surface barrier [1]. Here, $\lambda_{\text{eff}} = 2\lambda_L^2/d$ is the effective magnetic field penetration depth for the superconducting film, λ_L is the London penetration depth, and d is the film thickness. Experimentally, such a behavior has been until now confirmed only in one experiment [2]. Authors report on j_c of 10^9 A/cm^2 measured at 77 K in a 50 nm wide YBCO microbridge. Similar microbridges prepared on the same chip showed a two orders of magnitude lower critical current density. Although a submicron processing may give a random structural degradation, the reason for such a spread in j_c values is not completely understood. Thus, the limitation of critical current densities in high-T_c oxides, especially in a case of narrow filaments, continues to be an unresolved issue and requires further investigation. In particular, large vortex entrance fields for narrow superconducting channels [3] and the influence of inhomogeneities in the case of a restricted geometry have not been investigated.

In this paper, we report on supercurrent transport in submicron YBCO microbridges, with and without a predetermined grain boundary. An asymmetric 4° grain boundary is exploited as a tool to study the entrance of vortices and their influence on j_c and the I–V curves. A self-magnetic field, which is due to the transport current, serves as a source of vortices in the grain boundary, and therefore one can determine the value of the current at which the self-induced vortices start to contribute to dissipation. This characteristic current separates two different regimes, where depairing and flux-flow effects are the dominating mechanisms limiting the magnitude of the supercurrent. The interplay of these two mechanisms determines the unusual temperature dependence of j_c observed in our experiments.

2. Experimental details

We investigated YBCO microbridges 0.5–1 μm wide and 10 μm long. C-axis oriented YBCO thin films with thickness d of 120 nm were grown by laser deposition on Y-ZrO_2 bicrystal substrates. The films had a superconducting transition temperature T_c of 89–90 K with ΔT_c of 1 K before patterning. Three microbridges were patterned across the bicrystal boundary and two microbridges on both sides of the boundary. A mask of e-beam resist SAL601 and Ar ion milling were used to pattern microbridges and electrodes for four-point measurements. The samples were ion milled at −20 °C and the T_c of the microbridges decreased by 3–5 K in respect to the as-deposited films. The submicron bridges had a well-defined trapezoid geometry with a slope of the edges of about 55°, and according to SEM investigations no YBCO «foot» was observed around them.

Standard four-point probe measurements were performed on all microbridges. The critical current I_c was determined from current–voltage characteristics at the voltage level of 1 μV, and its density j_c was calculated using the geometrical cross-sectional area without taking into account the real current distribution.

3. Results and discussions

Current–voltage characteristics were measured at different temperatures. The I_c vs T dependence for a microbridge with a 4° bicrystal grain boundary junction (GBJ) is shown in Fig. 1. Two well-defined regions with different temperature dependences can be distinguished. Close to T_c the $I_c(T)$ dependence is described by a relation $I_c \propto (1 - T/T_c)^{3/2}$. This behavior is further illustrated in Fig. 2,*a* using the coordinates $j_c^{2/3}$ and reduced temperature T/T_c. Such behavior is similar to that expected for the depairing critical current, but it was observed only in a limited temperature range. At temperatures around $T^* = 81$ K, I_c becomes unstable. Below T^* the temperature dependence of I_c changes radically. Simultaneously, a change of I–V characteristics takes place. Above T^* the I–V curves are smooth, but at $T < T^*$ regular steps appear in the I–V curves which are periodic in current (Fig. 3). These steps are only observed

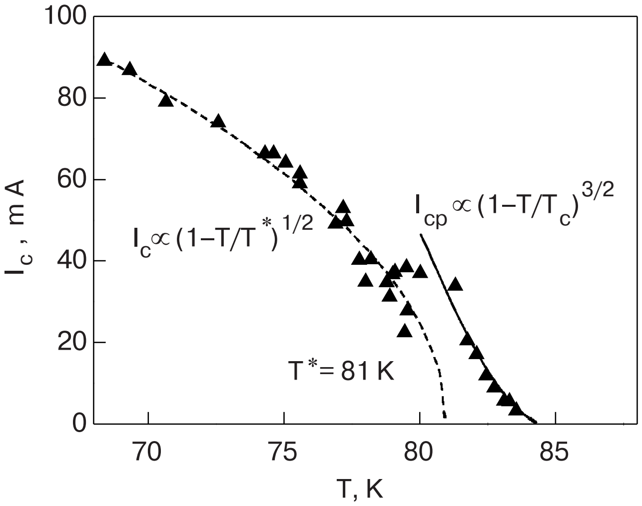

Fig. 1. $I_c(T)$ dependence for a YBCO microbridge ($W = 500$ nm) with a 4° bicrystal grain boundary junction. The solid line corresponds to the dependence $J_c \propto (1-T/T_c)^{3/2}$ and the dotted one to $J_c \propto (1 - T/T^*)^{1/2}$. Note the large spread in I_c within the crossover region.

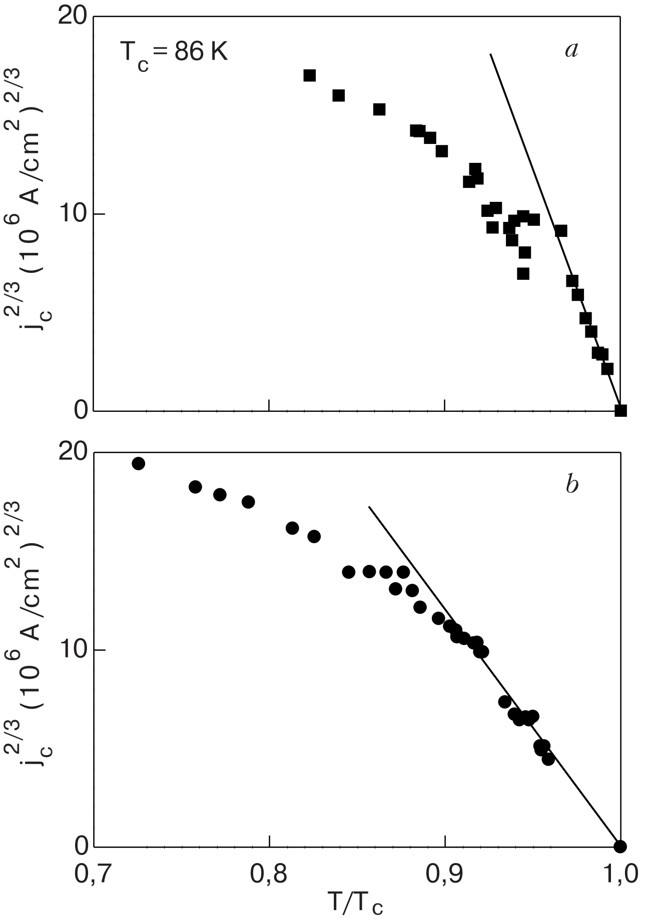

Fig. 2. $j_c^{2/3}$ vs T/T_c dependences for a microbridge with a 4° grain boundary junction (*a*) and for a uniform microbridge (*b*). The microbridges were 500 nm wide 120 nm thick and 10 μm long.

in a limited temperature range of 2–4 K, where also a large spread in j_c values was noted. At lower temperatures, the I–V characteristics are of the flux flow type with $V \propto (I - I_c)^2$.

The maximum value of I_c at $T \approx T^*$ corresponds to a high current density of $3 \cdot 10^7$ A/cm^2. We will show below that the critical current densities in the temperature range between T^* and T_c are very close to the depairing critical current not only qualitatively but quantitatively as well. As shown in Fig. 2,*b*, the critical current densities of the microbridge in the body of the grain are close to the j_c of the GBJ at the same reduced temperatures.

To explain the $I_c(T)$ dependence measured for microbridges with GBJ in the whole temperature range and the high values of j_c, two assumptions were made. First, the barrier of the small-angle GBJ may be described as a «weak» superconductor (S'), with a T_c lower than in the electrodes. Values of j_c approaching the depairing limit can be reached only in weak links with large transparency, and the S–S'–S model may than explain the high j_c values in our experiments in the vicinity of T_c. Another important assumption concerns the absence of vortices in the microbridge at $T > T^*$. As was shown by Likharev [3], the vortex entrance field, H_V, becomes width dependent when the microbridge width is comparable to λ_{eff} and it may attain large values exceeding the first critical field H_{c1} even in bulk superconductors. For a narrow microbridge [3]:

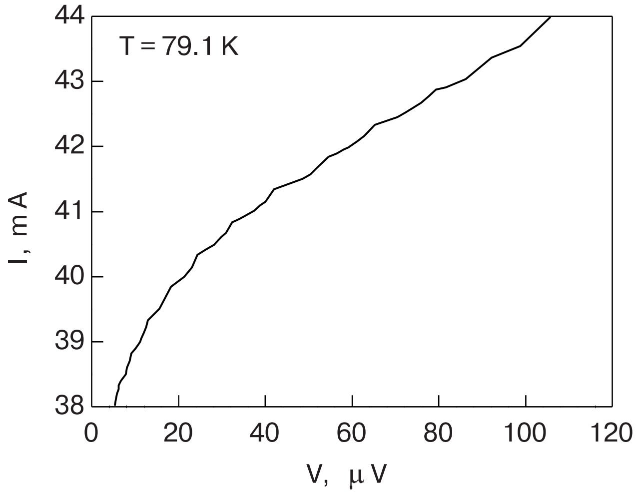

Fig. 3. I–V curve plotted for currents larger than the critical value in a 500 nm wide microbridge crossing a 4° grain boundary. T = 79.1 K. Note the periodic structure ($\Delta I \approx 0.5$ mA) and that the slope (resistance) in the intermediate regions is proportional to the step number.

$$H_V = \begin{cases} (2\Phi_0/\pi W^2)\ln(W/4\xi) & \text{at } W << \lambda_{\text{eff}} \\ (\Phi_0/\pi W \lambda_{\text{eff}})\ln(\lambda_{\text{eff}}/\xi) & \text{at } W >> \lambda_{\text{eff}} \end{cases}. \quad (1)$$

Here Φ_0 is the magnetic flux quantum. The $H_V \propto W^{-2}$ dependence was observed for narrow microbridges of conventional superconductors [4]. If the microbridge edges are smooth, the entrance field may even exceed the calculated H_V values due to the surface barrier [3]. Large entrance fields governed by the surface barrier and exceeding H_V have also been observed experimentally [5].

The properties of S–S'–S weak links have been investigated theoretically [6]. The authors considered a model of a weak link, S', which only differed in its properties relative to those of the bulk electrodes, S, in a shorter electron mean free path l. The weakness of the link was defined by a parameter $\gamma = \chi_{Wl}/\chi_{el}$, χ being a Gorkov universal function of the impurity parameter l/ξ_0 (ξ_0 is the BCS coherence length). The subscripts «Wl» and «el» denote the weak-link region and electrode regions, respectively. It was shown that the critical current density of the weak link exceeds its intrinsic value due to the proximity effect, especially in close vicinity to T_c (the coherence length diverges as $(1 - T/T_c)^{-1/2}$). If the condition $L/2\xi_{Wl} < \gamma^{1/2}$ is met (L is the geometrical length of the weak link and $L/2\xi_{Wl}$ is its normalized length) the critical current density of the weak region is only slightly below the value in the electrodes, i.e., it can be close to the pair-breaking density $j_{cp}(T)$. Nevertheless, since the order parameter in such a contact is depressed in the middle of the weak link, the current–phase relation is close to the Josephson one, and one can expect a Josephson-like behavior [6]. This assumption explains the $(T_c - T)^{3/2}$ dependence of j_c and its large value near T_c. Now let us try to understand the $I_c(T)$ dependence of the microbridges with GBJ obtained in the range $T < T^*$. Near T^*, the j_c of the junction attains values exceeding 10^7 A/cm^2. At such current densities and small cross sections of the microbridge, the self-magnetic field of the critical current, H_{Ic}, at the outer edge of the microbridge, with thickness d, is given by the expression:

$$H_{Ic} = 2\pi j_c d/c. \qquad (2)$$

The H_{Ic} is quite large and may play an essential role in determining the GBJ behavior. As long as this field is lower than H_V determined by formula (1), there are no vortices inside the sample, and the critical current is determined by pair-breaking. Estimates using (1) and (2) show that H_{Ic} equals to H_V at $T = 81$ K for the microbridge in Fig. 1.

Penetration of vortices begins at the weakest spot, i.e., in the Josephson contact. We believe that the instability that appears at $T \approx T^*$ is connected to the penetration of vortices into the weak link. The critical magnetic field H_{c1J} for penetration of a single vortex into a tunnel junction is [7]:

$$H_{c1J} = 2\Phi_0/(\pi^2\lambda_J L_{\text{eff}}). \qquad (3)$$

Here $\lambda_J = (c\Phi_0/8\pi^2 j_c L_{\text{eff}})^{1/2}$ is the Josephson penetration length, and $L_{\text{eff}} = 2\lambda_L + L$. Formula (3) is obtained for a tunnel junction, but one can assume that it is valid for an S–S'–S junction as well since the area occupied by a flux quantum is about $\lambda_J L_{\text{eff}}$. Assuming $L \ll \lambda_L$ and substituting for λ_J in (3) we obtain the following expression:

$$H_{c1J} = (4/\pi)(\Phi_0 j_c/c\lambda_L)^{1/2}. \qquad (4)$$

Near T_c, where $H_{Ic} < H_{c1J}$, the critical current of the weak link is close to the pair-breaking critical current $j_{cp}(T)$ for the bulk material. As the two fields become equal, the mechanism leading to disappearance of superconductivity changes. Starting with the assumption that at $T < T^*$ the critical current density may be defined by the condition $H_{Ic} = H_{c1J}$, one can find the critical current density connected to the vortex mechanism. Using formulas (2) and (4), we obtain

$$j_c(T) = 4c\Phi_0/\pi^4 d^2 \lambda_L(T). \qquad (5)$$

Relation (5), with the temperature dependence $\lambda_L(T) \propto (1 - T/T^*)^{-1/2}$ near T^* taken into account, is shown in Fig. 1 as a dotted line (T^* is assumed to be the transition temperature of the S' superconductor). The agreement of this approximation with the experimental data is good. $\lambda_L(0)$ in the GBJ region was the only fitting parameter. The value obtained, 62 nm, is less than the values of $\lambda_L(0)$ for YBCO known from the literature ($\lambda_L(0) = 100$–140 nm; see Ref. 8 and references therein). In view of the approximateness of our approach the agreement is quite reasonable. In particular, a numerical coefficient may appear in (5) to take into account the nonuniform distribution of the self-magnetic field of the transport current.

There is additional confirmation that crossover in the j_c temperature dependence is associated with the beginning of self-field vortex penetration into the microbridge. The crossover takes place at practically the same critical current density on different microbridges with equal widths (see Fig. 2).

As always, the critical current connected with vortex motion should be smaller than the pair-breaking one. Indeed, we found not only a drastically changed temperature dependence of j_c below T^*, but relatively small values of j_c in comparison with values extrapolated from the $(1-T/T_c)^{3/2}$ dependence. The suppression of j_c may also be considered as evidence for the validity of our model.

The data for an uniform microbridge cut in the body of a single grain (see Fig. 2,*b*) also demonstrate a $j_c \propto (1 - T/T_c)^{3/2}$ dependence near T_c. For a uniform microbridge with $W = 0.8$ μm, the deviation of the experimental points from a $(1 - T/T_c)^{3/2}$ dependence takes place at a lower T/T_c than for a microbridge with a GBJ, but the phenomenon determining this deviation from the $j_{cp}(T)$ dependence is of the same type as in the case of the microbridge with a GBJ, although it is less pronounced. In the uniform microbridge, features similar to those of the GBJ have been observed: instability of j_c around T^*, steps, in the I–V curves (although irregular), and a change of the $j_c(T)$ dependence below T^*. These data can be reasonably explained with the assumption that the uniform microbridge contains some random, uncontrolled S–S'–S weak links which are not as clearly defined as the specially introduced GBJ, but which influence the j_c and I–V curves in a similar way. One may conclude that only if such weak links are not present, can the depairing critical current be observed to low temperatures.

It is also easy to estimate the temperature T^* below which the inequality $H_{Ic} < H_{c1J}$ is violated. Using the experimental j_c temperature dependence obtained near T_c one can rewrite this condition as follows:

$$1 - T^*/T_c = 4c\Phi_0/\pi^4 d^2 j_c(0)\lambda_L(0)\,. \qquad (6)$$

Here $j_c(0)$ is the coefficient in the experimental dependence $j_c(T) = j_c(0)(1 - T/T_c)^{3/2}$. The resulting value T^*=79.4 K is rather close to that observed in the experiment (see Fig. 1), when the value $\lambda_L(0) =$ = 62 nm obtained above is used.

A comparison of the experimental $j_c(T)$ dependence at $T > T^*$ with the formula for the depairing critical current, [9]

$$j_{cp} = c\Phi_0/[12\sqrt{3}\pi^2\xi(T)\lambda_L^2(T)]\,, \qquad (7)$$

may also be used to estimate the value of $\lambda_L(0)$. It should be pointed out that there is some uncertainty in such an estimate because of the essential discrepancy in values of $\xi(0)$ obtained by different authors ($\xi_{ab}(0)$ = 1–3 nm, see Ref. 8 and references therein). Another source of error is connected with a coefficient $j_{cWl}/j_{cel} < 1$ which should be introduced in (7) to take into account the reduced value of the junction j_c in comparison with that of the «bulk». Using formula (7) with $\lambda_L(0)$ = 62 nm defined in the range $T < T^*$, one obtains $\xi(0)$ = 3.3 nm. This value is in the range of those from other measurements. Therefore, the parameter $\alpha = j_{cWl}/j_{cel}$ is close to unity. This is expected due to the proximity effect between S and S'.

Thus all the experimental numerical values and the temperature dependence of j_c in the whole temperature range may be described self-consistently in terms of an S–S'–S weak-link model using only one fitting parameter, $\lambda_L(0)$ = 62 nm. The distinction of this parameter from the values of $\lambda_L(0)$ known from the literature may be explained by the uncertainty in the numerical factors in formulas (5) and (7). This implies that the measurements of $j_c(T)$ in microbridges cannot be used for precise $\lambda_L(0)$ determination.

It is worthwhile also to mention here that a theory [10] considering the critical current of wide HTS epitaxial films with small-angle misorientation between grains predicts that the j_c (T) dependence is governed by the temperature dependence $(1 - T/T_c)^{3/2}$ of the depairing current if the distance between edge dislocations r_d on the bicrystal grain boundary is less than coherence length ξ (T). For a 4° grain boundary the value of r_d is equal to 5.7 nm. This means that such a dependence should be observed to temperatures very close to T_c $(T/T_c = 0.997)$.

The most remarkable feature of Fig. 1 is the crossover in the temperature dependence of I_c and the large spread in the values of the critical current around the crossover temperature. This I_c instability is not understood in detail, but most probably such a behavior is connected with the dynamics of vortex nucleation, and the motion in the conditions, when magnetic field of the transport current attains the threshold for the vortex pair penetration in the GBJ.

Besides the nontrivial $j_c(T)$ dependence, another remarkable feature that is characteristic for a small-angle GBJ is the presence of steps in the I–V curves. The steps are periodic with current and they appear within a limited temperature interval. At first sight, the origin of regular periodic steps in I–V, appearing in the temperature range where the critical current is governed by the penetration of Josephson vortices in the weak link can be connected with the oscillation behavior predicted in Ref. 11. It would then reflect the entrance of the second, third and further vortex–antivortex pairs into the Josephson junction. However, the periodicity of the steps in terms of the self-field of the current is found to be several Oe, while the expected periodicity for the entrance of the next vortices [11], $\Delta H = \Phi_0/2W\lambda_L(T)$, is more than an order of magnitude larger than the values obtained experimentally.

The interaction of moving vortices with the periodic inhomogeneities in the bicrystal boundary (regular misfit dislocation grid) may be considered as possible explanation of the step structure in the I–V curve [12]. The commensurability of the dislocation grid and the vortex spacing, which is determined by the magnetic field (i.e., transport current), may play the key role in this scenario.

In the case of the «uniform» microbridge, the steps are not periodic with current. This may be explained by the presence of a number of low-angle grain boundaries in the microbridge due to YBCO island growth. The question of the origin of the step-like behavior requires a closer investigation. The transition at lower temperatures to the usual flux flow behavior may be explained by a penetration of Abrikosov vortices along the whole length of the microbridge and their motion.

In summary, we have shown that near T_c the critical current density of a submicron microbridge is governed by the pair-breaking mechanism. This is also true for a microbridge containing a controlled weak link of the grain boundary type if the misorientation angle is small. The possibility of carrying a critical current close to the depairing limit is due, in particular, to the absence of vortices in the microbridge. This is caused by the high vortex entrance field for narrow superconducting channels. The properties of such small–angle junctions may be described in a model of an S–S'–S high current density Josephson contact. The value of j_c in such a contact differs only slightly from j_{cp} in the electrodes due to the influence of the proximity effect. At lower temperatures, when j_c becomes controlled by Josephson vortex penetration into the weak link, the $j_c(T)$ dependence changes radically and the j_c values become lower. The same is true for «uniform» microbridges that often contain low angle grain boundaries. The crossover to the vortex motion mechanism of dissipation is accompanied by the appearance of steps in the I–V curves. These disappear again when the whole microbridge enters the vortex state. The steps may be connected with the dynamics of vortex pair motion and annihilation.

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