Mechanisms of critical current limitation in YBCO thin film structures

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The limitation of critical current in high T_c superconducting YBCO thin films has a varied nature according to the quality of YBCO films. Our results showed that in strips from granular films the weak links of superconductor–normal metal–superconductor and superconductor–constriction–superconductor types were responsible for critical current limitation. In the YBCO strips with improved (preferential) crystallographic orientation a flux-creep critical current limitation was found and in the highly oriented YBCO strips the Ginzburg-Landau depairing mechanism approximated the critical current limitation for temperature close to T_c .

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1. Introduction

The critical current (or critical current density) is one of the most important parameters of the transport electrical properties of high temperature superconducting thin film strips. Various critical current limiting mechanisms (CCLM) take part according to the thin film quality. The nature of CCLM can be recognized from the critical current vs. temperature dependence ($I_c(T)$). The important contribution to these problems in low T_c film strips have been made by the I. M. Dmitrenko group from Kharkov (see the excellent review paper [1] and papers cited therein). In this contribution we review some of our results concerning $I_c(T)$ studies on high T_c superconducting thin films, strips and junctions, stimulated by Prof. I. M. Dmitrenko's results and personal contacts.

2. Experimental, results and discussion

The $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ (YBCO) thin films were deposited by dc magnetron sputtering or vacuum co-evaporation method on MgO, SrTiO_3 , or YSZ and CeO_2 buffered Al_2O_3 single crystal substrates. The strips were patterned by wet or ion beam etching.

In Fig. 1 we summarize $I_c(T)$ dependencies in normalized units, where $I_c(T)/I_c(0) \equiv j_c(T)/j_c(0)$ and $t = T/T_c$. We analyzed the $j_c(t)$ dependencies of superconducting strips prepared from granular YBCO

films (solid and open circles in dependencies a, b) in terms of weak link connections between grains, where the power dependence $j_c(t) = j_c(0)(1-t)^\alpha$ occurs and α characterizes the type of current transport through weak links. The fitted dependencies with $\alpha \geq 2.5$ (dashed line, curve a) are characteristic for YBCO films with depressed T_c and low critical current density [$j_c(0) < 10^3 \text{ A/cm}^2$ at self-field conditions] and can be ascribed to nonhomogeneous superconductors with large dispersion of individual connections in weak link network of our granular films [2,3]. In case of YBCO films, where $\alpha \approx 1.5-2$ (dashed line b in Fig. 1), weak links of ScS (superconductor–constriction–superconductor) or SNS (superconductor–normal metal–superconductor) type dominate. The maximal critical current density of these samples was $j_c(0) \approx 10^4 \text{ A/cm}^2$. On the basis of experimental observations one can conclude that the dc transport properties of granular films are determined by weak links between the superconducting grains, thus strongly reducing much higher critical current density of film grains [2].

The temperature dependence of critical current density of stripes, patterned from preferentially oriented YBCO thin films, exhibits downward curvature of $j_c(t)$ (solid and open triangles on curve c). In this case a new mechanism of critical current limitation begins to dominate. We ascribe this

Fig. 1. Temperature dependence of the critical current density of YBCO thin film strips of different quality (see text).

and the full line (curve *c*) represents the fit of experimental data computed from relation [4,5]

$$j_c(t) = j_c(0)(1 - mt - nt^2) \quad (1)$$

where $m = 0.5$, $n = 0.53$ and $j_c(0) = 2.6 \cdot 10^6$ A/cm². Because this type of $j_c(t)$ is characteristic for samples with $j_c(0) \approx 10^6$ A/cm² we suppose that the intergranular weak links are not responsible for critical current limitation. The current-voltage (*I-V*) characteristics of these samples in the low voltage range (just above I_c) also confirmed the flux-creep dissipation process [5].

The strips patterned from YBCO thin films epitaxially grown on SrTiO₃ single crystal substrate ($j_c(0) \geq 10^7$ A/cm²) usually displayed the $j_c(t)$ dependence corresponding to curve *d* in Fig. 1. The study of these temperature dependencies of critical current indicated a Ginzburg-Landau (GL) depairing mechanism in the temperature range close to T_c [6]. The critical current of the microstrip approaches GL depairing current $I_d(t)$ [1,7] when the width w and thickness d of the strip are smaller or comparable to the transverse magnetic penetration depth of the thin film

$$\lambda_{\perp} = \lambda \coth(d/2\lambda) \quad (2)$$

where λ is London penetration depth. If we consider the temperature dependence of magnetic field penetration depth $\lambda(t) = \lambda(0)/(1 - t^4)^{1/2}$ for temperature close to T_c we obtain $\lambda_{\perp} \approx 5-10$ μ m which fulfill the conditions $w \leq \lambda_{\perp}$ and $d < \lambda_{\perp}$ [$\lambda(0) = 200$ nm and $d = 50$ nm were used in Eq. (2)], i.e. homogeneous cross-sectional distribution of transport current in the strip. In Fig. 2 the experimental $j_c(t)$

Fig. 2. Ginzburg-Landau depairing critical current density limitation (full line) for «narrow» YBCO strips close to the critical temperature.

squares) is compared with GL depairing current density (full line)

$$j_d(t) = j_d(0)(1 - t)^{3/2} \quad (3)$$

where $j_d(0) = [\Phi_0/3\sqrt{3}\mu_0\pi\lambda^2(0)\xi(0)]$ is the depairing current density at $T = 0$; Φ_0 is magnetic flux quantum and $\xi(0)$ is coherence length. The value $j_d(0) \approx 2 \cdot 10^7$ A/cm² extrapolated from experimental dependence is in reasonable agreement with the value computed from (Eq. (3)): $j_d(0) \approx 8 \cdot 10^7$ A/cm² for $\lambda(0) \approx 200$ nm and $\xi(0) \approx 3$ nm. These experimental results have shown that $j_c(t)$ close to T_c may approach the GL depairing current as a limiting mechanism.

In the low temperature range (the dependence *d* in Fig. 1, $t < 0.6$) where $w > \lambda_{\perp}$ (wide strip) another CCLM takes place. Due to current concentration at the strip edges, the edge barrier to vortex entry is lowered, and dissipation process in microstrip starts at the current value [8]

$$I_{c1} \approx (\Phi_0/\mu_0\lambda_{\perp}) \ln(d/4\xi), \quad (4)$$

the «lower» critical current. The depression of $j_c(t)$ more than one order of magnitude [for wide strips $w > \lambda_{\perp}(t)$], in comparison to $j_d(t)$, can be explained by the entering of Abrikosov vortices into the superconductor and their motion across the strip [6].

Phase-slip phenomena (PSP) in the one-dimensional superconducting strips [9] as well as in wide strips (moving phase-slip centers or phase-slip lines), may occur as CCLM [1]. In this case the temperature dependence of the critical current density is described by the relation $j_c(t) = j_c(0)(1 - t)^{3/2}$, predicted by GL theory [Eq. (3), but $j_c(0) < j_d(0)$], and the dissipation process is characterized by

Fig. 3. The dependence of critical current I_c vs. temperature of a bicrystal grain boundary Josephson junction. Full line: modified Usadel equation for $L/\xi_N = 0.6 - 4.2$.

ases of differential resistance in the I - V characteristic. We observed properties similar to PSP in 10- μm wide and 100 μm long granular YBCO strips [10]. The estimated quasiparticle diffusion length ($\approx 25 \mu\text{m}$) and temperature dependence of current at voltage steps (i.e. differential resistance increases) are in accordance with the PSP theory. We have concluded that grain boundaries and quality of the strip edges play very important roles in the PSP, and in the critical current limitation in wide as well as narrow YBCO strips.

We also investigated the $I_c(T)$ dependencies of YBCO grain boundary Josephson junctions of bicrystal type [11]. The most adequate fit (full line in Fig. 3) to the experimental $I_c(T)$ dependence (solid squares) we explained by the model of the temperature dependent ratio L/ξ_N , where L is the length of a normal region in the YBCO strip at a bicrystal boundary in the direction of current flow and ξ_N is the coherence length of the normal region. In this case the temperature dependent transparency of the junction normal region for superconducting carriers is the main factor of CCLM. The Ambegaokar-Baratoff [12] $I_c(t)$ dependence (AB in Fig. 1) in our studies is not suitable for approximation of any one dependence for YBCO strips, sandwich YBCO/PrBaCuO/YBCO [13] or bicrystal grain boundary SNS junctions.

3. Summary

In this contribution we reviewed various mechanisms of critical current limitation in high T_c superconducting YBCO thin film strips and structures. We analyzed these mechanisms on the base of the temperature dependence of the critical current and corresponding models that are valid for low T_c superconductors. The weak links, mainly of SNS and ScS types, flux-creep, Ginzburg-Landau depairing current, phase slip phenomena and temperature dependent «transparency» of the bicrystal junction for transport superconducting current are responsible for critical current limitation in high temperature superconducting thin film samples.

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1. I. M. Dmitrenko, *Low. Temp. Phys.* **22**, 648 (1996).
2. V. Strbik, S. Benacka, S. Gazi, S. Chromik, J. Levarsky, and J. Sith, *Mod. Phys. Lett.* **B3**, 729 (1989).
3. N. Savvides, *Physica* **C165**, 371 (1990).
4. J. Mannhart, P. Chaudhari, O. Dimos, C. C. Tsuei, and T.R. McGuire, *Phys. Rev. Lett.* **61**, 2476 (1988).
5. V. Strbik, R. Adam, S. Benacka, and S. Chromik, *Proc. of the Intern. Workshop on Critical Current Limitations in High Temperature Superconductors* Zaborow (Poland) (1991) p. 366.
6. V. Strbik, S. Benacka, S. Chromik, R. Adam, P. Tomas, E. Pincik, and V. Smatko, *presented on International Conference: Critical Currents in High T_c Superconductors*, Vienna (1992).
7. K. K. Likharev, *Zh. Eksp. Teor. Fiz.* **61**, 1700 (1971) [*Sov. Phys. JETP* **34**, 906 (1972)].
8. K. K. Likharev, *Radiofizika* **14**, 919 (1971).
9. W. J. Skocpol, M. R. Beasley and M. Tinkham, *J. Low Temp. Phys.* **16**, 145 (1974).
10. V. Strbik, R. Adam, and S. Benacka, *Proc. of Weak Superconductivity Symposium, Smolenice* (Slovak Republic) (1989) p. 75.
11. V. Strbik, O. Harnack, S. Chromik, M. Darula, and S. Benacka, *Applied Superconductivity 1997, Proc. of EU-CAS'97*, H. Rogalla and D. H. A. Blank (eds), Inst. of Physics, Conf. series No. 158, p. 503.
12. V. Ambegaokar and A. Baratoff, *Phys. Rev. Lett.* **10**, 486 (1963).
13. Unpublished results of authors.