Nature of magnetic field and angular dependencies of the critical current density in epitaxial HTS $YBa_2Cu_3O_{7-\delta}$ films

Vladimir M. Pan [a,1], Yuri V. Fedotov [b], Sergey M. Ryabchenko [b], Ernst A. Pashitskii [b], Alexei V. Semenov [b], Victor I. Vakaryuk [b], Victor S. Flis [a], Yuri V. Cherpak [a]

[a] *Institute for Metal Physics, Vernadsky Blvd. 36, 03142, Kiev, Ukraine*
[b] *Institute of Physics, Nauki Av. 46, 03028, Kiev, Ukraine*

Abstract

Out-of-plane edge dislocations (mean 2D density is 10^{11} lines/cm^2) in low-angle tilt domain boundaries of single-crystalline YBCO films are shown to play a crucial role in $J_c(H\|c,T)$-behavior and J_c angular dependence. Dislocation cores and their vicinity, where T_c is locally suppressed, are shown to provide an extremely strong pinning force resulting in $J_c(77\ \mathrm{K}) \approx 2 \cdot 10^6$ A/cm^6. Peculiarities of $J_c(H\|c)$ are found in the low field range. A simple model of pinning by dislocation domain boundaries is developed. The model consistently describes the $J_c(H\|c,T)/J_c(0,T)$-dependencies, accounting for the fraction of vortices pinned by dislocations. Angular dependencies of J_c in rotating magnetic field were measured by four-probe transport technique. A satisfactory agreement with theoretically predicted behavior has been found.

Key words: high-T_c superconductivity; epitaxially grown thin films; pinning by edge dislocations

Epitaxially grown thin films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) high-temperature superconductor (HTS) exhibit high $J_c(77\ \mathrm{K})$, that is two orders of magnitude higher than the critical current in YBCO bulk materials. High average density (up to 10^{11} lines/cm^2) of growth-induced linear defects (dislocations) was revealed in YBCO films by high resolution electron microscopy [1-3]. The electromagnetic behavior of YBCO films, in particular J_c, associated with *out-of-plane* dislocations in a network of tilt low-angle boundaries (LABs) forming mosaic domains [1-3], was studied in a number of papers [4-8]. Typical $J_c(H\|c)$-dependencies consist of a low-field plateau region followed by a monotonic decline fitted usually by a power law $J_c(H\|c) \propto H^{-q}$, where q is about 0.5. In the present work, the $J_c(H\|c,T)$ behavior for pulse-laser deposited (PLD) YBCO films is studied at low fields. It is shown that the dependence just above the plateau is well fitted by a logarithmic rather than a power law. A theoretical model, which allows to fit $J_c(H\|c,T)$-curves, is developed. J_c angular dependence in a tilted magnetic field demonstrates a remarkable peak at $H\|c$. This peak is supposed to be an evidence of contribution of pinning by out-of-plane edge dislocations. A simple model of tilted vortex pinning on such linear defects is proposed.

Measurements of $J_c(H\|c,T)$ in PLD YBCO films on $LaAlO_3$ (100) substrates were carried out in the temperature range $T_c > T > 77$ K by AC magnetic susceptibility technique. The normalized dependencies $J_c(H\|c,T)/J_c(0,T)$ are presented in Fig. 1. The dependencies have a low-field plateau region $0 \le H \le H_m(\tau)$ and a crossover at $H = H_m(\tau)$ to the falling down behavior, that can be universally fitted at intermediate fields by the expression: $J_c(H\|c,T)/J_c(0,T) = \alpha \log H^*(\tau)/H$, where $\tau = 1 - T/T_c$, $H^*(\tau) = H_m(\tau)e^{1/\alpha}$ is proportional to τ, and α is a weakly temperature dependent coefficient ($\alpha \approx 0.19$ - 0.24).

The developed J_c-limitation model supposes vortex

[1] Corresponding author. E-mail: pan@imp.kiev.ua

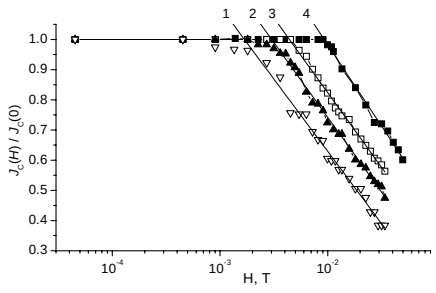

Fig. 1. Normalized $J_c(H)/J_c(0)$-dependencies: filled squares - 77 K; open squares - 80 K; filled triangles - 83 K; open triangles - 86 K. Solid lines 1-4 correspond to the equation $y = \alpha \log H^*(\tau)/H$ with α and H^* being 0.208 and 0.21 T; 0.215 and 0.31 T; 0.215 and 0.46 T; 0.234 and 0.64 T, respectively.

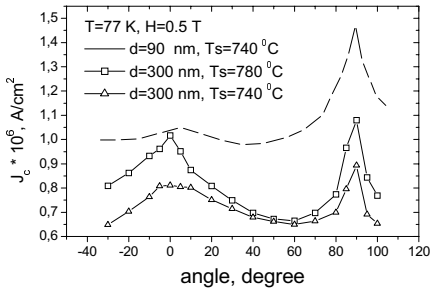

Fig. 2. Experimentally measured $J_c(\theta)$ curves for pulse-laser deposited YBCO films on (100) $LaAlO_3$ substrates.

depinning from out-of-plane edge dislocations, which form LABs surrounding a multitude of mosaic domains with the mean size $\langle L \rangle$, slightly misoriented to each other. $J_c(H,\tau)$ is shown to be determined by the fraction of pinned vortices in the distorted vortex line lattice (VLL). The critical displacement $\delta(H,\tau)$ for a vortex in 2D disordered VLL to be pinned is found from the condition $|\varepsilon_{pin}| \geq C_{66}\delta^2$, where δ is a displacement from equilibrium position in VLL, ε_{pin} is the energy of core-pinning and C_{66} is the elastic shear modulus of VLL. $J_c(H,\tau)$ is expressed through $\delta(H,\tau)$ and parameters of the size distribution function $W(L)$ of the area occupied by domains. $J_c(h\|c,T)/J_c(0,T)$ dependencies were calculated for the case of square domains with $W(L)$ being a statistical Γ-distribution [8]. The model reproduces experimentally observed scaling $J_c(H,\tau) \propto (\tau/H)^{1/2}$ at the logarithmic region as well as the values of its slope α. The details of this model and comparison with experiments have been published elsewhere [9].

The critical current density J_c in epitaxial films of cuprate superconductors with the $\bar{c}$-axis oriented perpendicular to the substrate in applied magnetic field $\bar{H}$ exhibits a highly anisotropic dependence on the angle θ between $\bar{H}$ and $\bar{c}$. Such dependencies were measured by the four-probe transport current technique for several YBCO films of different thickness d. The films were deposited with a use of two crossed beams pulse Nd/YAG lasers. Single crystalline $LaAlO_3$ (100) substrates were used. The obtained $J_c(\theta)$-dependencies are shown in Fig. 2.

There are two peaks on the $J_c(\theta)$ curves at $\theta = 0$ ($\bar{H}\|\bar{c}$) and at $\theta = 90°$ ($\bar{H}\perp\bar{c}$)). This dependence is apparently indicative of the existence of two pronounced systems of extended defects (dislocations) oriented along the $\bar{c}$-axis and in the ab-plane, and of the efficiency of pinning at such defects. The simplest model [10] of single-particle core pinning at δ-function dislocation core with the potential $U_{pin}(r) = U_0\pi r_0^2\delta^2(r)$ in a tilted magnetic field has been shown to describe correctly the experimental $J_c(\theta)$ dependencies in the cuprate epitaxial films.

In a summary, the model of vortex pinning by a dislocation domain LABs network in YBCO quasi-single-crystalline epitaxially grown films is shown to describe consistently the $J_c(H\|c,T)/J_c(0,T)$-dependencies with logarithmic regions. The simplest model of single-particle core pinning at dislocation cores in low tilted magnetic fields gives a qualitatively correct description of the orientational dependencies of pinning force and critical current.

Acknowledgements

This work was supported in part by the INTAS project 99-0585 and NAS of Ukraine project 1.4.1.VC/95.

References

[1] V.M. Pan et al., Cryogenics **33** (1993) 21.

[2] Y. Gao, et al., Physica C **174** (1991) 1.

[3] V. Svetchnikov, et al., IEEE Trans. Appl. Supercond. **7** (1997) 1396.

[4] V. Pan, et al., IEEE Trans. Appl. Supercond. **11** (2001) 3960.

[5] B. Dam, et al., Nature **399** (1999) 439.

[6] E. Mezzetti, et al., Phys. Rev. B **60** (1999) 7623.

[7] E.A. Pashitskii, et al., Low Temp. Phys. **27** (2001) 96.

[8] G. Ghigo, et al., Proc. 10th Internat. Workshop on Critical Currents - IWCC 2001, June 4-7, 2001, Goettingen, Germany, p.100-102.

[9] Yu.V. Fedotov, et al., Low Temp. Phys **28** (2002) 172.

[10] E.A. Pashitskii and V.I. Vakaryuk, Low Temp. Phys **28** (2002) 11.