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Peak-effect and angular hysteresis in $J_c(H, \theta)$ dependencies for $YBa_2Cu_3O_{7-\delta}$ epitaxial films

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Abstract. New phenomena - peak-effect and angular hysteresis - in field/angle $J_c(H, \theta)$ dependencies are detected for YBCO epitaxial films at moderate dc magnetic fields *H* parallel to the film. Films (300-350 nm thick) are deposited by off-axis dc magnetron sputtering onto r-cut sapphire substrate buffered with CeO_2. Surface roughness (peak-to-valley) determined by AFM does not exceed 2 nm. $J_c(H, \theta)$-curves are measured by low-frequency ac magnetic susceptibility and four-probe transport technique. $J_c(H)$ at $H \| ab$-plane for the most smooth films reveal dome-shape enhancement of J_c(up to 10 p.c.) above $J_c(0)$ value, starting from the field H^* ascribed to the first critical field H_{c1} of thin film. $J_c(H)$-plots at $H \| c$-axis with a plateau at low fields followed by monotonic fall-down are consistent to our model of vortex lattice depinning from the out-of-plane linear defect network (growth-induced edge dislocations). Field dependencies of J_C at arbitrary inclination angles may be recalculated from $J_c(H, \theta=0)$ and $J_c(H, \theta=\pi/2)$, assuming independent effects of normal $H\cos\theta$ and parallel $H\sin\theta$ field components on J_c. Angle $J_c(\theta)$−dependencies evolution with *H* is shown to be consistent with dominant mechanism of pinning on edge dislocations. The most surprizing feature of this evolution is emergence of the peak in $J_c(\theta)$-dependence for $H \| c$-direction, becoming observable only above threshold magnetic field H_p dependent on film thickness and surface roughness. Angular hysteresis in $J_c(H, \theta)$ dependence is detected for magnetic field directions close to $H \| ab$-plane. This hysteresis is sensitive to magnetic/angular pre-history and together with observed peak-effect at $H \| ab$-plane can be understood by account for surface (and/or geometrical) barrier as additional pinning source for Abrikosov vortices.

1. Introduction

The highest critical current density J_c(77 K) for high-temperature superconductors (HTS) is achieved in $YBa_2Cu_3O_{7-\delta}$ (YBCO) *c*-axis oriented epitaxial thin films [1,2]. A few models distinguished by Abrikosov vortex pinning mechanism were proposed to comprehend such a high values and peculiarities of $J_c(H,\theta)$ behavior in YBCO films at external magnetic fields of different orientations (θ is the angle between magnetic field vector and *c*-axis). As the most effective pinning centers were suggested (1) linear extended crystal defects – nonsuperconducting cores of edge dislocations (ED's), with cross section approximately equal to coherence length, ξ_{ab} [3], (2) planar defects (twins and anti-phase boundaries) [4], (3) point-like defects (oxygen vacancies and normal phase Y_2O_3 inclusions) [5,6], (4) film surface and its irregularities [7]. The dominating contribution of extended linear defects in vortex pinning and critical current was proved out in our previous papers [8-11]. Out-of-plane EDs, emerging during the epitaxial growth of YBCO film and forming the tilt low-angle boundaries (LABs) between single-crystal domains, appear to be the most effective pinning centers for Abrikosov vortex lattice (VL). Mean density of EDs according to electron microscopic studies achieves 10^{11} cm^{-2} [12]. Our model of collective VL depinning from EDs ensemble described quantitatively $J_c(H, \theta=0)$ field dependencies through statistical parameters of LABs nanoscale structure in YBCO films [8,9]. A consistency of the model with $J_c(H,\theta)$ magnetic field and orientation dependencies was shown in [10,11]. This study is done to clarify some peculiarities of $J_c(H,\theta)$ due to the contribution of electromagnetic pinning to the main pinning mechanism on a multitude of out-of-plane EDs in perfect YBCO films for a wide range of orientation angles and magnetic field values. Moderately thin ($d \approx \lambda$, d is film thickness and λ is the London penetration depth) quasi-single-crystal YBCO films are deposited by off-axis *dc* magnetron sputtering (OMS) onto single-crystal *r*-cut sapphire substrates buffered with CeO_2 layer. $J_c(H,\theta)$-dependencies are measured by contact-free technique of *ac* low-frequency magnetic susceptibility, as well as by four-probe transport current technique.

2. J_c (H) dependencies at various field orientations

$J_c(H)$-dependencies were measured for $(H||c)$- and $(H||ab)$- orientations of magnetic field and demonstrate J_c-plateau at $H<H_m(\theta)$. A few important peculiarities should be noted: (1) the plateau for $(H||ab)$- appears to be much longer than for $H||c$-orientation; (2) some "peak-effect" is observed at the $(H||ab)$ plateau end before the falldown of $J_c(H)$ in the most perfect films; (3) $J_c(H||ab)$ falldown is steeper. The curves in Fig. 1 are measured by the *ac* magnetic susceptibility technique and Clem-Sanchez' analysis of $\chi''(h_{ac})$ data [13]. Similar results for $J_c(H||ab)$ are obtained by transport current four-probe technique for OMS YBCO film K6300 (Fig. 2).

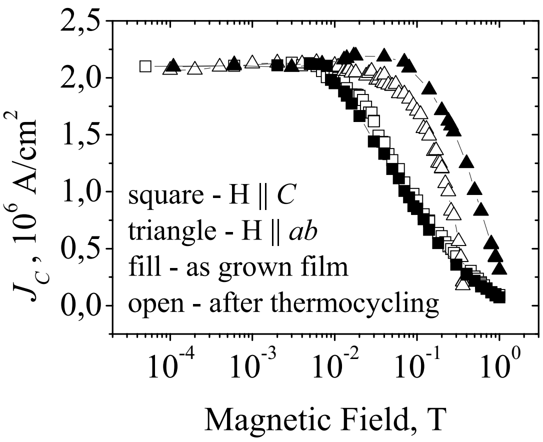

Figure 1. $J_c(H||c)$ (■, □) and $J_c(H||ab)$ (▲, Δ) dependencies for OMS YBCO film K2 (300 nm thick). Measured at 77 K by *ac* magnetic susceptibility technique on as-grown film (■, ▲) and after thermocycling 77 <=> 300 K (□, Δ).

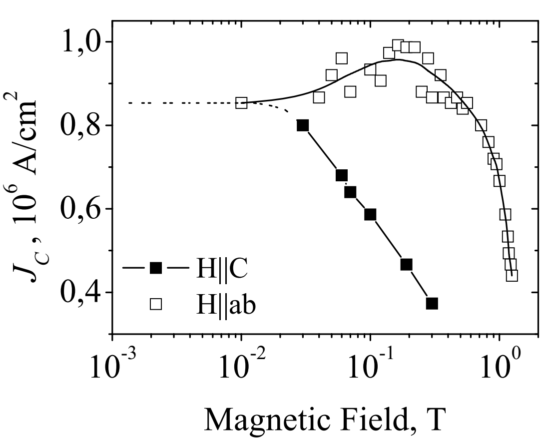

Figure 2. $J_c(H||c)$ (■) and $J_c(H||ab)$ (□) dependencies for OMS YBCO film K6300 (300 nm thick) at 77 K (transport four-probe technique).

$J_c(H||ab)$-dependencies in Fig. 1 (full simbols) and Fig. 2 are obtained for as-grown YBCO films. The analogous dependence for film K2 is measured after several thermocycles 300 K<=>77 K (Fig. 1, open simbols). One can see $J_c(H||ab)$-dependence changed essentially: "peak-effect" disappeared and the decreasing branch above $H_m^{||}$ shifted towards the $J_c(H||c)$ dependence which remained almost unchanged. The steeper decrease of $J_c(H||ab)$ resulted in a crossing of $J_c(H,\theta=0°)$ and $J_c(H,\theta=90°)$ dependencies at a certain characteristic field H_{cr}. For K2 film $H_{cr} \approx 0.34$ T (Fig. 1).

3. Angle $J_c(\theta)$-dependencies at various fields

Angle $J_c(\theta)$-dependencies for YBCO films were rather controversial with either one maximum at $\theta=0$ and minimum at $\theta=\pi/2$ [14], one maximum at $\theta=\pi/2$ and minimum at $\theta=0$ [6,10] or two maxima at $\theta=0$ and $\theta=\pi/2$ [4,11] had been reported. The second case was considered as the main objection [6] against *c*-oriented EDs-pinning mechanism, while it was shown [10, 11] that for rather low fields and thin ($d << \lambda$) films there is no any contradiction. Here we show that all three cases can be obtained for the same rather thick film with $d \approx \lambda$ and degraded surface at different field values (Fig. 3).

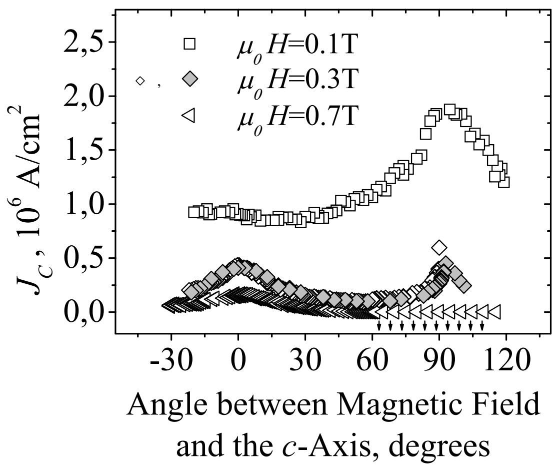

Figure 3. Angle dependencies Jc(H, θ) for the K2 film at three different applied fields. Angular hysteresis at 0.3 T: filled and open symbols correspond to increasing and decreasing branches, respectively.

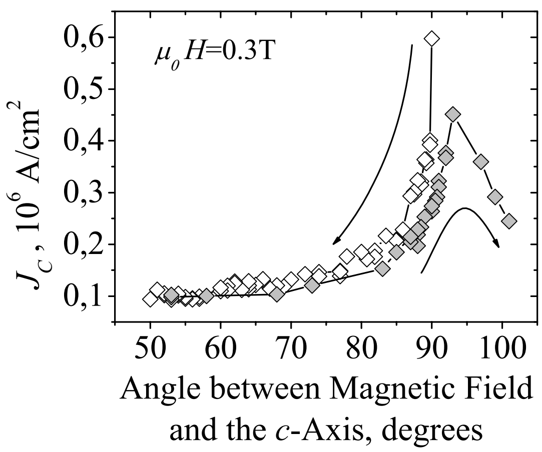

Figure 4. Angular hysteresis of the critical current at intermediate parallel field for the K2 film.

At low field values there is only one broad maximum at $\theta=\pi/2$ (Fig. 3) in accordance with [6,10]. Steep falldown of $J_c(H, \theta=\pi/2)$ dependence (Fig. 1) permits the emerging of second maximum in the angular dependence at $\theta=0$. This maximum becomes more remarkable at applied field elevation while maximum at $\theta=\pi/2$ diminishes and becomes sharper. The heights of two maxima equalize at $H_{cr} \approx$ 0.34 T for degraded K2 film, were the $J_c(H||c)$ and $J_c(H||ab)$ plots (Fig. 1) cross each other. The $J_c(H||c)$-peak is observable at 0.7 T for this film, while in the vicinity of $H||ab$ at 0.7 T J_c appears to be lower than 10 kAmp/cm^2 and *ac* magnetic susceptibility does not allow to measure it with sufficient accuracy.

At the near vicinity of $\theta=\pi/2$ in intermediate fields (0.3 T in Fig. 4) $J_c(\theta)$ exhibites a hysteretic behavior. After field cooling at $\theta=\pi/2$ and field rotation to $\theta=0$ and backward $J_c(\pi/2)$ does not return to the same but somewhat lower value. Such a hysteretic behavior is supposed to be an evidence of strong pinning of longitudinal parts of Abrikosov vortices.

4. Discussion

The absence of the $J_c(H||c)$ maximum at certain field region is just the consequence of the fact that in low fields the "plateau" in $J_c(H||c)$ dependence in thin films is shorter than the one in $J_c(H||ab)$ case.

In the normal case $H_m^{\perp}$ is determined by the accommodation function of the Abrikosov VL on the ED ensemble in thin film [8,9] and may be rather low for a perfect films with large monocrystallic domains. For the in-plane field orientation $H_m^{||}$ is governed by surface Meissner currents induced by the parallel field tending to bend the ends of all vortices out from dislocation cores and to diminish the total pinning force. This is the field for which the value of the Meissner current at the film surface equalize to the critical current in the zero field (or at the plateau) $J_c(0)$: $H_m^{||} = (4\pi\lambda/c)\cdot \coth(d/2\lambda)\cdot J_c(0)$ [11].

For as-grown film a kind of weak "peak-effect" in $H||ab$ can be understood by suggestion of electromagnetic pinning on the Bean - Livingstone type surface barrier admixture to the core pinning on ED. In the vicinity of $H_{c1}^{||}$ the critical current density supported by electromagnetic mechanism alone is [15]: $J_c(H) = c\cdot d\cdot H\big/\left(4\pi^2\lambda^2\right)\left\{\arccos\left(H_m/H\right)^{1/2} - \left[\left(H_m/H\right)\cdot\left(1-H_m/H\right)\right]^{1/2}\right\}$, where $H_m = \pi\phi_0/4d^2$ is the field of metastable vortex appearance. Electromagnetic critical current increases with H until second row of vortices formation in film when J_c diminishes abruptly and for large H decreases as $H^{-1/2}$. The effectiveness of Bean - Livingstone barrier is known to be strongly dependent on surface quality, so the suppression of "peak-effect" in OMS film after several thermocycles (Fig. 1) may be comprehended by surface degradation.

$J_c(H,\theta)$ hysteretic behavior at field close to H^{CR} can be comprehended by diminishing the quantity of parallel vortices after consequent field straight and backward rotation. Primarily these parallel vortices which contribute to electromagnetic pinning mechanism enter film during field switching at precise longitudinal configuration

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