8th European Conference on Applied Superconductivity (EUCAS 2007) IOP Publishing
Journal of Physics: Conference Series 97 (2008) 012225 doi:10.1088/1742-6596/97/1/012225

Angular dependence of critical currents in $YBa_2Cu_3O_{7-\delta}$ vicinal films.

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Abstract. The angular dependence of the critical current density in a patterned 8° vicinal thin film of $YBa_2Cu_3O_{7-\delta}$ has been investigated. The transport critical currents were measured on a T track under a variable Lorentz force and under a maximum Lorentz force configuration at different temperatures and fields. The expected critical current minima due to channelling of vortices were observed. String and pancake forces per unit length have been determined.

1. Introduction

The critical currents in type-II superconductors are directly related to flux pinning effects in the material. Technical applications of high temperature superconductors (HTS) often depend on high critical currents in external magnetic fields. A better understanding of different states of the flux lattice and its interaction with pinning sites is an important prerequisite for developing and improving HTS conductors and their applications. Angular measurements of the critical current on vicinal films offer the possibilty to investigate different states of the flux line lattice in a single experiment and provide access to varying pinning contributions.

The anisotropy of $YBa_2Cu_3O_{7-\delta}$ (YBCO) is relatively moderate in comparison to two dimensional HTS like $Bi_2Sr_2CaCu_2O_{8+x}$ (Bi-2212). Depending on the direction of the applied magnetic field, one finds therefore in YBCO a transition between three dimensional anisotropic vortices to a kinked vortex state, where the votices are built up of pancake vortices connected by Josephson vortex strings along the ab planes [3]. With θ being the angle between the magnetic field direction and the ab planes, two critical angles, θ_1 and θ_2, are defined. $\tan(\theta_1) = d/\xi_{ab}$, where d is the distance between the superconducting CuO_2 planes and ξ_{ab} is the Ginzburg-Landau (GL) coherence length in the ab plane, and $\tan(\theta_2) = 1/\gamma$ with γ being the anisotropy parameter. At sufficiently low temperatures, the rectilinear anisotropic vortex state breaks down and a kinked vortex structure emerges for angles $|\theta| < \theta_1$. This kinked vortex state is fully developed for $|\theta| < \theta_2$. For very small angles ($\approx 0.2\,°$) the vortices "lock-in" to the planes and the magnetic field is perfectly aligned with the ab planes. At temperatures above a critical temperature T_{cr}, where T_{cr} is defined by the condition, that the GL coherence length in c direction $\xi_c(T_{cr}) = d/\sqrt{2}$, a rectilinear vortex state persists for all θ and no lock-in transition is expected.

In the case of YBCO $\gamma \approx 5$, $d \approx 1.2\,\mathrm{nm}$ and $\xi_{ab}(0) \approx 1.6\,\mathrm{nm}$. Therefore one gets for $\theta_1 \approx 35\,°$, $\theta_2 \approx 11\,°$ at $T = 0\,\mathrm{K}$ and $T_{cr} \approx 80\,\mathrm{K}$ [3].

For transport measurements on vicinal thin films, the current direction perpendicular to the tilt axis of the cuprate planes, the T track, is the most interesting. In a T track the current direction is not aligned with the ab planes of the film. Thus, a component of the Lorentz force parallel to ab remains even when the magnetic field is applied in the direction of the planes. Because the vortex strings in the ab planes are weakly pinned below the critical temperature T_{cr} in perfectly epitaxial materials, a decrease in the critical current due to vortex channelling is observed. Tracks in the direction of the tilt axis, are called L tracks. They show a similar angular behaviour in J_c as would be expected for an untilted sample.

2. Sample

The sample was a 150 nm thick YBCO thin film grown by pulsed laser deposition on a $8\,°$ $SrTiO_3$ vicinal substrate. The film was patterned by photolithography and Ar ion milling. A layer of Ag followed by a layer of Au were sputtered onto the film surface to form the contacts.

The pattern provides seven $10\,\mu\mathrm{m}$ wide tracks in different directions: One L track, three T tracks and three tracks, which form an angle of $60\,°$, $45\,°$ and $30\,°$, respectively, with the tilt axis.

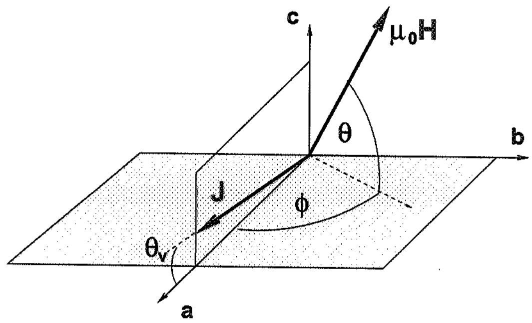

Figure 1. Definition of the angles used in this paper. θ_v refers to the miscut angle of the substrate, ϕ and θ specify the orientation of the magnetic field, where θ is measured from the ab plane. $\phi = 90°$ and $\phi = 0°$ correspond to the MLF and the VLF configuration, respectively. This convention follows Ref. [1].

3. Experimental

The measurements were carried out with a two axis goniometer mounted in a 6 T split coil magnet in a He gas flow cryostat. Four spring loaded contacts with small indium pads between the contact tip and the film were used for standard four probe measurements. The sample current was limited to about 100 mA to avoid contact heating.

The critical current density was evaluated from single IV-curves employing an arbitrary 0.5 μV criterion.

All measurents presented here were performed on one T track of the sample. The rotation of the magnetic field was done in two different configurations, a "Maximum Lorentz Force" (MLF) configuration, where the magnetic field vector is orientated perpendicular to the track, and a "Variable Lorentz Force" (VLF) configuration, where the magnetic field rotates in the plane spanned by the c-axis of the film and the current direction (see Fig. 1).

4. Results and Discussion

The transition temperature T_c^{onset} of the film was 89.1 K. The critical current density J_c at 77 K was $3.0 \cdot 10^{10}$ A/m^2.

In Fig. 2 the results of a rotation experiment at a magentic field of 1 T and at various temperatures is depicted. In both, the MLF and the VLF measurement, a vicinal channelling minimum of the critical current densitiy is observed at $\theta = 0°$. The channelling effect is strongly temperature dependent and still present at 60 K.

In the VLF configuration the channelling minimum is offset by 8° (the c axis tilt) from the

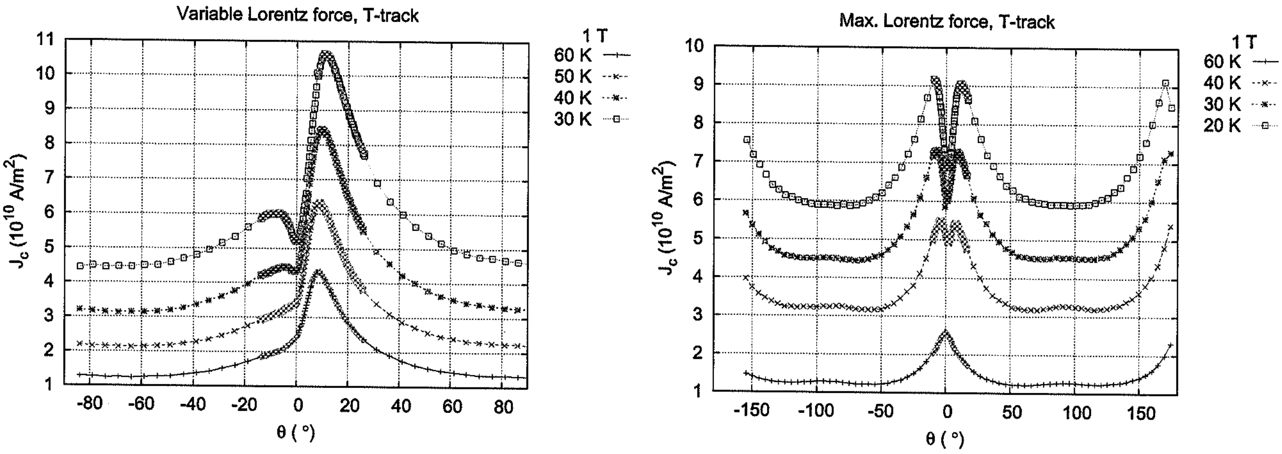

Figure 2. Angular dependence of J_c at different temperatures measured on a T track at 1 T.

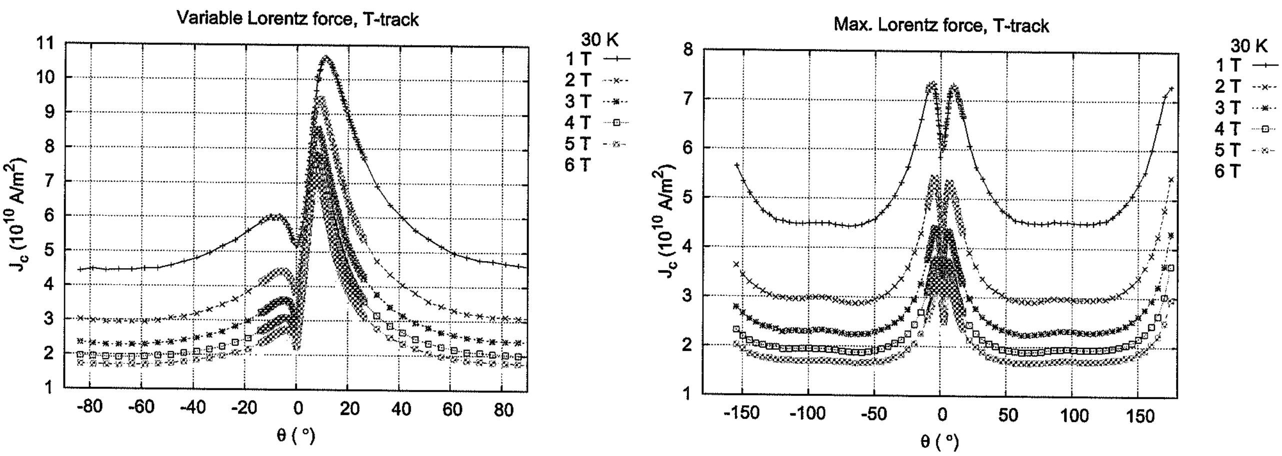

Figure 3. Angular dependence of J_c at different fields measured on a T track at 30 K.

"force free" orientation, where the magnetic field is aligned with the current direction. In the MLF curves the channelling minimum coincides with the angular position of the intrinsic peak and leads to a suppression of the peak. Additional peaks at $\theta = \pm 90°$ are visible in the MLF measurements, which could be attributed to twin-boundaries or other defects aligned along the c-axis and causing an anisotropic pinning mechanism. The Lorentz force density decreases upon moving away from $\theta = 90°$ in about the same way in both cases, VLF and MLF. In the VLF configuration the decline comes from the decreasing Lorentz force, in the MLF configuration from the anisotropic pinning mechanism. The loss of pinning force in both configurations is, therefore, compensated by the decline of the Lorentz force in the VLF configuration.

The VLF $J_c(\theta)$ dependence measured at different temperatures scales with the critical current density at $\theta \approx 90°$. For the MLF curves the critical current density at $\theta = 90°$ cannot be used for scaling because of the anisotropic pinning shown by most of the measurements at this angle. In these cases some minimal critical current value in the neighborhood of the peak was chosen, which still led to reasonable scaling results. The scaling behaviour confirms the expected range $\theta > |\theta_1|$, where the angular variation should be determined by three dimensional Abrikosov vortices.

The overall shape of the angular dependence of J_c does not vary with magnetic field as can be seen in Fig. 3.

An attempt was made to apply the models describing the kinked vortex region proposed in [1]. The results for a VLF measurement at 1 T and 30 K are as follows: pancake flux pinning force per unit length, $f_{p,pc}$, $1.5 \cdot 10^{-4}$ N/m, string pinning force per unit length, $f_{p,str}$, $1.5 \cdot 10^{-5}$ N/m and flux cutting force, f_{cut}, $3.6 \cdot 10^{-14}$ N. These data agree well with results published in [1] and [2].

5. Summary

Angular dependent measurements of J_c were performed on 8 ° vicinal films in a MLF and a VLF configuration. The expected channelling minima in the ciritcal current density were observed. A model describing the kinked vortex region proposed in [1] was applied to determine $f_{p,pc}$, $f_{p,str}$ and f_{cut}. The results agree with previously published data.

6. References

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