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Anisotrophic currents and flux jumps in high-T_c superconducting films with self-organized arrays of planar defects

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ABSTRACT

Regular arrays of planar defects with a period of a few nanometers can be introduced in superconducting $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films by depositing them on vicinal (also called miscut or tilted) substrates. This results in the anisotropy of critical currents flowing in the plane of the film. We present results of real-time magneto-optical imaging (MOI) of magnetic flux distribution and dynamics in a series of YBCO thin films deposited on $NdGaO_3$ substrates with different miscut angles θ. MOI allows reconstructing the current flow profiles. From the angle formed between domains with different directions of the current flow we determine the anisotropy parameter of the in-plane current, as well as its field and temperature dependences. The artificially introduced defects also have a dramatic effect on the dynamics of the flux propagation: for $10^\circ < \theta < 14^\circ$ the magnetic flux propagates along the easy channels intermittently, i.e. in a form of flux jumps. This behavior is indicative of thermo-magnetic instability in superconductors, but we argue that this effect can be of a different nature.

1. Introduction

Originally, the interest in superconducting (SC) films on vicinal substrates was dictated by the necessity to suppress misalignment of grains in high-T_c superconducting films, which is known to substantially reduce their current-carrying properties. The characteristic feature of miscut substrates is the presence of sub-nanometer high steps on their surfaces [1–4]. Besides larger grain size and better alignment, the films grown epitaxially on such substrates contain arrays of planar defects, e.g. anti-phase boundaries, that also enhance pinning. An increase of the critical current density, j_c, by the factor of 2.5 was reported [5]. Introduction of well aligned planar defects results in pronounced anisotropy of the in-plane critical currents. The anisotropy parameter, defined as the ratio between the critical current flowing parallel to the defects, j_{c_L}, and across them, j_{c_T}, to a great extent depends on the density of the planar defects, which is determined by the miscut angle θ.

Another driving interest for this research is the fabrication of the so called "tilted out-of plane bi-epitaxial" Josephson π-junctions (TOP-junctions) [6–8]. An advantage of the TOP-junctions compared to other methods is that the junctions can be produced at any selected place on a substrate in any reasonable number. For controlled and reproducible fabrication of the junctions in the SC films on tilted substrates, anisotropic current properties have to be thoroughly scrutinized.

One of the best methods for investigation of the in-plane anisotropy of j_c is magneto-optical imaging. An extensive analysis of the critical currents, their dependence on magnetic field [3], temperature [5,9–11], and film thickness [1–3,5] has been given for YBCO films on STO. Here, we present results of MOI investigation of a series of YBCO samples deposited on $NdGaO_3$ (NGO) substrates with different miscut angles. This substrate was chosen because its lattice constants have one of the best matches to the (ab) plane of YBCO: lattice mismatch along the [110] YBCO directions is 0.32%. Furthermore, for their low surface resistance in GHz frequency range YBCO films on NGO are considered as promising candidates for microwave components [13].

2. Experiment

The films were prepared by pulsed laser deposition, have thickness $d \approx 200$ nm and $T_c \approx 88$ K. More details can be found in Ref. [8]. A "flat" reference film corresponding to $\theta = 0^\circ$ was grown on

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(1 1 0) NGO plane. Three samples were deposited on the surfaces tilted from the (1 1 0) plane around [0 0 1] axis of NGO by the angles 10°, 14°, and 33°. Detailed information regarding the samples structure and morphology can be found in Ref. [12]. The particular angles were chosen in order to probe properties of the films grown in three different angular regimes: (i) c-oriented, small-angle "vicinal" regime, (ii) intermediate angles, 10° and 14°, correspond to the "step-flow" growth, and (iii) the large-angle regime, i.e. 33° sample, characterized by "step-bunching" [4,13].

Distribution and dynamics of magnetic flux was investigated by MOI based on the Faraday effect. In-plane magnetized garnet film $(Lu,Bi)_3(Fe,Ga)_5O_{12}$, grown as a few micron thick epitaxial layer on transparent gadolinium gallium garnet substrate, was used as a magneto-optical sensor. The garnet film with a thin mirror layer was put directly on the surface of a sample, which was placed in an optical He-flow cryostat. Images were acquired at different temperatures and magnetic fields by a computer-controlled CCD camera attached to a commercial Leica microscope equipped with a polarizer and an analyzer. The latter two were set at 90° with respect to each other, so that the light that did not experience the Faraday rotation was filtered out. External field, applied perpendicular to the sample surface, was controlled by a pair of conventional coils synchronized with the camera via LabView software.

3. Results and discussion

The anisotropy of the in-plane currents can be conveniently quantified by measuring the angle between the so called discontinuity lines (D-lines) and sample edges (see Fig. 1). The current stream lines run parallel to the sample edges, but close to the corners they have to form sharp bends in order to preserve the current continuity. Hence, their direction is changed discontinuously while the magnitude of the current remains constant. Apparently, in the case of anisotropic currents the magnitude changes too. Schematically it can be represented by drawing the stream lines evenly spaced with the distances $d_{1,2}$, which are inversely proportional to the corresponding critical current densities $j_{c_{T,L}}$. The D-line goes from the corner through the points where the stream lines intersect. Then one immediately comes to an expression for the anisotropy parameter $A = \frac{j_{c_L}}{j_{c_T}} = tan(\alpha)$.

A distinctive feature of all the samples on miscut substrates is a presence of a preferential direction for flux motion. In magneto-optical images (Figs. 2–4), it is manifested by bright/dark vertical stripes that correspond to the easy channels. The periodicity of the channels ranges from 3 to 10 μm and depends on the miscut angle. We believe that the channels mark the so called planar "ex-

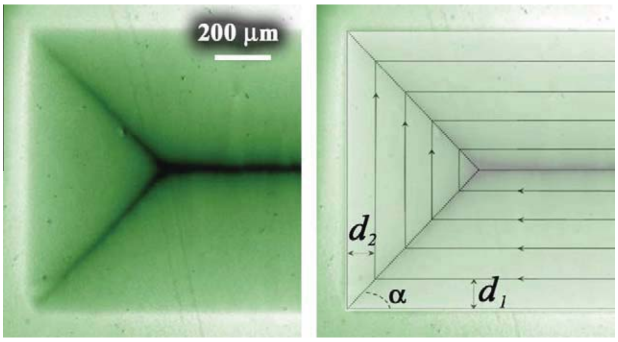

Fig. 1. (Color online) *Left*: distribution of magnetic field in the "flat" sample at $T = 20$ K, at $B = 85$ mT. *Right*: current flow profiles are shown schematically. Anisotropy parameter can be obtained as the tangent of angle α.

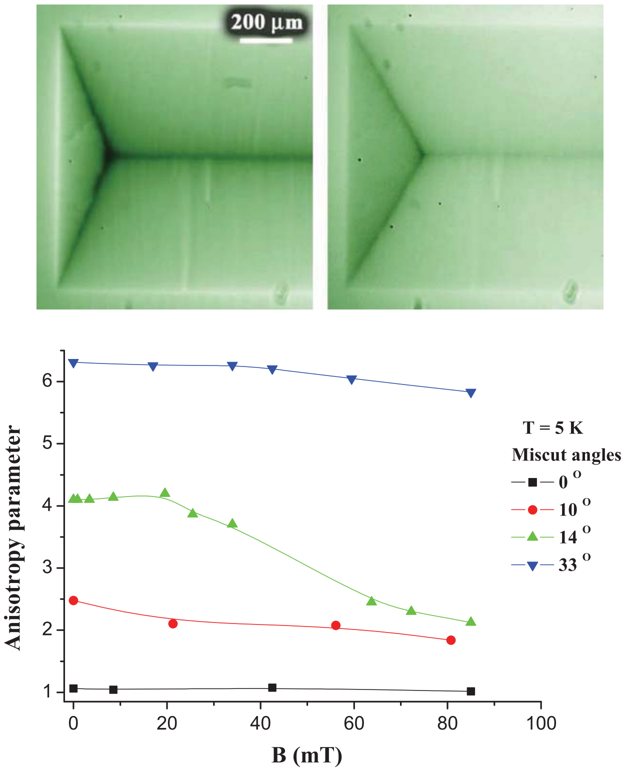

Fig. 2. (Color online) *Top*: distribution of magnetic flux in the 14° sample at $T = 20$ K at $B = 34$ mT (left) and $B = 85$ mT (right). *Bottom*: resulting plot of the anisotropy parameter versus applied magnetic field in the samples on different miscut substrates at $T = 5$ K.

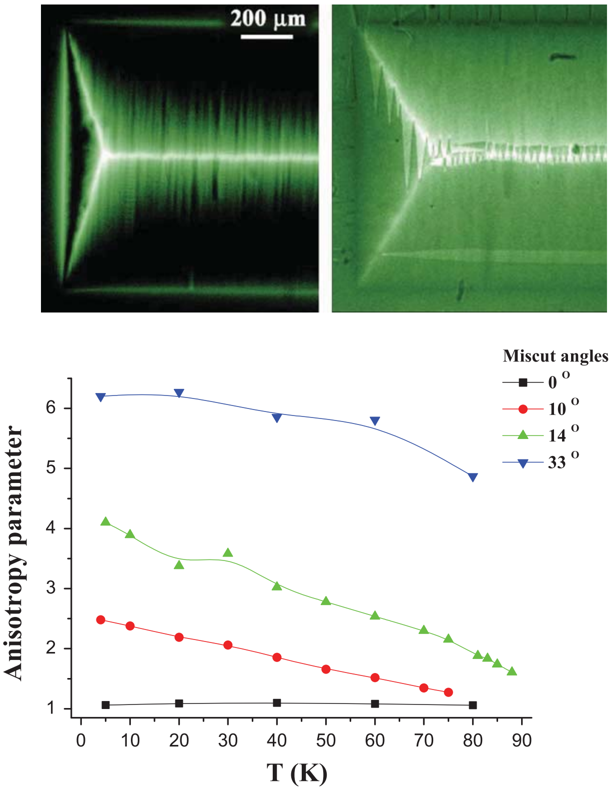

Fig. 3. (Color online) *Top*: distribution of magnetic flux in the "14°" sample in remanent state after applying field $B = 85$ mT at $T = 20$ K (left) and $T = 60$ K (right). *Bottom*: resulting plot of the temperature dependence of the anisotropy parameter measured in the remanent state in the samples on different miscut substrates.

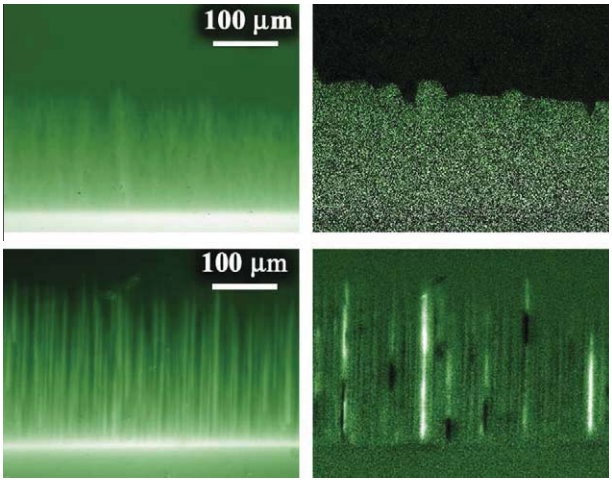

Fig. 4. (Color online) *Top*: magneto-optical image of the sample on "flat" substrate at $T = 10$ K in external magnetic field $B = 53$ mT (left) and the change in the flux distribution after increasing the field by $\Delta B = 210\ \mu$T (right). Change in the flux front appears as a noisy random background. *Bottom*: magneto-optical image of the sample on 14°-miscut substrate at $T = 10$ K in external magnetic field $B = 10.75$ mT (left) and the change in the flux distribution after increasing the field by $\Delta B = 43\ \mu$T (right). Elongated flux jumps are clearly seen.

tended defects" (in nomenclature introduced in previous articles, for instance [3]).

Dependences of the anisotropy parameter on temperature T and applied field B were measured in all four samples. The dependency $A(B)$ was measured after the flux front had reached the centre of the sample and the D-lines had formed. In magneto-optical images in Fig. 2 one can clearly see changes in the angles between the D-lines and the sample edges in the 14°-sample at $B = 34$ mT (left), corresponding to the full penetration, and $B = 84$ mT (right) at $T = 5$ K. Similar dependences were measured in the other samples and are summarized on the graph at the bottom of Fig. 2. The anisotropy decreases with increasing field, which agrees with the results obtained for YBCO on STO [3].

The temperature dependence of the anisotropy parameter was measured in the remanent state. After decreasing the field to zero, the temperature was swept from 5 K to T_c, or up to the temperature at which the D-lines were still distinguishable, since the contrast is reduced as j_c decays. The anisotropy parameter is a decreasing function of temperature for all angles θ. From the very definition of $A(T)$, it is determined by the ratio of $j_{c_L}(T)$, which for intermediate θ is a linear function of temperature $j_{c_L}(T) \sim (1 - T/T_c)$, and j_{c_T}, which is similar to Ambegaokar–Baratoff temperature dependence of S–I–S Josephson junctions [9]. For larger miscut angles non-linearity of $A(T)$ becomes more pronounced. This can be explained by an increasing role of the inter-granular links in the current-carrying properties of the films. The large-angle growth regime leads to the height of the steps on the substrate comparable to their width. It results in a "pseudo-*a*" epitaxial growth of the film (i.e. YBCO starts to grow on the lateral walls of the steps with the *c*-axis oriented in-plane [13]) and larger misalignment of the grains. Tunneling through the weak inter-granular links, with the corresponding non-linear temperature dependence, becomes the dominating current-limiting mechanism.

More detailed analysis of $A = A(B, T)$ based on the quantitative MOI, which includes the intensity-to-field calibration and the inversion of the field maps into the current values, will be presented in Ref. [12]. Instead, we would like to focus on an intriguing dynamic effect observed in the samples with the intermediate miscut angles: 10° and 14°. In these samples the flux propagates along individual channels intermittently: in the real-time MOI experiments flux jumps were observed to occur sporadically without evident signs of spatio-temporal correlations. Magneto-optical images in Fig. 4, taken at $T = 10$ K demonstrate this behavior. In increasing magnetic field, vortices propagate in the "flat" sample forming a smooth flux front (Fig. 4, top, left). A differential image (on the right), obtained by subtracting the previous image at $B = 53$ mT from the one taken with the interval $\Delta B = 210\ \mu$T, shows a background influx of vortices everywhere within the flux front. A differential magneto-optical image of the 14°-sample (Fig. 4, bottom, right) demonstrates the change in the flux distribution at $T = 10\,K$ induced by a $\Delta B = 43\ \mu$T increase of the applied field above $B = 10.75$ mT (bottom, left). Individual jumps are seen as elongated bright spots. This magnetic dynamics resembles small flux jumps preceding dendritic avalanches in SC with thermo-magnetic instability [15,16]. However, unlike the avalanches that start on edges and may span all over the sample, these jumps in YBCO do not necessarily occur on the edges and never extend over the flux front. We have not observed any thresholds (temperature, field [16]) for the onset of the jumps, which together with the former arguments excludes the thermo-magnetic scenario. Previously, non-dendritic flux jumps were observed in MgB$_2$ films with thickness variations [14]. However, unlike in that case, the places where the jumps occur in the miscut YBCO films are not bound to the samples defects, and the exact flux profiles are absolutely irreproducible. We have strong reasons to believe that this behavior is a consequence of a dynamic ordering in the flux line lattice, with a ruling mechanism most probably similar to the flux-line shear mechanism described in [17,18] and references therein. Results of quantitative investigations on the intermittent flux motion will be published in a separate paper.

4. Conclusion

We present results of the real-time MOI of a series of YBCO films on miscut substrates with different miscut angles θ. The observed flux profiles in the samples on tilted substrates exhibit stripe patterns, showing the presence of easy channels for vortex penetration. This results in the pronounced anisotropy of the in-plane critical currents. The anisotropy parameter exhibits noticeable field and temperature dependences. Finally, we observed a new dynamic effect in the flux line lattice, namely, the flux jumps that are not associated with thermo-magnetic instability. Even though the intermittent flux propagation does not have dramatic consequences as the dendritic flux avalanches, it may seriously compromise the performance of superconducting applications that are sensitive to small changes of the magnetic flux, e.g. the ones employing the Josephson contacts.

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