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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$_2$Cu$_3$O$_{7-x}$ (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 $\theta$. 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.

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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, $j_{cL}$, and across them, $j_{cH}$, to a great extent depends on the density of the planar defects, which is determined by the miscut angle $\theta$.

Another driving interest for this research is the fabrication of the so called “tilted out-of plane bi-epitaxial” Josephson $\pi$-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
Three samples were deposited on the surfaces tilted from the (1 1 0) plane around [001] 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)5O12, 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 $d_{ij}$, which are inversely proportional to the corresponding critical current densities $J_{ij}$. 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 $A = \frac{d_{ij}}{J_{ij}} = \tan(\alpha)$.

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-
For intermediate cut angles: 10° dynamic effect observed in the samples with the intermediate miscut angles non-linearity of $A(T)$ of $S$–$I$–$S$ Josephson junctions [9]. For inversion of the field maps into the current values, will be pre-

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 tempera-
ture 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 $\theta$. From the very definition of $A(T)$, it is determined by the ratio of $j_c(T)$, which for intermediate $\theta$ is a linear function of temperature $j_c(T) \sim (1 - T/T_c)$, and $j_{la}$, 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 pro-
nounced. 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 tempera-
ture 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 pre-

We present results of the real-time MOI of a series of YBCO films on miscut substrates with different miscut angles $\theta$. The observed flux profiles in the samples on tilted substrates exhibit stripe patterns, showing the presence of easy channels for vortex penetra-
tion. 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, 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 $\theta$. The observed flux profiles in the samples on tilted substrates exhibit stripe patterns, showing the presence of easy channels for vortex penetra-
tion. 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, 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.

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