J Supercond Nov Magn (2011) 24: 179–181
DOI 10.1007/s10948-010-0915-5

ORIGINAL PAPER

Intermittent Flux Penetration at Different Temperatures in $YBa_2Cu_3O_{7-x}$ on $NdGaO_3$ Substrates

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Received: 7 September 2010 / Accepted: 9 September 2010 / Published online: 6 October 2010

Abstract In type-II superconductors, increasing applied magnetic field penetrates gradually in the form of magnetic vortices. It is of great interest to understand the dynamics of magnetic flux in different superconducting materials, as this phenomenon can severely limit the performance of superconductors in applications. $YBa_2Cu_3O_{7-x}$ (YBCO) is an important high-temperature superconductor, but until recently, it has been hard to make wires from it due to misalignment of superconducting grains. A solution to this problem is to deposit YBCO on vicinal substrates to better align the grains. Some of these samples show a strongly intermittent flux penetration at low temperatures. In this work, we have studied flux penetration in YBCO deposited on a 14° vicinal substrate of $NdGaO_3$ (NGO) at different temperatures.

Keywords Flux avalanches · Thermomagnetic instability · Magneto-optical imaging · Miscut substrate · Vicinal substrate

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1 Introduction

The interest in high-temperature superconducting cuprates deposited on tilted (miscut, vicinal) substrates was originally motivated by improved alignment of grains, resulting in higher transport currents [1]. Also, the possibility to manufacture Josephson junctions with arbitrary tilt angles (TOP-junctions) from these films has become another motivating factor [2]. Films of $YBa_2Cu_3O_{7-x}$ (YBCO) grown on tilted substrates differ in several respects from YBCO films grown on flat substrates, as anti-phase boundaries (APBs) are introduced in the film along the substrate microsteps. Flux penetration is therefore anisotropic, resulting from different critical currents longitudinal (L) and transverse (T) to the APBs; see [1] for details. Instead of a smooth flux front, flux penetrates more easily in filaments along extended defects along the L-direction.

2 Experimental

2.1 Samples

By laser ablation of stochiometric targets, films of YBCO were deposited on $NdGaO_3$ (NGO) substrates with different miscut angles. The temperature during the deposition was 800 °C and the beam energy density 1.5 J/cm^2 in a surrounding atmosphere of 20% oxygen content and a pressure of 0.8 mbar. Selected for the present measurements was a film grown on a 14° miscut substrate. The superconducting film has a thickness of 150 nm. Detailed information about the sample preparation can be found in [3].

2.2 Magneto-Optical Measurements

A Leica polarized light microscope and a Faraday active ferrite garnet indicator film placed on top of the sample mounted in an Oxford Microstat continuos flow cryostat constitutes the setup used for magneto-optical imaging. A Delta Elektronika power supply and a pair of coils provided external magnetic fields in the range $B = 0$ mT to $B = 85$ mT. With the help of an Oxford temperature controller, the sample was cooled to $T = 5$ K in one experiment and $T = 15$ K in another. At both of these temperatures, the external field was ramped up from zero to 21.25 mT, with field steps of $\Delta B = 4.25$ μT. Images were captured by a RetigaExi camera at every tenth step. Four series of images were recorded at both temperatures. A series of images was also recorded just above the sample T_c of 90 K in order to calibrate the light intensity response of the indicator film. By combining these measurements, quantitative magnetic field values were extracted from the magneto-optical images.

2.3 Image Analysis of Jumps

In Fig. 1, a magneto-optical image of the sample in an applied field of 17 mT at $T = 8$ K is shown as an in-set in the upper panel.[1] The main panel of Fig. 1 shows the part of the image marked by a rectangular window, and gives a magnified view to clearly show the structure of flux filaments transverse to the strip direction. The lower panel of Fig. 1 shows a *differential image* created by subtracting two images taken at subsequent field steps. Bright regions correspond to increased flux density and dark regions correspond to decreased flux density. It is evident that the flux invades the film in a non-uniform way, in the form of quasi 1-dimensional filaments.

In order to make a statistical analysis of the flux jumps, the differential images were subjected to a median filter and converted into binary images defined by a threshold intensity. Every pixel with an intensity value below this threshold was given the color black, every pixel above was given the color white. A MATLAB algorithm was then used to identify the jumps and put a rectangular box around each of them. By superposing these boxes on the original image, the total number of flux quanta in each jump and the spatial dimensions of each jump were calculated. Different median filters and thresholds were tried and the resulting distributions converged for flux jump sizes larger than about $50\varphi_0$. The size distributions of jumps appear insensitive to the field step size, as $\Delta B = 42.5$ μT and $\Delta B = 25.5$ μT have resulted in nearly identical size- and length distributions of jumps.

[1] A strange anisotropy of the flux penetration in this sample is here evident.

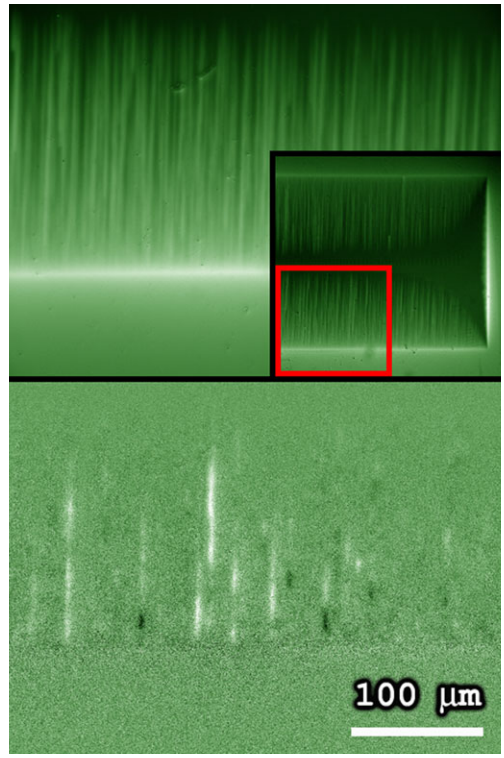

Fig. 1 (Color online) *Upper panel in-set*: The sample at $T = 8$ K, $B = 17$ mT. *Upper panel*: Magneto-optical image, $T = 8$ K, $B = 17$ mT. *Lower panel*: Differential image. $T = 8$ K, $B = 17$ mT and $\Delta B = 42.5$ μT.

3 Results and Analysis

In earlier experiments [1], a pattern of flux filaments has been seen in YBCO deposited on $SrTiO_3$ (STO) samples with a miscut angle of 9.5°. These filaments are also present in YBCO samples deposited on NGO substrates, as visible in Fig. 1, top. They originate from the edge of the superconducting sample, which is seen as the bright, horizontal line in Fig. 1, top. The in-set shows that filaments are only present in one direction, which is longitudinal to the microsteps of the substrate. Filaments are most visible below $T = 30$ K and more pronounced at lower temperatures. At higher temperatures, the flux motion is non-intermittent in both directions and no filaments are seen. At temperatures below $T = 30$ K, the flux motion become intermittent in the direction longitudinal to the substrate microsteps. There is still a smooth background flow of flux in this direction, but now, entire flux bundles displace collectively, as can be seen in Fig. 1, bottom. There are never jumps in the direction transverse to the microsteps of the substrate. The appearance of the flux jumps has a similar temperature dependence as the filaments, they are better defined at low temperatures, and become more and more smeared out at higher temperatures, disappearing at about $T = 30$ K.

Figure 2 shows the length-distribution of jumps at $T = 5$ K and $T = 15$ K temperatures, occuring as the applied

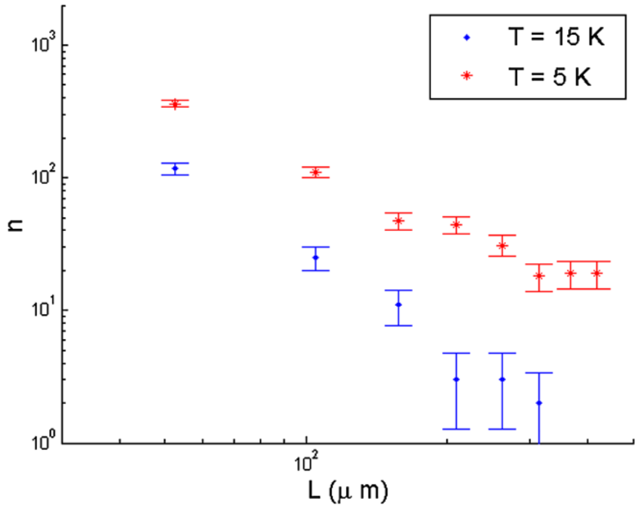

Fig. 2 (Color online) Length of flux jumps at $T = 5$ K and $T = 15$ K

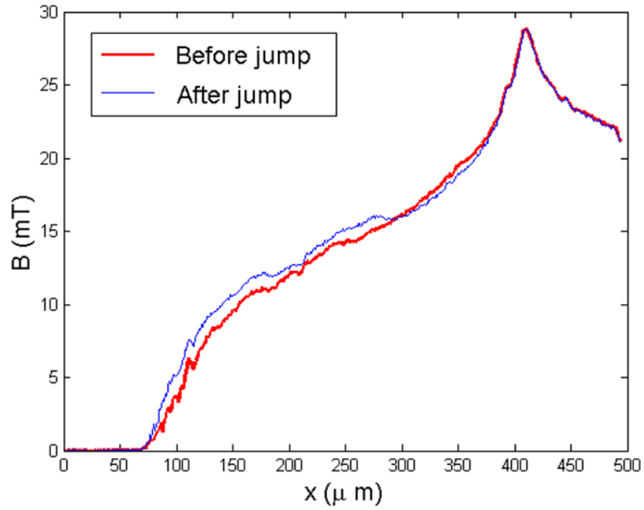

Fig. 3 (Color online) The field profiles before and after a relaxation occuring at $B = 17$ mT

magnetic field was increased from $B = 19.25$ mT to $B = 21.25$ mT in four different measurement runs at each temperature. It is evident that much fewer jumps of a given length are seen at the higher temperature. Otherwise, the statistical distributions have a similar shape. So far we have not found clear kinks or extrema in the distributions, indicating no characteristic size or length of the flux jumps in a wide range of fields.

Flux relaxations is an important phenomenon in high temperature superconductors and the effect often manifests itself as a smooth flux creep. In order to check whether our sample also showed relaxations of an abrupt kind, we performed the following experiment: The magnetic field was increased from $B = 0$ mT to $B = 17$ mT in a single step and then held at the latter value. Most flux jumps occurred immediately, while a few jumps occurred several seconds after the field increase. Shown in Fig. 3 are flux profiles before and after a flux jump happening at constant externally applied field. A redistribution of flux has occurred, but the magnetic field has changed very little at the flux front and at the edge of the sample.

4 Conclusions

Flux filaments and an intermittent flux penetration were seen in a YBCO sample deposited on a 14° miscut NGO substrate. The flux jumps were identified and statistics of their lengths were collected. At higher temperatures, the jumps are gradually disappearing by getting more smeared out. As a result, there are fewer jumps, though the shape of the length distributions of jumps are similar. Abrupt flux relaxations also occur in this sample.

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