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Crossover from Fractal to Non-Fractal Flux Penetration In Vicinal $Tl_2Ba_2CuO_{6+\delta}$ Thin Films

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The role of anisotropy on magnetic flux penetration and critical current density j_c in c-axis epitaxial $Tl_2Ba_2CuO_{6+\delta}$ (Tl2201) films is investigated by magneto-optics. Thin films of Tl2201 are deposited by a sputtering technique on vicinal (001) $SrTiO_3$ substrates with miscut angles of 0.5 and 2.5 degrees and patterned into various shapes. Circular samples are used to determine the current anisotropy axis, whereas square samples allow to evaluate the amplitude of this anisotropy. A cross-over from fractal to uniform anisotropic flux penetration is observed with increasing miscut angle.

1. INTRODUCTION

Magneto-optical (MO) investigations of magnetic flux penetration in high-T_c superconducting thin films show a flux front with a very irregular fractal shape even in high quality films [1] . This behavior is in contrast with the smooth and well-defined flux penetration observed in most single crystals [1-3]. In this paper we study the cross-over from fractal to non-fractal flux penetration in thin films as a function of anisotropy in the critical current density. Previous work [3] on anisotropic thin films was done on $YBa_2Cu_3O_{7-\delta}$. In this paper we study epitaxial $Tl_2Ba_2CuO_{6+\delta}$ (Tl2201) thin films. An advantage of such films is the simplicity of their structure: tetragonal symmetry with only one CuO_2 plane per unit cell and no CuO chain [4].

2. EXPERIMENTAL

Epitaxial Tl2201 thin films are deposited on vicinal (001) $SrTiO_3$ substrates with different miscut angles by RF magnetron sputtering and subjected to a two-step post-deposition annealing as described elsewhere [4]. The miscut angle of the substrates was determined with X-ray Laue diffraction. The films are patterned in shapes of a disk, 2 squares with the sides oriented parallel (P) with the edges of the substrate, and one square tilted (T) with respect to the edges with 45^0. The T_c of the samples is about 83K as determined by resistivity.

To determine magneto-optically the magnetic flux in the sample we used Bi-doped YIG films with in-plane anisotropy. A complete description of the MO experimental setup and method can be found in refs. [1] and [2].

3. RESULTS AND DISCUSSION

We present first the results on a 0.5^0 miscut Tl2201 thin film, with a thickness of 500 nm. Figure 1 shows an image at 57 mT, after a zero field cooling down to 4.2 K for one of the (P) square samples. Three features can be observed: (1) the flux penetration is very irregular and fractal like. Possibly small defects at the edges lead to preferential flux penetration, but further penetration in the film is observed to take place in 'tree'-like patterns for which the reason at present is unclear. The shape of these 'trees' remains the same when ramping down the field, the flux leaving the sample faster in those regions; (2) similar behavior is observed in all the samples deposited on the substrate, regardless of the shape of the samples and their position on the substrate; (3) because

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of the very high irregularity of the flux penetration, no so-called current discontinuity lines are observed. Furthermore no preferential direction for the superconducting current is observed. For this reason an estimate of the current's anisotropy cannot be made.

As an example of the behavior for larger miscut angles we now consider the 2.5^0 miscut angle film with a thickness of 200 nm. Figure 2 shows the MO image at 28 mT, after a zero-field cooling down to 4.2K. The edge of the square is parallel with the edge of the substrate. On the basis of the flux pattern shown schematically in fig. 3, we can determine the ratio between the current densities flowing in the directions parallel to the edges, as being $j_1/j_2 = tg\alpha$. This is, however, not the 'real anisotropy' A_{real} since the directions of minimal and maximal critical current are at an angle β with respect to the sides of the square as is clear from the flux penetration in the disk in Fig. 2. From the 'apparent anisotropy' $A_{app}=j_1/j_2$, the 'real anisotropy' A_{real} can be calculated by the formula:

$$A_{real} = \frac{\tan\beta - A_{app}}{A_{app}\tan\beta - 1} \quad (1)$$

which gives, for the case of figure 2, the value $A^{-1}_{real}= 11$. (Note that we are not in the case described in ref. [5], fig. 2h.)

Another striking feature which appears in the 2.5^0 miscut sample is that the flux front is now completely regular (not fractal) as observed for single-crystals. This very important observation is the main result of this paper.

The fact that the direction of the 'real anisotropy' is systematic for one substrate was demonstrated by a sample (with 4^0 miscut) on which we patterned 4 disks. The axis of anisotropy was found to be the same for all disks.

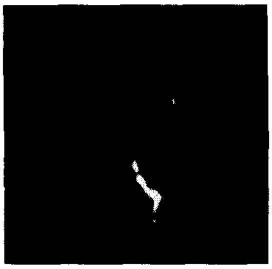

Fig.1. (a) MO image of 0.5^0 miscut Tl2201 thin film, $\mu_0 H_{ext}$=56mT, T=4.2 K.

The origin of the critical current anisotropy is probably related to the steps at the growth interface with the vicinal substrate since the direction of lower j_c corresponds to the direction of the steepest descent of the substrate.

4. CONCLUSIONS

From an analysis of the behavior of the flux front in several Tl2201 thin films grown on vicinal substrates with miscut angles of $0.5^0$and 2.5^0 we find that the flux penetration changes dramatically from a fractal, very irregular one, to a regular, uniform penetration for increasing miscut angle. The cross-over is correlated with an increase in the critical current anisotropy and takes place in the interval 0.5^0-2.5^0 for the miscut angle.

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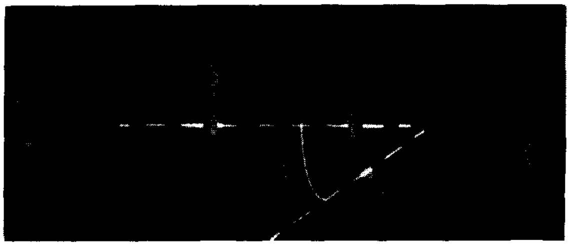

Fig. 2. MO image of 2.5^0 miscut Tl2201 thin film, $\mu_0 H_{ext}$=28 mT, T=4.2 K.

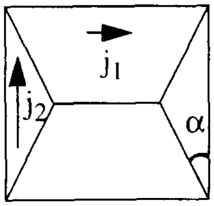

Fig. 3. Schematic picture for the current flow in a sample with anisotropy in the critical current.