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Effect of columnar defects on the critical current anisotropy of epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films and $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ multilayers

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Abstract

Epitaxial $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films and $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ (Y/Pr) multilayers were irradiated with high energy heavy ions (770 MeV ^{208}Pb and 340 MeV ^{129}Xe) under varius directions Φ relative to the c-axis. The irradiation resulted in columnar defects tilted by Φ from the c-axis. The angular dependence of their pinning activity was studied by measuring the anisotropy of the critical current density. The $J_c(B,T,\Theta)$ behaviour of the irradiated YBCO thin films showed an additional peak, which exceeds the intrinsic pinning peak, exactly at the irradiation direction. The Y/Pr multilayers, however, showed an isotropic J_c-enhancement by a factor of 5, without any additional structure in the $J_c(B,T,\Theta)$-curve.

1. Introduction

The crystal structure of the high-T_c superconductors, where the superconducting CuO-planes are separated from each other by distances greater than the coherence length in c-direction ξ_c, leads to a more or less 2-dimensional superconductivity which has strong implications on the anisotropy of their superconducting properties and on the structure of the flux lines (FL) penetrating the superconductor in the mixed state. In this sense, YBCO is a rather 3-dimensional superconductor (anisotropy parameter $\Lambda=\xi_{ab}/\xi_c\approx5$) with conventional Abrikosov-vortices , whereas BSCCO ($\Lambda\approx60$) and the Tl-system ($\Lambda\approx100$) are 2-dimensional systems [1] with FL, which are separated into very weakly coupled 2-dimensional point vortices or "pancakes" [2,3]. An elegant method to increase the anisotropy of the YBCO system is the preparation of Y/Pr multilayers [4]. According to the number of PrBaCuO unit cells introduced and the modulation wavelength of the superstructure, one can vary the coupling between the YBCO layers. Therefore the flux line structure also should be variable in the YBCO system by preparing these multilayers. To test the structure of the FL in YBCO thin films and in Y/Pr multilayers, we used the strong pinning activity of linear defects induced by heavy ion irradiation. As shown by TEM investigations [5], the irradiation of YBCO with high energy heavy ions results in the formation of linear tubes along the ion tracks, consisting of amorphous or at least strongly disorderd material [6], caused by the high electronic energy loss of the ions inside the ceramic superconductor. It was shown, that these linear defects act as strong pinning centers in the YBCO and BSCCO (2212) system [7]. In this paper we reported on the effect of linear defects (tilted relative to the c-axis) on the anisotropy of the critical current density $J_c(B,T,\Theta)$. If the FL are rather rigid ones, then a J_c-enhancement should be present exactly in the irradiation direction, on the other hand if the FL are strings of 2-dimensional pancakes, no additional peak should appear after the irradiation.

2. Experimental

The YBCO thin films and Y/Pr multilayers were prepared using a conventional pulsed laser deposition arrangement [8], or by a new off-axis laser deposition method, described in detail elsewhere [9]. Briefly, the beam of a XeCl excimer laser (Siemens XP2020) operating at 5-10Hz with a pulse energy of up to 2J is directed onto stoichiometric YBCO or PrBCO targets with an energy density of $2J/cm^2$ at the targets. At an oxygen pressure of 0.4 mbar this results in the deposition of epitaxial YBCO and PrBaCuO thin films at deposition rates between 2 and 8 Å/s. The Y/Pr multilayers were prepared in-situ by use of a computer controlled multi-target holder. Generally, we prepared multilayers with 3 unit cells YBCO and variable PrBaCuO layer thicknesses between 3 and 20 unit cells

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(e.g. a 12 period multilayer, each period consisting of 10 unit cells PrBaCuO and 3 unit cells YBCO, is abbreviated by (10 Pr/3 Y)*12). The number of periods of a multilayer was adjusted so that the total film thickness was between 150 and 200nm. The structural quality of the Y/Pr multilayers was confirmed by X-ray diffraction, where satellite peaks of the (00l)-peaks, corresponding to the modulation wavelength of the superstructure, up to the fifth order could be observed. The superconducting transition temperatures of the Y/Pr multilayers follows the recently observed T_c dependence on the YBCO and PrBaCuO layer thicknesses [4]. The YBCO films and the Y/Pr multilayers were patterned by standard photolithography combined with EDTA wet etching into bridges for conventional four-probe transport measurements, typically 20μm wide with bridge length of up to 2mm.

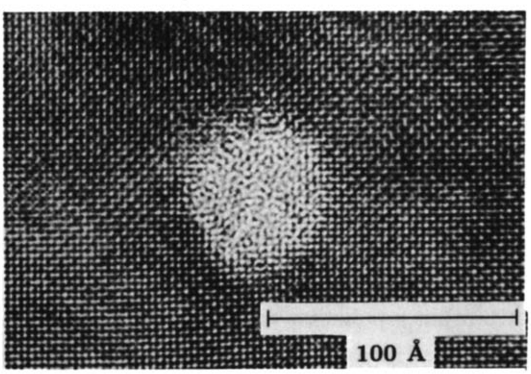

Fig. 1) HRTEM plan-view micrograph of a 340MeV ^{129}Xe irradiated YBCO thin film. (Irradiation direction $\phi=0^o$)

To generate linear defects, the samples were irradiated by 770MeV ^{208}Pb ions in the IRASME facility of the CIRIL at the GANIL or by 340MeV ^{129}Xe ions at the VICKSI of the HMI. To get a homogeneous distribution of the ions over the sample, the ion beam was swept magnetically over an area of 2cmx2cm. The electronic energy loss of the 770MeV ^{208}Pb and 340MeV ^{129}Xe ions in YBCO is about 3.9 keV/Å (Pb) or 2.9 keV/Å (Xe) and therefore dominant in relation to the nuclear energy loss of about 0.01 keV/Å. The value of the electronic energy loss exceeds for both ions the threshold of 2 keV/Å [10], where the ions cause a continuous linear defect along their trajectory. The total energy loss of the ions leads to an implantation depth of more than 10μm, therefore no ion implantation takes place inside the films. High resolution TEM pictures (Fig.1 and Fig.2) show, that these defects consist of amorphous tubes with diameters of 50Å (^{129}Xe) or 80Å (^{208}Pb). The samples were irradiated under an angle ϕ, which means that the direction of the linear defects is tilted relative to the c-axis of the YBCO lattice by that angle ϕ. Samples were irradiated under $\phi = 0^o$, 30^o or 60^o. The fluence of the irradiation was kept constant at 8.0×10^{10}ions/cm^2 for all samples. This fluence was chosen to get a significant effect of the pinning behaviour of the linear defects, but without a significant lowering of T_c. At the fluence chosen the T_c reduction is less than 1K.

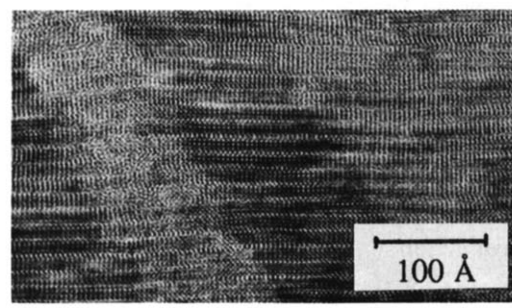

Fig. 2) HRTEM cross-section micrograph of a 770MeV ^{208}Pb irradiated Y/Pr multilayer. ($\phi=30^o$)

The anisotropy of the critical current density $J_c(B,T,\Theta)$ was measured using a rotatable refrigerator cooling stage which is placed in a normal-conducting split coil magnet with a maximum field strength of 2 Tesla. Rotation of the refrigerator is performed by a computer controlled stepping motor with a relative angle resolution below 0.01^o. J_c was determined using standard 4-probe I-U measurements with a voltage criterion of 1μV. The current direction was always perpendicular to the magnetic field direction, which rotates in a plane defined by the c-axis of the film and the irradiation direction, as shown in Fig. 3. The irradiation angle ϕ and the magnetic field direction Θ are defined relative to the c-axis of the YBCO films, i.e. the normal of the substrate surface. If the magnetic field direction Θ equals the irradiation direction ϕ or $\phi+180^o$, the magnetic field points exactly in the direction of the irradiation induced amorphous tubes.

3. Results and Discussion

Fig. 4 shows the angular dependence of the critical current density $J_c(B,T,\Theta)$ for a YBCO thin film measured at 79K and a magnetic field strength of 1T before and after irradiation with 770MeV ^{208}Pb. Before the irradiation the critical current anisotropy shows the well-known structure. The J_c-peaks are caused by the intrinsic pinning of the separated CuO-planes. Their different heights are due to the differences in the pinning behaviour of the film-substrate and the film-vacuum interface [11]. After irradiation with an irradiation angle of $\phi=60^o$ the sample shows a drastically different J_c-anisotropy.

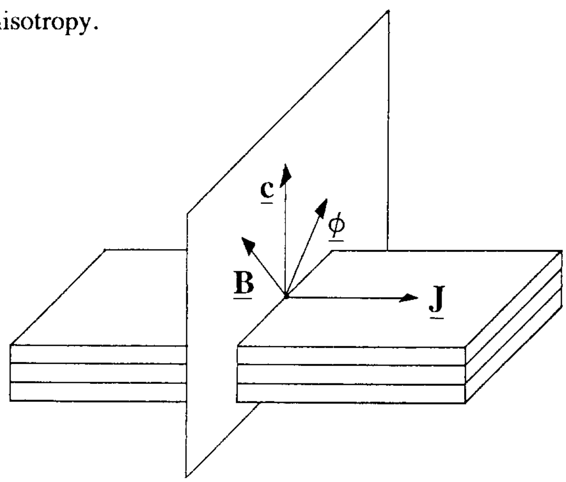

Fig. 3) Schematic representation of the irradiation and measurement directions. (c : c-axis of the YBCO films, J : current flow direction, ϕ : irradiation direction, B : magnetic field direction; $\Theta = \angle$ (c,B) and $\phi = \angle$ (c,ϕ))

The intrinsic pinning peaks were reduced by the irradiation, but their relative height ratio remained unchanged. The main difference however is the occurence of two new peaks in the J_c-anisotropy. These two peaks appear exactly at that angle, that corresponds to the irradiation introduced linear defects and therefore are caused by them. The heights of these two peaks are identical indicating the symmetric pinning behaviour of the linear defects.The absolute heights of these J_c-peaks are comparable to the intrinsic pinning peaks before the irradiation indicating, that the pinning strength of the artificially introduced defects is comparable to the normal intrinsic pinning. Due to the fact, that the intrinsic pinning peaks are reduced by the irradiation, the pinning of the linear defects dominates the angular dependence of the critical current density of YBCO. This drastical irradiation effect could also be observed for a 340MeV ^{129}Xe irradiation. Figure 5 shows $J_c(B,T,\Theta)$ regions of two YBCO thin films irradiated under different directions (Fig. 5a : $\phi=60^o$, Fig. 5b : $\phi=0^o$). For both irradiation directions the J_c-peaks of the columnar defects exceed the intrinsic pinning. The strong modification of the J_c anisotropy of angle irradiated YBCO thin films is explainable by the presence of 3-dimensional rigid flux lines, pinned coherently along the linear defect on distances significantly larger than the intrinsic CuO layer spacing.

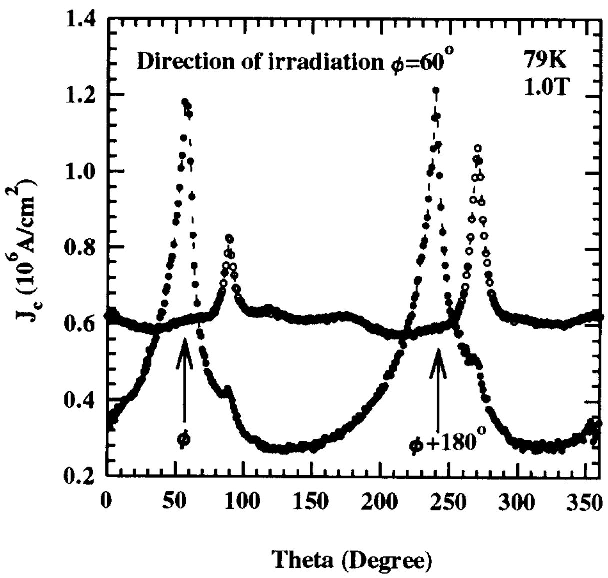

Fig. 4) $J_c(B,T,\Theta)$ of a YBCO thin film before and after irradiation with 770MeV ^{208}Pb ions (Irradiation direction $\phi=60^o$).

For the Y/Pr multilayers, the situation is quite different. Fig.6 shows $J_c(B,T,\Theta)$-measurements of a (3 Pr/3Y)*25 multilayer before and after the irradiation with 770MeV ^{208}Pb ions (irradiation angle $\phi=30^o$, $B_o=1.0T$, $T=70K$).

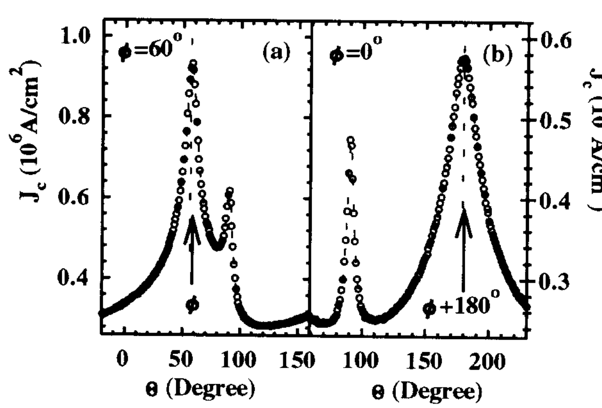

Fig. 5) $J_c(B,T,\Theta)$ of YBCO thin films after irradiation with 340MeV ^{129}Xe ions (Irradiation direction in Fig.5a : $\phi=60^o$, in Fig.5b : $\phi=0^o$).

Before the irradiation the sample shows the well-known $J_c(\Theta)$ curve which is very similar to the $J_c(\Theta)$ behaviour of the highly anisotropic BSCCO (2212) system [12]. Due to the magnetic transparency relative to the $B \perp c$ direction, resulting from the introduced PrBaCuO layers [13], $J_c(B,T,\Theta)$ follows the equation

$$J_c(B,T,\Theta)=J_c(B=B_\perp=B_o*\cos(\Theta),T,\Theta=0^o)$$

After the irradiation, the J_c-peaks of the intrinsic pinning were reduced, similary to the irradiated pure YBCO thin film. In contrast to YBCO there is a strong, but isotropic J_c-enhancement detectable. This J_c-enhancement by a factor of 5 is completely independent on the irradiation direction.

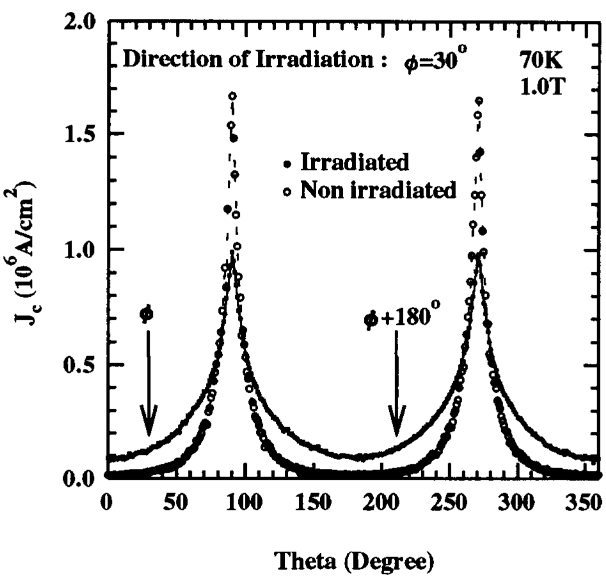

Fig. 6) $Jc(B,T,\Theta)$ of a (3 Pr/3 Y)25 multilayer before and after irradiation with 770MeV ^{208}Pb ions (Irradiation direction $\phi=30^o$).

This means, that the flux lines are separated into point vortices, which depin individually. For these 2-dimensional pancakes the 3-dimensional direction ϕ of the linear defects is not important any more, so only disks of the amorphous tubes act for each pancake separately as strong pinning centers. The reduced dimensionality of the FL is a direct consequence of the increased anisotropy of the Y/Pr multilayers. The characteristic depinning length L_c could be expressed as $L_c \approx a/\Lambda$ [14], where a is the typical distance between the amorphous tubes (here a = 400Å) and Λ is the anisotropy parameter ξ_{ab}/ξ_c. Therefore the depinning length of YBCO is about 80Å >> d, resulting in the strong irradiation direction effect of the linear defects. Because of the total isotropic pinning effect of the (3 Pr/3 Y)*25 multilayer the chararacteristic depinning length L_c of the multilayer is in the range of the interlayer spacing of the CuO-planes. Therefore the anisotropy parameter Λ of the multilayer is about a factor of 10 greater than that for pure YBCO.

4. Summary

After irradiation with high energy heavy ions, new peaks appear in the angular dependence of the critical current density of epitaxial YBCO thin films exactly at the irradiation direction. This dominant additional structure is caused by the strong pinning of the irradiation induced columnar defects. The appearence of these peaks is explainable by coherent pinning of the FL by the linear defects over distances which exceed clearly the CuO-plane interlayer spacing. In (Y/Pr) multilayers no such additional peak structure is detectable. This is due to a modified structure of the FL, which consist, in this case, of point vortices which can depin individually.

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