Flux Pinning Forces in Irradiated A-Axis Oriented $EuBa_2Cu_3O_7$ Films

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ABSTRACT: *a*-axis oriented $EuBa_2Cu_3O_7$ films have been irradiated with high energy heavy ions in different configurations to study the possible pinning role of the artificial defects in this kind of samples. The original pinning limiting mechanism of the samples is not essentially altered when the irradiation is parallel to the CuO_2 planes. However, when it is deviated from this direction, an increase in critical current density and a change in pinning force are observed when the magnetic field is parallel to the columnar defects at values around the matching field.

1. INTRODUCTION

One of the most challenging fields in the Applied Physics of High Temperature Superconductivity is the study and control of the critical current density (J_C) and flux pinning mechanisms. In this way, many studies have been focussed in the interaction between vortex motion and the natural defects of the superconductors (Kwok et al 1990, Díaz et al 1998). Also, several studies have been done to create different kind of artificial defects in the material that could act as good pinning centers (Van Dover et al 1989, Civale et al 1990). One of the most successful methods is the artificial production of columnar tracks by heavy ion irradiation (Budhani et al 1992, Civale et al 1991). In particular, it has been shown that these linear defects can move the irreversibility line (H-T) to higher fields and increase the J_C values by one order of magnitude on superconductors of the 123 family (Konczykowski et al 1991, Civale et al 1991). However, up to now, most of this research has been performed in platelet single crystals (Paulius et al 1997, Schuster et al 1996) and *c*-axis oriented films (Doyle et al 1995), where the CuO_2 superconducting planes of the structure are parallel to the sample plane. Therefore, it is very interesting to analyze the influence of heavy ion irradiation in other samples which present different geometrical configurations. In this work, we have studied the behaviour of critical current density and pinning force in heavy ion irradiated *a*-axis oriented $EuBa_2Cu_3O_7$ films, where the CuO_2 planes are perpendicular to the film plane.

2. EXPERIMENTAL

a-axis oriented $EuBa_2Cu_3O_7$ thin films have been prepared on $SrTiO_3(100)$ substrates by dc magnetron sputtering. As it has been reported earlier (Martín et al 1996), the as-grown samples show good structural properties, with pure *a*-axis orientation as analyzed by x-ray diffraction; the CuO_2 planes are perpendicular to the film plane and can be aligned parallel to the two main perpendicular directions of the cubic substrate surface, so that the samples present a microstructure of 20 nm domains separated by 90^0 boundaries.

Three different a-axis oriented films have been irradiated by high energy heavy ions at ATLAS (Argonne Tandem Linear Accelerator System). The irradiation experimental conditions are selected to create amorphous columnar tracks in the material (Paulius et al 1997); they are parallel to the irradiation direction and thread the whole film thickness of 300 nm. One film was irradiated with 0.87 GeV $^{238}U^{41+}$ in the perpendicular direction to film plane (that is, parallel to a axis and CuO_2 planes) and at a dose that corresponds with an average defect density which is the same as the number of vortices per unit area with an applied field of $B_\Phi = 0.5$ T (the so-called matching field). The second sample was irradiated by 1.4 GeV $^{238}U^{67+}$ ions at an angle $\Theta = 30^0$ respect to the film normal and with a dose that corresponds to $B_\Phi = 0.5$ T. The irradiation process in the third film was performed with 2.5 GeV $^{129}Xe^{+31}$ ions at $\Theta = \pm 45^0$ for $B_\Phi = 1$ T. In the following we will name these samples as FA0, FA30 and FA45 respectively and according to the irradiation angle.

The irradiated samples have been studied by transport measurements in a helium cryostat with a 9 T superconducting solenoid and a rotatable sample holder. The $\rho(T)$ curves show a small decrease of about 1-2 K in the superconducting transition temperature in the samples after the irradiation. There is also an increase in the normal state resistivity values but the samples keep the metallic behaviour; the reduction of the effective crossection for the transport current due to the presence of the columnar tracks could be the origin of these changes. The critical current density values have been obtained with the 1 μV/mm criterium, and applying the magnetic field in the plane perpendicular to the transport current at a certain angle Θ respect to the film normal.

3. RESULTS AND DISCUSSION

Figure 1 shows the J_C measurements in sample FA0 compared with the values obtained before the irradiation of the film. As the columnar defects are parallel to the CuO_2 planes in this sample, the possible artificial pinning mechanism is competing with the natural intrinsic pinning of the structure. In Fig. 1(a) the normalized $J_C(T)$ data with $H = 0$ are presented. The curve after the irradiation shows the same behaviour as before; the temperature dependence of the unirradiated samples has been attributed earlier to the 90^0 boundaries present in the films (Vélez et al 1994), and the new result indicates that this limiting mechanism is not changed by the irradiation. The field dependence with H parallel to the irradiation direction can be seen in Fig. 1(b). There is a small decrease in J_C values in the low field range, where boundaries act as the main limiting mechanism; however the curves before and after irradiation present similar values in the high field range, revealing that the usual flux pinning mechanisms that limit the critical current in this range (Vélez et al 1994) have not been changed by the artificial defects. The results of this film reveal that, in this geometrical configuration, the columnar tracks are not acting as very effective pinning centers, but their possible role is masked by the pinning due to the natural structure of the samples.

A very different behaviour is found in FA30 sample. Fig. 2(a) shows the angular dependence of the critical current density at a constant field $B = 0.5$ T $= B_\Phi$. Besides the usual maximum in J_C at $\Theta = 0^0$, resulting from the natural anisotropy of the sample, the curve presents a new maximum close to $\Theta = 30^0$, that is, when the applied field is parallel to the irradiation direction. At this angle J_C is increased by a factor 2 compared with the value at the initially symmetric $\Theta = -30^0$, becoming comparable to $J_C(\Theta = 0^0)$. Also the data indicates that this increase in the critical current density induced by the irradiation is extended over a range of about $\pm 20^0$ around the new maximum. These results reveal that, in this configuration, the columnar tracks induced by the heavy ion irradiation are indeed behaving as good pinning centers for the vortices at fields similar to the matching field B_Φ. It is interesting to plot the pinning force density $F_P = J_C \times B$ measured in this sample at the same T value and with the magnetic field applied parallel to the irradiation direction $\Theta = 30^0$ (see Fig. 2(b)). The field dependence of F_P shows that, in this temperature range where an increase in J_C is observed, the characteristic maximum of these pinning force curves appears in a field range similar to $B_\Phi = 0.5$ T. It is worth to note that minima in the vortex motion dissipation resistivity and an increase in the irreversibility field have also been found around $\Theta = 30^0$ in similar temperature and field ranges.

This enhancement of vortex pinning by the artificial columnar tracks is lost in sample FA45 where a splayed irradiation has been performed. In previous works in crystals (Kwok et al 1998, López et al 1997), it has been found that this irradiation configuration can induce a reduction in the resistivity around $\Theta = 0^0$ (that is, when B is perpendicular to CuO_2 planes), which has been attributed to the entanglement of the vortices with the columnar tracks in both directions. Our results show no significant enhancement in J_C when field is at $\Theta = 0^0$ (in this case parallel to CuO_2 planes) or at any angle, but an uniform decrease respect to the unirradiated samples measurements. It indicates that the damage induced by these irradiation conditions is not favoring vortex pinning in a-axis films.

A good summary of the different behaviours found in irradiated a-axis films is presented in Fig. 3, where several normalized pinning force densities are shown. The field dependence of these curves is related with the involved pinning mechanisms, so that a curve shape change indicates different vortex pinning origin. All data curves plotted in Fig. 3 present the same behaviour below the field corresponding to the maximum, but there are different dependences in the high field range. First of all, as it has been discussed earlier (Vélez et al 1994), all the measurements in unirradiated a-axis samples lie on the same curve implying an universal behaviour for these kind of samples. This particular dependence in F_P is not changed in the case of FA0 film when B is parallel to the irradiation direction ($\Theta = 0^0$), indicating that the columnar tracks are not essentially affecting vortex pinning. This is different when the irradiation is not parallel to the CuO_2 planes; the normalized pinning force density in the FA30 sample is more localized around its maximum in comparison with the reference curve, as corresponds to an enhancement of pinning force around the matching field where the artificial pinning is stronger. On the other hand, the $F_P(B)$ curve of FA45 film when the field is parallel to CuO_2 planes changes in the opposite direction and its maximum is diffused, revealing that the splayed irradiation is modifying the natural pinning mechanisms although no enhancement in critical current density is found.

Summarizing, critical current density and pinning forces have been studied in heavy ion irradiated a-axis oriented $EuBa_2Cu_3O_7$ films. While no significant new pinning effect is observed when ion irradiation is parallel to the CuO_2 planes, an enhancement in J_C values and modifications in flux pinning force can be found as the artificial columnar defects form an angle with the CuO_2 planes.

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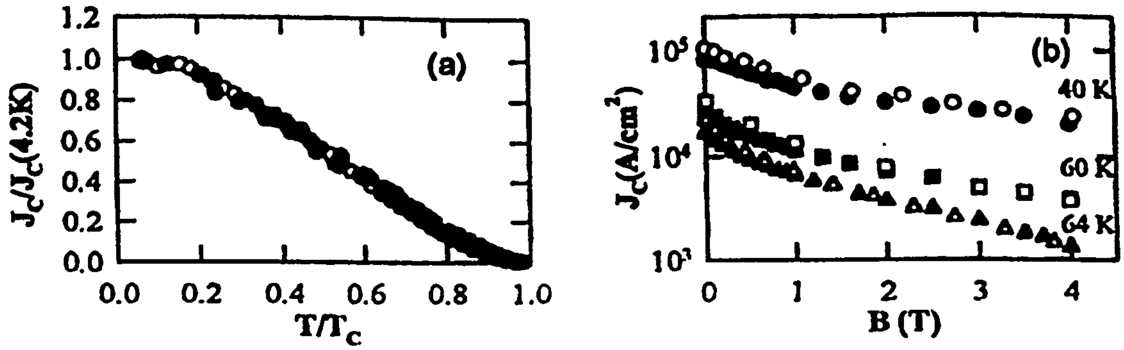

Fig 1: (a) Temperature dependence of the zero field critical current for FA0 film, normalized by the value at 4.2 K $J_C(4.2K)$: hollow symbols, as grown; filled symbols, after irradiation. (b) Field dependence of the critical current density for FA0 sample: hollow symbols, as grown; filled symbols, after irradiation.

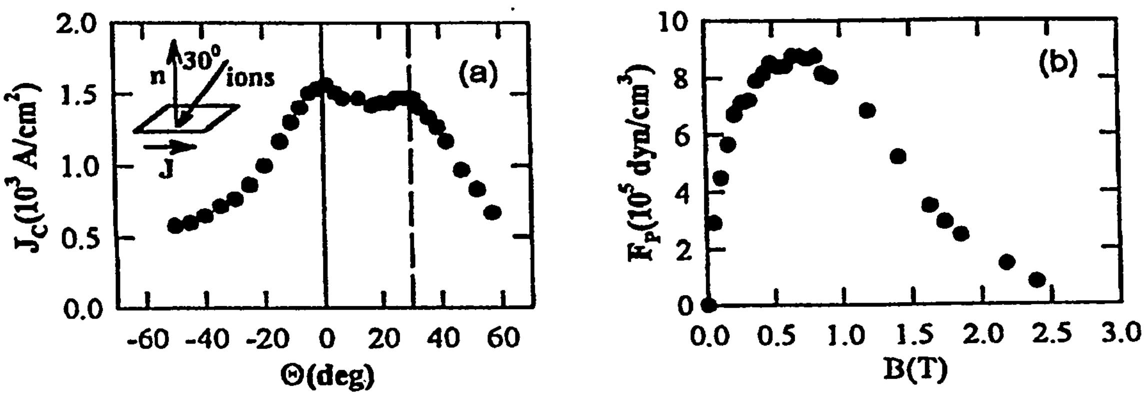

Fig.2: (a) Angular dependence of the critical current for FA30 film, at $0.9T_C$ and B = 0.5T. Straight line indicates the field direction parallel to the CuO_2 planes at $\Theta = 0^0$, and dashed line indicates the irradiation direction at $\Theta = 30^0$. Inset shows a sketch of the irradiation geometry. (b) Field dependence of the pinning force for FA30 film at $0.9T_C$ and $\Theta = 30^0$.

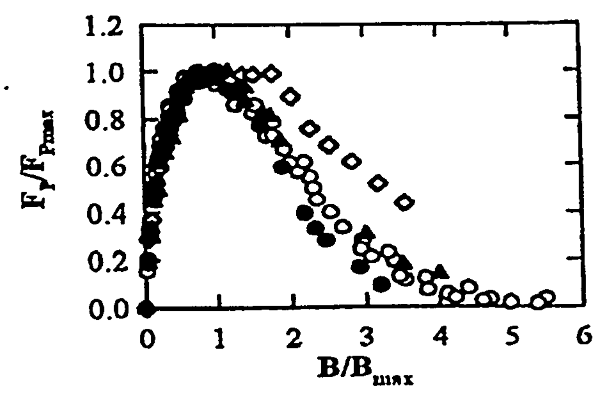

Fig.3: Field dependence of the normalized pinning force for: as grown a-axis films with B at $\Theta = 0^0$, hollow circles; FA0 film with B at $\Theta = 0^0$, filled triangles; FA30 film with B at $\Theta = 30^0$, filled circles; FA45 film with B at $\Theta = 0^0$, hollow rhomboids.