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Flux pinning by discontinuous columnar defects in 74 MeV Ag-irradiated $YBa_2Cu_3O_7$ coated conductors

N.M. Strickland [a,*], E.F. Talantsev [a], N.J. Long [a], J.A. Xia [a], S.D. Searle [a], J. Kennedy [b], A. Markwitz [b], M.W. Rupich [c], X. Li [c], S. Sathyamurthy [c]

[a] Industrial Research Ltd., P.O. Box 31310, Lower Hutt 5040, New Zealand
[b] GNS Science, P.O. Box 31312, Lower Hutt, New Zealand
[c] American Superconductor Corp., 64 Jackson Rd., Devens, MA 01434, USA

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ABSTRACT

Linear damage tracks are created in production-quality YBCO coated conductors by irradiation with 61–74 MeV Ag ions. The ion tracks are observed by transmission electron microscopy to be elongated but discontinuous. The in-field transport critical current (I_c) is enhanced significantly for fields applied parallel to the irradiation direction with a broad peak appearing in the magnetic field-angle dependence of the critical current, coinciding with the irradiation direction. The zero-field I_c is typically reduced somewhat, however annealing at 200 °C partially restores this and enhances the in-field I_c even for field parallel to the irradiation direction. Lower energies tend to produce a weaker peak, but also retain the zero-field I_c to a greater extent, consistent with a trend of greater discontinuity in the ion tracks.

1. Introduction

Second-generation high-temperature superconducting (HTS) wires, based on $YBa_2Cu_3O_7$ (YBCO) coated conductors are poised to surpass first-generation wires due to a number of economic, performance, and manufacturing advantages. In contrast to the first-generation wires, these conductors are more amenable to laboratory-scale research, and for this reason an enormous variety of alternative fabrication routes and potential enhancements have been documented.

Advances in flux pinning have come particularly rapidly in recent times, opening up a new parameter space of relatively accessible temperatures for high-field applications. Flux pinning can be enhanced by introducing nanoscale defects or secondary-phase particles, and a wide variety of quite different possibilities have been identified for the methods and materials required to produce these types of pinning sites [1–11].

Metal–organic deposition followed by *ex situ* growth typically results in laminar growth rather than the columnar growth that is observed with vapor-deposition methods [12]. This gives rise to large grains and a high density of planar defects, while the vertical propagation of defects tends to be suppressed. Point-like defects—particles of secondary-phase materials—are also common and can be beneficial flux-pinning centers, if appropriately sized and distributed [1,5,6].

Irradiation by high-energy ions has long been known to produce linear damage tracks in YBCO having radii that are ideally suited to enhance flux pinning [13–26]. A splay of tracks was shown to further enhance flux pinning in single crystal YBCO by leading to vortex entanglement and reducing the propagation of double-kink formations [21–23]. Typically heavy, high-energy ions have been used to produce continuous, fully amorphised columns. Recently, it has been pointed out that such continuous columns are not in fact the ideal pinning centers for two reasons: firstly, they provide a benefit only when the magnetic field is aligned with the columns, and secondly, they might reduce the superconducting percolation path [24]. Instead, it has been argued, discontinuous ion tracks, such as produced by fission fragments or lower-energy ion beams, can give a greater total enhancement to the critical current at moderate and high magnetic fields. The nature of the damage tracks, continuous or discontinuous, depends principally on the electronic

* Corresponding author. Tel.: +64 4 931 3455; fax: +64 4 931 3117.
E-mail address: n.strickland@irl.cri.nz (N.M. Strickland).

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energy loss S_e of the irradiating ions, with a threshold energy loss of around 35 keV/nm for the formation of continuous columns in YBCO [24–26].

The energy loss is generally calculated numerically using Monte-Carlo simulations and depends on the mass and energy of the ion. Through these parameters, ion irradiation offers an opportunity to produce a tunable defect morphology and concentration. If sufficiently effective, incorporation into a wire production line could be contemplated. Direct applicability aside, there is nevertheless an opportunity to examine a controllable range of defect dimensions and concentrations with the aim of identifying those that give the greatest performance benefits for particular regimes of magnetic field and temperature.

2. Methods

YBCO films were deposited by metal–organic deposition on oxide-buffered RABiTS substrates with a liquid precursor based on metal-trifluoroacetates as described elsewhere [1]. These coated conductors were deposited in a continuous-length process and either reacted in a continuous process (50% Dy-added samples, Y(Dy)BCO) or as short static samples (undoped YBCO samples). Silver cap layer deposition and oxygen annealing were carried out on static samples. Ion irradiation using up to 74 MeV ^{106}Ag ions was carried out at the National Isotope Centre of GNS Science. A 12^+ charge state was used in the experimental setup. The ion current was set to 1–1.5 nA to avoid heating of the tapes by the high-energy ion beam and also to allow for a reasonably short time of irradiation; the irradiation time for a fluence of 1.0×10^{11} ions/cm^2 was 70–80 s. The sample was mounted in a Faraday-like setup that prevented secondary electron emission from negatively influencing the current measurement. The incident irradiation direction was perpendicular to the tape, i.e. parallel to the average YBCO *c*-axis, or inclined at 30° or 60° to this axis but still always perpendicular to the transport current direction.

Samples were characterized using transmission electron microscopy (TEM) and by in-field critical-current anisotropy measurements. TEM shows directly the physical form and extent of potential flux-pinning defects and gives direct insight into YBCO growth and irradiation damage. Samples for cross-sectional TEM were prepared and studied as described elsewhere [29].

The critical current is highly dependent on flux pinning and is usually the physical property most relevant in HTS devices. Measurement of the critical-current anisotropy—the dependence on magnetic field orientation—is a useful indicator of the geometry of flux-pinning centers, while the dependence on the magnetic field intensity reflects the size and number density of the pinning centers [30]. Knowing the form of the pinning anisotropy is also absolutely critical for device design; the complex extended and correlated defects vary greatly in samples prepared even with only minor adjustments to process conditions or precursor preparation, not to mention completely different deposition methods.

The I_c's were measured using a standard 4-terminal transport method with samples immersed in liquid nitrogen using the usual voltage criterion of 1 μV/cm. Samples were patterned lithographically prior to irradiation to ensure that the entire bridge was exposed evenly. A magnetic field of up to 3 T was applied and the sample rotated relative to this field such that the current direction was always perpendicular to the field. We define the rotation angle such that at 0° the field is normal to, and at 90° parallel to, the plane of the film. X-ray diffraction analysis generally confirmed that the film normal coincided with the average YBCO *c*-axis direction.

3. Results

3.1. Microstructure

The cross-sectional TEM of Y(Dy)BCO irradiated to a fluence of 1×10^{11} ions/cm^2 (matching field 2.0 T) with 74 MeV ^{106}Ag ions is shown in Fig. 1. The irradiation direction was perpendicular to the film, parallel to the YBCO *c*-axis. Several ion tracks (vertical, some indicated by arrows) are seen passing through the YBCO film, perpendicular to a number of *ab*-plane defects. There is also a moderate density of nanoparticles consisting of Dy_2O_3 [1,6,29]. The tracks appear to be discontinuous and/or varying significantly along their length, which is consistent with the calculated electronic energy loss of 19 keV/nm (see Section 3.6) being below the threshold of 35 keV/nm for the formation of continuous columns [26]. The clearly damaged sections vary from 20 to 60 nm in length and these are separated by a similar distance of undamaged or more lightly damaged material. The splay of the tracks is slight, being no more than about 2° for the limited sample of tracks observed here. The track diameter is 2–4 nm, which is similar to the superconducting coherence length at 77 K and therefore expected to give a strong flux pinning enhancement.

3.2. Fluence dependence in undoped YBCO

Nominally undoped YBCO tapes were irradiated perpendicular to the tape (parallel to the average *c*-axis) with 74 MeV Ag ions to fluences of (0.3, 1.0, 3.0) $\times 10^{11}$ ions/cm^2 giving dose-equivalent matching fields (at which the areal density of incident ions matches the vortex density) of (0.6, 2, 6) T. This level of fluence was previously shown to be in the appropriate range for enhancing the pinning force while maintaining T_c and the zero-field I_c at reasonable levels [31]. The virgin (un-irradiated) tapes were high-quality samples with zero-field 77 K I_c in the range 235–260 A/cm-width for 0.8 μm thickness, corresponding to J_c of 2.9–3.3 MA/cm^2.

The irradiations reduced the transition temperature T_c by approximately 0.5, 0.7, 1.5 K, respectively (Fig. 2), though there is variability of around 0.5 K in the T_c of un-irradiated films. Similarly the zero-field 77 K I_c was reduced by 4%, 8%, 26% relative to the virgin value.

The I_c anisotropy in Fig. 3 shows a broad peak developing in the *c*-axis (irradiation) direction, and that this enhancement extends to within 10° of the *ab*-plane. The normalized I_c's in Fig. 3a show the monotonic growth of the irradiation peak, while the absolute val-

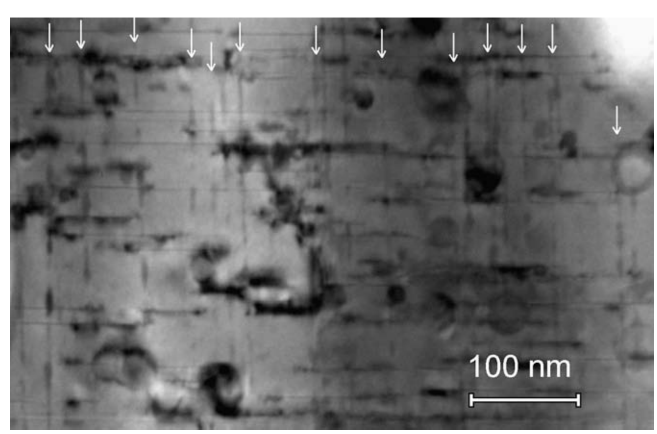

Fig. 1. Transmission electron micrograph of discontinuous ion tracks (vertical, indicated by arrows) in Y(Dy)BCO resulting from irradiation by 74 MeV Ag ions to a fluence of 10^{11} ions/cm^2.