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Magnetic field orientation dependence of flux pinning in (Gd,Y)$Ba_2Cu_3O_{7-x}$ coated conductor with tilted lattice and nanostructures

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ABSTRACT

The dependence of the critical current density (J_c) on the orientation of an applied magnetic field was studied for a prototype (Gd,Y)$Ba_2Cu_3O_{7-x}$ (GdYBCO) coated conductor fabricated by MOCVD on an IBAD-MgO template. Additional rare-earth cations (Y and Gd) and Zr were incorporated into the superconducting film to form $(Y,Gd)_2O_3$ and $BaZrO_3$ nanoparticles extended nearly parallel to the *a*–*b* planes and to the *c*-axis, respectively, to enhance the flux pinning. In-field measurement of J_c was carried out with electrical current flowing either along or perpendicular to the longitudinal axis of the tape, while a maximum Lorentz force configuration was always maintained. Details in the angular dependence of J_c were related to the unique structure of the film, specifically the tilt in the GdYBCO lattice and the tilts in the extended $(Y,Gd)_2O_3$ and BaZrO3 nanoparticles. XRD and TEM were used to study the structure of the coated conductor. The effect of the misalignment between the external field **H** and the internal field **B** on the angular dependence of J_c is discussed.

1. Introduction

The development of $YBa_2Cu_3O_{7-x}$ (YBCO)-based coated conductors aims at many applications such as motors, generators and transformers, all involving the presence of magnetic fields from intermediate to high strengths. In-field performance of the superconducting tapes, dependent on not only the strength but also the orientation of the applied magnetic field, is crucial for these applications. The in-field performance, specifically the critical current density (J_c), can be enhanced by introducing various structural and morphological defects with appropriate size and distribution that effectively pin the magnetic vortices [1]. In the last several years, extensive efforts in engineering and optimizing the defects at a nanometer scale using various techniques have made great progress, leading to significant advance in the coated conductor technology.

The relationship between critical current densities and the orientation of an applied magnetic field has been a topic of enormous theoretical and technological importance for high-T_c oxide superconductors. Electronic and structural anisotropy is recognized as a major source, accounting for the phenomenon that the J_c value varies with applied field orientation. Indeed, the layered lattice itself can provide strong vortex pinning, arising from the intrinsic periodic modulation of the order parameter from inter- to intra-CuO_2 layers [2–4]. For a typical coated conductor where an epitaxial film is deposited on a biaxially textured template, the *a*–*b* plane of the lattice is normally parallel to the film surface or the film/substrate interface. The magnetic field angular dependence of J_c usually features a maximum when the applied field is parallel to the tape surface. This J_c maximum, denoted as the *a*–*b* peak, which is produced by a combined effect of the electronic mass anisotropy, intrinsic pinning, and layered defects has been reported for YBCO films fabricated by various techniques such as PLD (pulsed laser deposition) [5,6], sputtering [7], MOCVD (metal organic chemical vapor deposition) [8], MOD (metal organic deposition) [9] and electron-beam evaporation [10]. It is worth to note that layered intergrowths typically contribute significantly to the observed *a*–*b* peak, and that for any practical HTS coatings, there are always various types of structural defects acting as flux pinning centers. A finite $J_c(\theta)$, including a J_c maximum, is sustained by the combined effects from the layered lattice and from any contributing struc-

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tural defects. In general, $J_c = F_p/B$, where F_p is the macroscopic volume pinning force exerted on the flux lines by all possible pinning centers. The angular dependence of J_c is just a reflection of how these pinning effects vary with the external magnetic field orientation.

In an angular dependence measurement system, the orientation of the applied magnetic field is usually referenced to the film surface or normal. Under certain circumstances, the crystal lattice of the superconductor layer may tilt by a small angle from the film/substrate interface, so that the *a*–*b* planes are no longer parallel to the film surface. Consequently, the *a*–*b* peak may be found to shift from its "usual" reference position. The crystal lattice may tilt when a film is deposited on a vicinal single crystal substrate surface [11–13], on an IBAD (ion beam assisted deposition) template [14], or on an ISD (inclined surface deposition) template [15,16]. The exact mechanism responsible for this out-of-plane tilt is beyond the scope of this paper, but its effect on in-field J_c anisotropy is to be considered.

When analyzing angular dependent J_c data, it is important to note that there may be a misalignment between the orientations of the internal field (**B**) and the external field (**H**). It is the orientation of **B** rather than **H** that determines when a flux pinning effect is maximized. For example, strictly, the *a*–*b* peak should occur where the internal field (**B**) is parallel to the *a*–*b* plane. If there are other J_c peaks, they should appear where **B** is parallel to the responsible extended pinning centers, e.g., columnar nanoparticles, which have an angularly preferential distribution.

The orientation of the internal field **B** is determined by several combined or competing factors. Firstly, vortex lines have a strong tendency to minimize the total energy by shortening their lengths. For a thin film sample, the geometric demagnetizing effect tends to align the vortex lines parallel to the normal to the surface. Secondly, vortex lines prefer to be parallel to the magnetizing field in order to minimize the magnetic energy. Thirdly, vortex lines in an anisotropic superconductor such as YBCO tend to tilt toward the direction of the *a*–*b* plane to reduce their line energy per unit length. Lastly, since pinning by correlated disorder always reduces the system energy, vortex lines incline to align themselves parallel to extended defects that act as effective pinning centers, such as those columnar nanoparticles formed during the process of film fabrication. Depending on the strength and the relative orientation of the applied field, one factor can be dominant while another or others may be small. It is the combined effect of all the above factors that determines the final orientation of **B** and that is why the internal field **B** often does not coincide with the external field **H**. As an angular dependence of J_c is most likely documented with respect to the orientation of the external applied field, this misalignment between **B** and **H** needs to be carefully considered when experimental results are interpreted and analyzed.

Structural defects play a central role in vortex pinning. Potential pinning defects include point defects such as vacancies and cation disorder, dislocations, twin boundaries, stacking faults, grain boundaries, and precipitates or inclusions of secondary phases. Insight into the nature of an effective flux pinning defect can be found within the $J_c \sim \theta$ relationship. For uncorrelated defects, which have a random distribution and an isotropic geometry, the pinning effect should depend on the effective field described by the supercarrier electronic mass anisotropy according to, $J_c(\theta) = J_c(H_{eff}(\theta))$, where, $H_{eff} = H\varepsilon(\theta)$, and $\varepsilon(\theta) = \left[\sin^2(\theta) + \left(\frac{m_{ab}}{m_c}\right)\cos^2(\theta)\right]^{1/2}$, for θ measured from the tape plane. In this case, the $J_c(\theta)$ curve normally has a minimum when **H** is parallel to the *c*-axis and only one peak at the *a*–*b* plane due to the mass anisotropy and the intrinsic pinning. For correlated disorder that has a distribution extended in a preferential direction, an additional peak should appear at the angle when the internal field **B** is parallel to the defect. A typical example of correlated defects is the linear amorphous tracks produced by an irradiation with high-energy heavy ions [17,18]. Correlated defects can also be naturally formed during a film synthesis process. For example, the intergrowths formed during the laminar growth in many *ex situ* films are nearly parallel to the *a*–*b* plane, resulting in a superimposed effect over the intrinsic pinning, raising and broadening the *a*–*b* peak. On the other hand, a columnar film growth mode may generate correlated defects, such as dislocations, twin and/or grain boundaries, which are nearly parallel to the *c*-axis, yielding an additional J_c peak accordingly [19,20].

From an application standpoint, it is very important to purposely introduce additional defects into the superconducting layer of a coated conductor to enhance the flux pinning. It is expected that additional correlated defects can be tailored to improve the in-field performance not only in the *a*–*b* plane but also in other directions such that the overall anisotropy in $J_c(\theta)$ is reduced. Among various methods for introducing structural defects, incorporation of non-superconductive nanoparticles has evolved as the most effective one due to its strong effects. *c*-Axis columnar defects (CD's) comprised of nanoparticles of $BaZrO_3$ (BZO) [21–23], $BaSnO_3$ (BSO) [24], or more recently the rare-earth oxides RE_3TaO_7 (RTO) [25] have been introduced into YBCO-based films fabricated by PLD, demonstrating greatly enhanced flux pinning in this direction, analogous to the irradiation-induced defects. BZO nanoparticles have also been proven to be effective in improving flux pinning isotropically when introduced into films made by chemical solution method such as MOD [26]. In-field performance improvement has also been achieved by the formation of a multi-layered structure with nanoparticles of Y_2O_3 [27] or YBa_2CuO_5 (2 1 1) [28] dispersed parallel to the *a*–*b* plane.

Recently, correlated defects aligned parallel to the *a*–*b* plane and/or along the *c*-axis have been incorporated into YBCO-based films made by MOCVD [29,30], leading to a significant overall enhancement of the in-field performance. Using IBAD-MgO on Hastelloy as a template, MOCVD has evolved as a successful technology for the practical fabrication of HTS coated conductors because of its capability of producing high quality films with high throughput [31]. In this paper, we have studied the magnetic field angular dependence of J_c of a prototype GdYBCO coated conductor fabricated by the MOCVD technology. BZO as well as $(Y,Gd)_2O_3$ nanoparticles were introduced into the film by doping the precursor with Zr and Gd to the appropriate levels [30]. These nanoparticles are distributed either parallel to the *c*-axis (BZO) or to the *a*–*b* plane (RE_2O_3) so that flux pinning is enhanced in the respective orientations. Our goal is to establish the relationship between the in-field angular behavior of the coated conductor and its microstructure.

2. Experimental

The GdYBCO film was deposited by MOCVD on an IBAD-MgO template which has a multilayer structure of $LaMnO_3$/homoepitaxial-MgO/IBAD-MgO/Y_2O_3/Al_2O_3/Hastelloy tape. Details about the IBAD-MgO template and the MOCVD process, which uses a liquid precursor delivery system, can be found elsewhere [32]. In previous work [30], it was found that the angular dependence of J_c was impacted mostly by the composition of the films. The composition of the GdYBCO coated conductor studied in this work was $Zr_{0.5}Gd_{0.65}Y_{0.65}Ba_2Cu_3$, where the numbers denote the atomic ratio of the elements in the liquid precursor. With the addition of the extra rare earth elements and Zr, it was shown that arrays of aligned $(Y,Gd)_2O_3$ and BZO nanoparticles formed in the directions parallel to the *a*–*b* plane and to the *c*-axis, respectively [30]. In addition to composition, deposition temperature and growth rate are among the parameters that influence the in-field performance of