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ORIGINAL PAPER

Angular-Dependent Vortex Pinning Properties of $YBa_2Cu_3O_{7-\delta}/Y_2O_3$ Quasi-Multilayers

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Abstract A series of quasi-multilayers of $YBa_2Cu_3O_{7-\delta}$ (YBCO)/Y_2O_3 specifically 70× (m YBCO/n Y_2O_3) were prepared on $SrTiO_3$ single crystal using pulsed-laser deposition (PLD) with a controlled deposition pulses of m = 40 and n = 2, 5, and 10 for YBCO and Y_2O_3, respectively. The x-ray diffraction patterns indicate that all the present quasi-multilayers exhibit good c-axis orientation. The angular dependence of critical current density (J_c) on applied magnetic field directions are systemically measured to study the anisotropic vortex pinning performances for those quasi-multilayers. It is revealed that compared with the pure YBCO films, the quasi-multilayers with $n = 2$, i.e., a proper constituent pulse of Y_2O_3, exhibits the enhanced vortex pinning abilities in all angles between c-axis orientation and the applied magnetic field direction. As well, such a quasi-multilayer film (n = 2) shows the higher lift factor $J_c(\Theta)/J_c(90°)$ and much better vortex pinning properties at high fields and high temperatures, showing promising potential for coated conductor application.

Keywords YBCO · Quasi-multilayer · Angular-dependent

1 Introduction

The coated conductors (CCs) based on epitaxial $REBa_2Cu_3O_{7-\delta}$ (rare earth (RE); Y, Gd Sm, etc.) possess high critical current density (J_c) values at liquid nitrogen temperature (77 K) and self-filed. For technical applications, it is necessary to enhance in-field J_c of coated conductors. In the past decade, vortex pinning issue has been one of the most important keys for coated conductors. There are several types of crystalline defects that can act as pinning centers, such as non-superconducting phases, dislocations, vacancies, grain boundaries, and twins [1]. Substrate decoration, secondary phases, multilayers with ultrathin interlayers, and various artificial pinning centers (APCs) have been also suggested and evidenced to be effective to enhance $RBa_2Cu_3O_{7-\delta}$ thin films performance [2–4].

Recently, different approaches have been proposed to improve the REBCO film in-field performance. It is revealed that the growth controlling of RE_2O_3 is a typical way to deposit multilayers or quasi-multilayers, which normally results in a high density of APCs [5–12]. The measurement of field angular dependence of J_c (H) in REBCO films is an important way to characterize the anisotropic properties of flux pinning centers. The J_c decreases significantly as the magnetic field is applied from the parallel direction with c-axis to the perpendicular direction with c-axis. As the nanoparticles are insufficient and uncorrelated along c-axis, the J_c angular dependence appear anisotropic without the peak modified at $B//c$ [13].

In the present work, a series of growth-controlled quasi-multilayers consisting of $YBa_2Cu_3O_{7-\delta}$ (YBCO) and Y_2O_3 are prepared. Electrotransport measurements were made at different applied directions of magnetic fields (H), characterized by the angles (Θ) between the c-axis orientation and magnetic field direction. A methodology based on angular-dependent J_c measurement is proposed to identify the in-field properties and the effect of the artificial defects.

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2 Experimental

Quasi-multilayers namely, $p\times$ (mYBCO/$n$$Y_2O_3$) were fabricated on (100) $SrTiO_3$ single crystal through pulse laser deposition (PLD with a KrF excimer laser ($\lambda = 248$ nm, Lambda Physik), where m and n denote the number of laser pulses on YBCO and Y_2O_3, respectively, and p is the periodic number. The laser ran at a repetition rate of 5 Hz and an energy density of 2.4 J/cm^2. Commercial stoichiometric YBCO and Y_2O_3 targets and standard deposition conditions for YBCO were applied, with a heating temperature of 820 °C, a background pressure of 0.3 mbar O_2, and oxygen loading under 400 mbar. The growth rates of YBCO and Y_2O_3 were around 1 and 0.4 Å per pulse, respectively. After each $m = 40$ pulses on YBCO target, Y_2O_3 target was set into position and a certain number of pulses ($n = 2$, 5 and 10) were deposited. This was repeated 70 times ($p = 70$). Hence, 40 pulses of YBCO produced roughly 3.4 unit cells, while 2–10 pulses of Y_2O_3 were assumed as incomplete layers of 0.075–0.375 unit cells. This results in a so-called quasi-multilayer, consisting of a YBCO film matrix and an island-like Y_2O_3 nanoparticles. A pure YBCO film as a reference sample was prepared using the same conditions. The thickness of YBCO is around 280 nm for each sample.

The texture was determined by x-ray diffraction (XRD). J_c was measured in various fields up to 9 T with a Quantum Design PPMS system by standard four-probe method on a bridge of 0.8 mm length and 50 μm width. The angular dependence of J_c was measured in a maximum force configuration, i.e., the sample was rotated around the current axis to achieve various angles Θ between the c-axis orientation and the magnetic field direction. The critical current density was determined by an electric field criterion of $E_c = 1$ μV/cm.

3 Results and Discussion

Figure 1 shows the XRD patterns of pure YBCO film ($n = 0$) and YBCO/Y_2O_3 quasi-multilayers ($n = 2, 5, 10$), YBCO (00l) indicating good c-axis orientation for YBCO, and the absence of other extra peaks except Y_2O_3 reflections confirm the phase purity. The intensity of Y_2O_3 increases with the used pulse number. The above phenomenon is due to good chemical stability and lattice matching between Y_2O_3 and YBCO.

The self-field critical current density(J_{cs}) of YBCO/ Y_2 O_3 quasi-multilayers ($n = 2$, 5, 10), about 2.6, 2.3 and 2.1 MA/cm^2, respectively. As shown in Fig. 2, although their J_{cs} are a little lower than that of the pure YBCO sample which is about 3.6 MA/cm^2, the magnetic field dependence of J_c for the pure YBCO film ($n = 0$) and the YBCO/Y_2O_3 quasi-multilayer ($n = 2$) at 77 K are much different. It

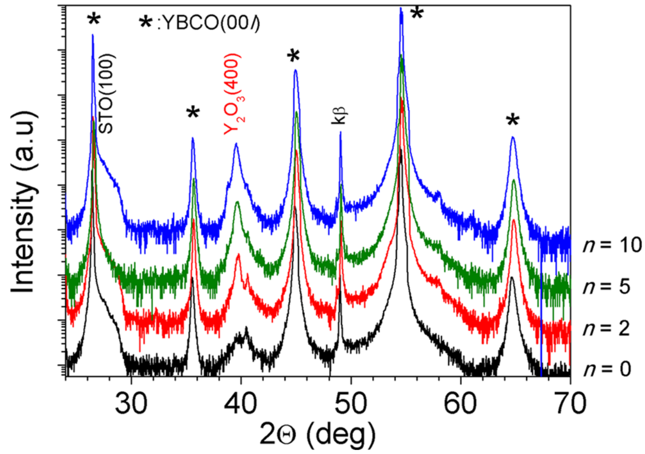

Fig. 1 XRD patterns of pure YBCO film ($n = 0$) and YBCO/Y_2O_3 quasi-multilayers ($n = 2, 5, 10$)

implies that the enhanced flux pinning occurs due to the proper Y_2O_3 doping at high fields, giving rise to a crossover behavior. The crossover behavior at logarithmic coordinate diagram of the J_cH is frequently observed in case of low-doped YBCO films. That means it might be difficult to improve J_c in the whole range of magnetic fields using precipitates. In films with nanoparticles, it is reported that the irreversibility field H_{irr} may be improved, while the self-field J_c value is reduced due to lower T_c values or disturbed crystallinity [14, 15]. The crossover behavior of the $J_c - H$ can be understood from the difference in H_{irr} ($T = 0$ K). If the H_{irr} is increased, $J_c(H)$ is in most cases reduced in the range of several thousands of Oersted with the crossover behavior described above.

We compared the angular-dependent vortex pinning properties of $YBa_2Cu_3O_{7-\delta}$/Y_2O_3 quasi-multilayers. As shown in Fig. 3 we found that J_c (Θ)/J_c (90°) of YBCO/Y_2O_3 quasi-multilayer ($n = 2$) is clearly enhanced

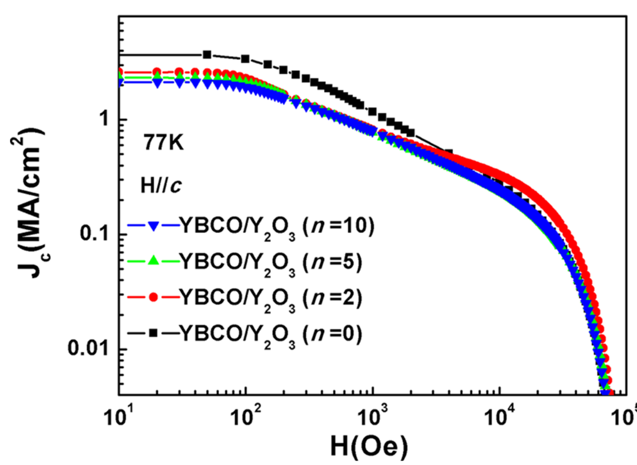

Fig. 2 Magnetic field dependence of J_c of pure YBCO film ($n = 0$) and YBCO/Y_2O_3 quasi-multilayers ($n = 2, 5, 10$) sample

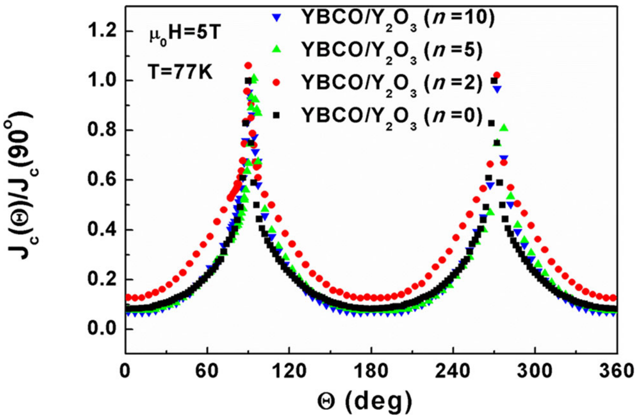

Fig. 3 J_c (Θ)/J_c (90°) for the YBCO/Y_2O_3 quasi-multilayers (n = 0, 2, 5, 10) at 77 K and 5 T

compared with pure YBCO in all angles, indicating a contribution of Y_2O_3 doping to flux pinning even at high temperature and high fields. However, when $n = 5$ to 10 the enhancement of the J_c (Θ)/J_c (90°) for YBCO/Y_2O_3 quasi-multilayers are not obvious. The films with a high content of Y_2O_3 ($n = 5$, 10) hardly demonstrate the doping contribution to flux pinning, due to no pronounced increase in H_{irr} at this temperature. Those films with lower $H_{\text{irr}}(T = 0\text{ K})$ may easily switch to the flux-flow phase, leading to lower flux pinning force, even though the amount of potential pinning centers are sufficient enough [15].

The anisotropic defects may modify the J_c, depending on the angle between the directions of applied field and transport current. In case of $H//ab$, the pinning source mainly arise from the intrinsic (a, b) plane pinning associated with the periodic modulation of the order parameter, i.e., the layered structure of YBCO. In case of $H//c$, the c-axis peak of J_c (H) is mainly attributed to correlated defect [16]. To further investigate the flux pinning characteristics in those quasi-multilayers with different doping levels, the angular dependence of J_c in various applied magnetic fields from 0.25 to 5 T are measured. Figure 4 shows the angulardependent J_c (Θ)/J_c (90°) for the YBCO/Y_2O_3 quasi-multilayers with the $n = 2$, 5, and 10 at 77 K in the magnetic fields of 0.25, 1, 3 and 5 T, respectively. All the curves of angular dependence present a main strong peak at $H//ab$ which is attributed mainly to intrinsic pinning including defects parallel to (a, b) planes like linear or planar defects. In contrast, a second weak peak can be observed at $H//c$ in case of $n = 2$, which may emerge from the correlated defects parallel to c-axis [17–20].

One may estimate the intrinsic flux pinning contribution to J_c according to the model of Tachiki and Takahashi, giving $J_c\ (\Theta) = J_c\ (0)|\cos\ \Theta|^{-0.5}$ [21]. An example for $\mu H = 1$ T and $T = 77$ K is shown in Fig. 5. The model shows a good fit for the angles around 90° or 270°. In view

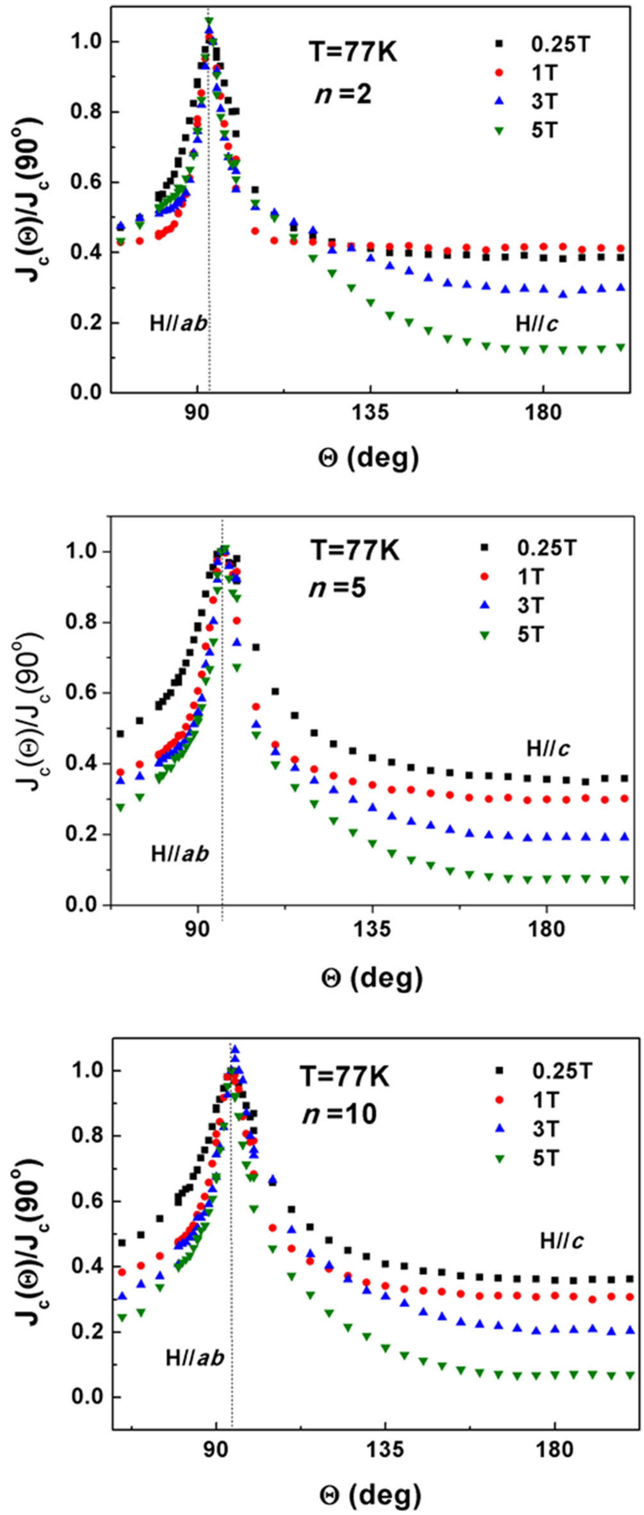

Fig. 4 Angular dependence of J_c (Θ)/J_c (90°) for the YBCO/Y_2O_3 quasi-multilayer (n = 2, 5, 10) samples at 77 K in different magnetic fields

of isotropic defects and mass anisotropy, however, an obvious difference emerged at the region of $H||c$. The discrepancy at this region suggests that there may exist correlated

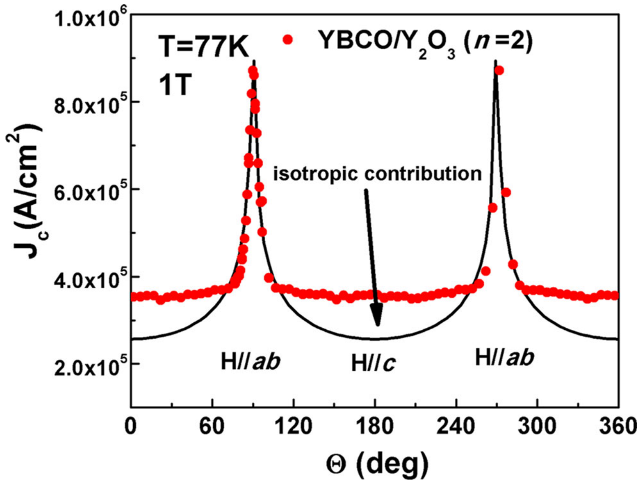

Fig. 5 J_c for the $YBCO/Y_2O_3$ quasi-multilayer sample at 77 K and 1 T. The *solid line* is a fit according to the original Tachiki–Takahashi model

defects along the c-axis. The c-axis correlated defects are assumed to be either interface or lattice mismatch between YBCO and Y_2O_3 The Y_2O_3 particles are evenly distributed on the quasi-multilayer plane and produce a certain stress field. The Y_2O_3 particles and dislocation due to the stress field may act as strong flux-pinning centers. Thus, Y_2O_3 particles enhance J_c of low-doped quasi-multilayer films at magnetic fields.

Moreover, the crossover behavior shows the diversity of flux pinning effect for $YBCO/Y_2O_3$ quasi-multilayer ($n = 2$) at different magnetic fields. As shown in Fig. 6, the lift factor defined as J_c (180°)/J_c (90°) mostly reduced by increasing magnetic fields. It is revealed that the sample with $n = 2$ shows a higher lift factor than other samples

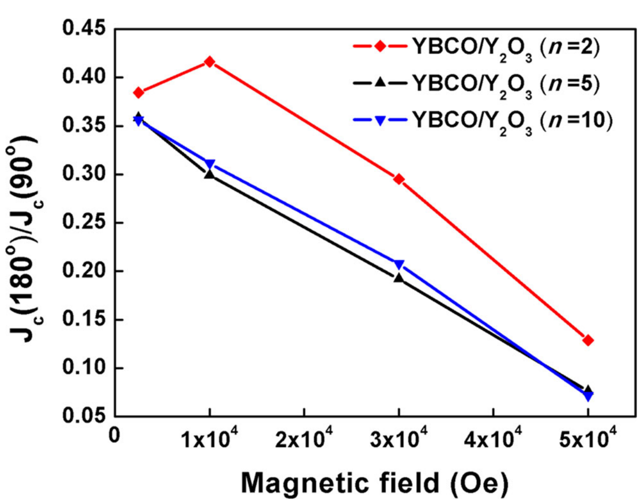

Fig. 6 The lift factor of J_c (180°)/J_c (90°) for the $YBCO/Y_2O_3$ quasi-multilayers ($n = 2, 5, 10$) at 77 K

in all studied fields, and the lift factor achieved the highest value when the magnetism is 1^4 Oe. It means that at 10^4 Oe the vortex pinning reach saturation. For the case of $n = 5$ and 10, a high level of doping, the increasing Y_2O_3 defects degraded the superconducting components too much, leading to the hardly remarkable vortex pinning properties.

4 Conclusion

In summary, we have successfully fabricated a series of quasi-multilayers of $YBCO/Y_2O_3$ by using the intermediated pulsed laser deposition. The $\theta 2\theta$ diffraction pattern indicates the good c-axis orientation of YBCO, showing no additional phases for all the present $YBCO/Y_2O_3$ quasi-multilayers. Our results revealed that growth controlling of secondary phase (Y_2O_3) appears hard to introduce an effective vortex pinning at high fields and high temperature, while the J_c (Θ)/J_c (90°) of quasi-multilayers is clearly enhanced compared with pure YBCO in all angles. Especially at the case of $n = 2$ the $YBCO/Y_2O_3$ quasi-multilayer film exhibits anisotropic correlated defects demonstrating the optimized angular-dependent vortex pinning properties and potential power application for coated conductors.

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