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Critical current anisotropy in nanostructured HLPE coated conductors

F Hengstberger[1], M Eisterer[1], H W Weber[1]
A Kursumovic[2], J L MacManus-Driscoll[2]

[1]Atomic Institute of the Austrian Universities, Stadionallee 2, 1020 Vienna, Austria
[2]Department of Materials Science and Metallurgy, University of Cambridge, Cambridge CB2 3QZ, UK

E-mail: hengstb@ati.ac.at

Abstract. Coated conductors can be produced by hybrid liquid phase epitaxy (HLPE) with high growth rates and excellent critical current densities. Samples with a thickness of about 1 µm carrying a current of several 100 A/cm-width were reproducibly fabricated in this way.

In this paper we report on the critical current densities in HLPE coated conductors focussing on the angular dependence of $J_c(H,\theta)$. Of particular interest for future technical applications is a reduction of the ratio $J_c(H\|ab)/J_c(H\|c)$. This can be achieved by defects induced during crystal growth and correlating with the c-axis of the conductor, which therefore predominately contribute to $J_c(H\|c)$. The correlation of the pinning sites will be discussed in terms of the J_c-anisotropy in fields of up to 6 T.

1. Introduction

Recently much attention was paid to the incorporation of nanoprecipitates in YBCO-based coated conductors. Embedded in the matrix material, particles of nanometer size can act as strong pinning centers due to the local suppression of superconductivity on a scale comparable to the superconducting coherence length ξ. This strategy was successfully employed in both PLD and MOD growth using $BaZrO_3$ [1],[2],[3],[4] or $BaHfO_3$ [5], respectively.

Alternatively yttria decoration of the STO substrate was shown to improve the current carrying capability considerably [6],[7]. In this case the enhancement in pinning is attributed to dislocations extending from the nanoislands at the substrate–YBCO interface to the c-axis of the film.

Hybrid liquid phase epitaxy (HLPE) is capable of reproducibly fabricating high quality coated conductors with a thickness above 1 µm [8]. The main advantage of this technique is that high growth rates can be achieved [9]. Although the current carrying capability is excellent in self-field, the critical current density drops significantly in high fields.

Since the need for additional pinning is evident, the introduction of artificial effective pinning centers represents an obvious choice. Although neutron irradiation was shown to improve the critical current density in fields of up to 5 T at 77 K [10], this route is inapplicable for any industrial production process, but these experiments serve as a benchmark and demonstrate the potential performance of HLPE coated conductors, which can be achieved if strong pinning centers on the nm-scale are present in the material. Consequently, different approaches to modify the nanostructure of HLPE coated conductors by various precipitates are examined.

Table 1. Overview of sample properties.

Samplecode	Precipitate	T_c (K)	ΔT_c (K)	$J_c(\mathrm{Am}^{-2})$	α
FH750	None	89.8	1.3	$1.16{\cdot}10^{10}$	0.46±0.04
FH751	$BaZrO_3$	89.8	1.6	$1.05{\cdot}10^{10}$	0.41±0.06
FH752	$BaHfO_3$	90.7	1.8	$0.61{\cdot}10^{10}$	—
FH753	Y_2O_3	89.5	0.6	$1.16{\cdot}10^{10}$	0.52±0.08

2. Sample Preparation

A total of 4 samples were deposited on STO single crystalline substrates using a 3BaO–7CuO flux containing 10 wt% YBCO. One sample was grown without any precipitates and is used as a reference (FH750). Two samples were processed using YBCO targets containing 5 mol% $BaZrO_3$ (FH751) and $BaHfO_3$ (FH752), respectively. Sample FH753 was grown after ablating 4 Y_2O_3 pulses on the substrate surface. The growth temperature was held constant at 825 °C for all the samples. Further aspects of the sample growth are described in detail elsewhere [8],[9].

The high critical current densities achieved in these samples together with the finite contact resistance make a reduction of the current carrying cross-section inevitable. Therefore all the sample were patterned to 10 µm wide bridges about 200 µm long. Although the same number of YBCO pulses (12 000) was used during processing, a sample to sample variation in thickness cannot be excluded, since different targets were used for the samples containing $BaHfO_3$ and $BaZrO_3$. Therefore, a thickness of 1 µm is assumed for all the samples in the following.

3. Experimental

Transport measurements were carried out in a gas-flow cryostat equipped with a 6 T split-coil magnet. The magnetic field was always perpendicular to the current (maximum Lorentz-force) during the anisotropy measurements. The temperature was set to the target temperature for future applications (77 K).

The commonly used $E_c = 1\,\mu\mathrm{V/cm}$ criterion is not applicable when measuring short bridges in the presense of a voltage noise of typically a few ten nV. Therefore, a voltage criterion of $U_c = 1\,\mu\mathrm{V}$ was used to define J_c ($E_c \approx 50\,\mu\mathrm{V/cm}$).

4. Results and Discussion

4.1. Transition Temperature

The transition temperature was determined by resitive measurements applying a current of 0.2 µA to the bridge ($\sim 2 \cdot 10^4\,\mathrm{Am}^{-2}$). The intersection of a linear fit to the steepest part of the transition with the extrapolated normal state resitance and zero resistance defined T_c and the transition width ΔT_c, respectively. The onset of the transition is close to or above 90 K in all samples and transition widths of around 1 K (Tbl. 1) are obtained. There is no systematic difference between the samples containing nanoprecipitates and the reference sample.

4.2. Angular Dependence of the Critical Current

Critical current densities of around $1.1 \cdot 10^{10}\,\mathrm{Am}^{-2}$ were obtained in zero field in all but the $BaHfO_3$ sample (Tbl. 1). The normal state resistance of the latter (approximately two times higher when compared to the other samples) together with the comparably small critical current density might indicate a thinner YBCO layer.

Prominent peaks for fields parallel to the c-axis appear in all the samples at fields above 1 T (Fig. 1). This feature of the anisotropy in HLPE coated conductors was attributed to correlated pinning by growth or misfit dislocations earlier [9]. The yttria decoration of the

substrate (FH753) and the $BaHfO_3$ additions in FH752 increase the anisotropy, the latter quite significantly. By contrast, an increase in height relative to $J_c(H \parallel ab)$ and a broadening of this peak is observed in the $BaZrO_3$ sample for fields of up to 1 T. Higher applied fields narrow the width of the c-axis peak until it nearly matches the c-axis peak of the reference sample at 5 T.

An interesting feature is the occurence of shoulders in the anisotropy curve for fields close to $H \parallel ab$, which are absent only in the $BaHfO_3$ sample. This peculiarity has previously been seen in YBCO thin films by other groups [13],[11],[14],[12],[7] but its nature remained unclear. Therefore, the anisotropy for fields close to $H \parallel ab$ will be subject to future investigations.

4.3. Field Dependence of the Critical Current

It is evident from Fig. 2 that for fields parallel to the c-axis, the $J_c(H)$ dependence consists of two regions: a region of almost constant critical current density for small applied fields and a region with a strong decay of the critical current at higher fields.

So far this behaviour has been discussed in terms of a so call accomodation field B_{acc}. However, there is evidence from recent work that the self-field of the sample plays an important role also in the thin film geometry [15],[16]. Vortex pinning depends on the magnetic induction B, the sum of the external applied field $\mu_0 H_{ext}$ and the field generated by the supercurrents in the sample $\mu_0 H_{self}$. Hence the latter cannot be ignored if both are of comparable magnitude. A calculation of the maximum self-field occuring in a bridge of the given dimensions and for the critical current density of the constant J_c region ($\approx 1.1 \cdot 10^{10}\,\mathrm{Am}^{-2}$) results in $\max(\mu_0 B_{self}) = \max(\mu_0 B_{self,z}) \approx 8\,\mathrm{mT}$. The results are in good agreement with the end of the plateau in low fields in Fig. 2.

At higher fields the dependence of the critical current density is well described by a power-law $J_c(H) \propto H^{-\alpha}$ for all samples except the film containing $BaHfO_3$ (Fig. 2). Fits to the curve ranging from 30 mT (exceeding the self-field estimate from above by a factor of 4) to 1 T show enhanced pinning for the $BaZrO_3$ sample ($\alpha = 0.41 \pm 0.06$) when compared to the reference sample ($\alpha = 0.46 \pm 0.04$). Accordingly also the ratio $J_c(0\,\mathrm{T})/J_c(1\,\mathrm{T})$ drops from ~ 7 to ~ 5. Note that the uncertainty in the thickness of the samples leaves the slope of the curve unaffected. No improvement is found for the Y_2O_3 seeded sample ($\alpha = 0.52 \pm 0.08$).

The right-hand panel of Figure 2 quantifies the pinning improvement by the addition of $BaZrO_3$ particles in FH751 relative to the reference sample FH750 in more detail. The $J_c(H \parallel c)$ ratio in both samples peaks at about 0.5 T, decreases at higher fields and approaches the $J_c(H \parallel ab)$ ratio at 4 T.

It is interesting to note that the peak field in the relative improvement of $J_c(H \parallel c)$ correlates with the occurence of the broad c-axis peak in the $BaZrO_3$ sample (Fig. 1). The width and the height of the peak decrease at fields above 0.5 T, thus confining the anisotropy reduction to intermediate fields. This suggests that the improvement in pinning is mainly due to c-axis correlated defects in the sample containing $BaZrO_3$ particles. A higher dislocation density, resulting from the $BaZrO_3$–YBCO lattice mismatch, may form preferentially along the c-axis and improve pinning [1] at fields of up to 0.5 T.

5. Summary

A total of 4 samples grown by HLPE—two of them containing precipitates ($BaHfO_3$, $BaZrO_3$), one deposited on an yttria decorated substrate—were analysed. Pinning was enhanced only in the sample containing $BaZrO_3$. This demonstrates that the strategy of incoporating precipitates in the superconductor, which is currently widely used in PLD and MOD growth, is also applicable to HLPE.

The relative improvement in $J_c(H \parallel c)$, when compared to a standard HLPE sample, correlates with the occurence of broad c-axis peaks in the anisotropy curve. Therefore, the additional pinning can be attributed to c-axis correlated defects. The fact, that the anisotropy

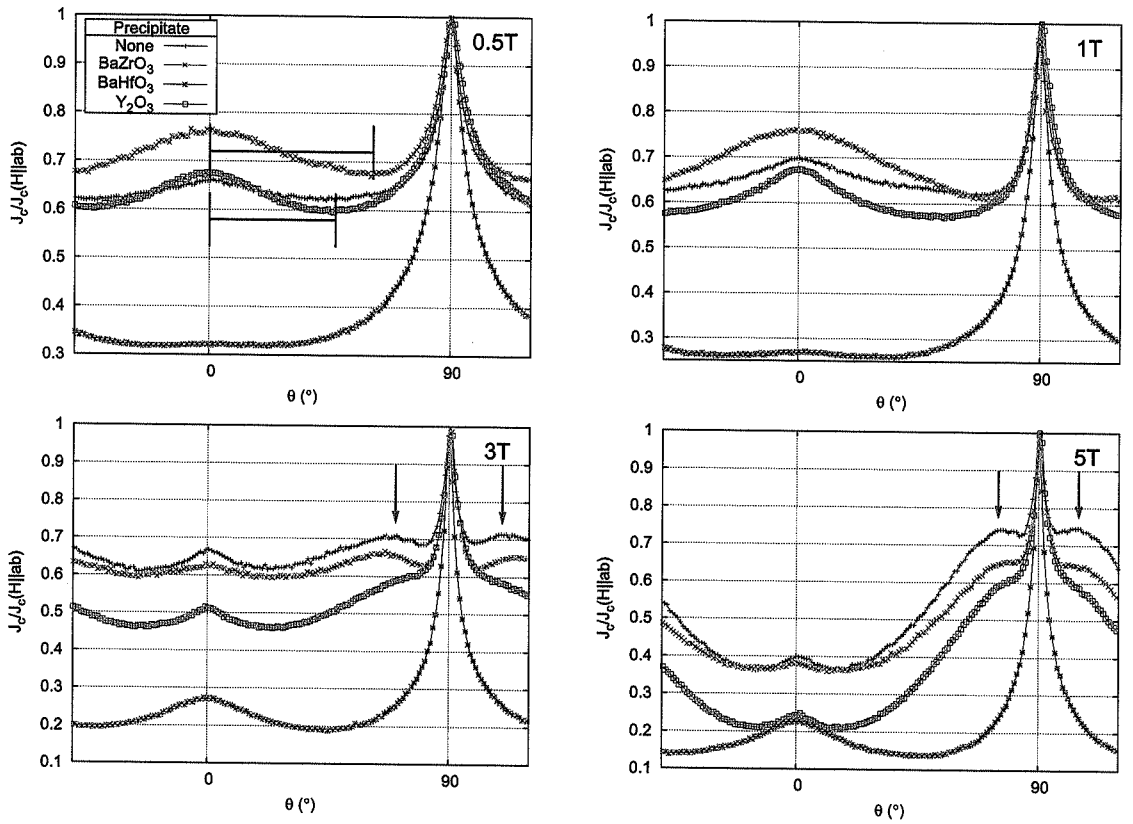

Figure 1. Angular dependence of the critical current density normalized to $J_c(H \parallel ab)$ ($\theta = 0$ corresponds to $H \parallel c$). At lower fields (0.5 T) a broadening of the c-axis peak due to the $BaZrO_3$ precipitates is observed (indicated by the bars in the upper left panel) which gradually dissapears at higher fields (lower panels). Shoulders occur close to $H \parallel ab$ in all samples except the one containing $BaHfO_3$ (arrows in the lower panels).

reduction was limited to moderate fields (~ 0.5 T), and the absence of a decrease in T_c suggest that conductors with even higher $BaZrO_3$ concentrations should be investigated in detail.

The existence of a plateau in $J_c(H \parallel c)$ was observed, independently of the microstructure of the samples and discussed in terms of the self-field generated by the supercurrents. A simple estimate of the field range, where such effects become important, is in excellent agreement with the experimental results.

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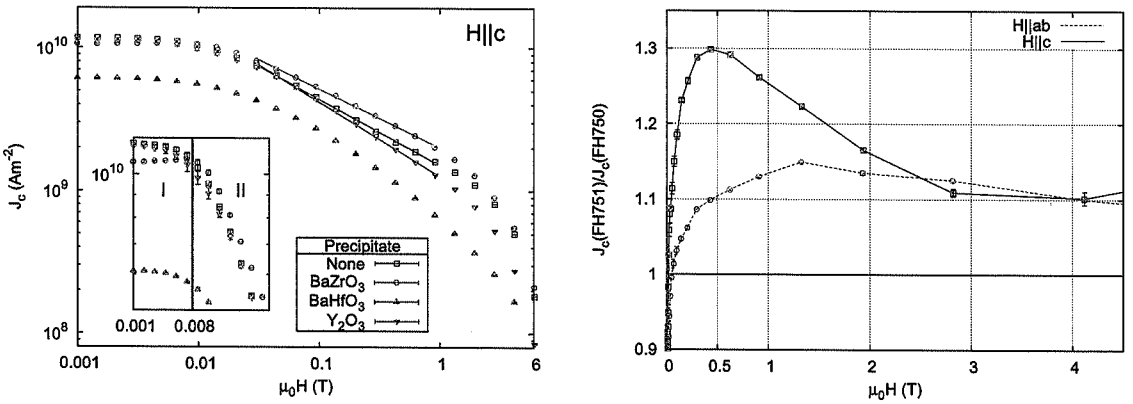

Figure 2. Field dependence of the critical current density for fields applied parallel to the c-axis of the samples (left). Power-law fits are plotted as solid lines within the fit-range. The inset is a magnification of the regime governed by the self-field, the solid vertical line separates the plateau (I) from the power-law decrease (II). The right-hand panel shows the relative J_c-enhancement due to the $BaZrO_3$ particles in FH751 compared to the reference sample FH750. The improvement in $J_c(H \| c)$ peaks at about 0.5 T, which confines the anisotropy reduction to intermediate fields. (The final ratio of about 1.1 in both sample might result from the thickness uncertainty.)

References

[1] MacManus-Driscoll J L, Foltyn S R, Jia Q X, Wang H, Serquis B, Maiorov B, Civale B, Hawley M E, Maley M P and Peterson D E 2004 *Nature* (London) **3** 439
[2] Kang S, Goyal A, Li J, Gapud A A, Martin P M, Heatherly L, Thompson J R, Christen D K, List F A, Paranthaman M and Lee D F 2006 *Science* **311** 1911
[3] Traito K, Peurla M, Huhtinen H, Stepanov Y P, Safonchik M, Tse Y Y, Paturi P, Laiho R 2006 *Phys. Rev.* B **73** 224522
[4] Gutierrez J, LLordes A, Gazquez J, Gibert M, Roma N, Ricart S, Pomar A Sandiumenge F, Mestres N, Puig T and Obradors X 2007 *Nature Materials* **6** 376–373
2006 *Supercond. Sci. Technol.* **19** 534
[5] Engel S, Thersleff T, Hühne R, Schultz L and Holzapfel B 2007 *Appl. Phys. Lett.* **90** 102505
[6] Mele P, Matsumoto K, Horide T, Miura O, Ichinose A, Mukaida M, Yoshida M and Horii S 2006 *Supercond. Sci. Technol.* **19** 44
[7] Matsumoto K, Horide T, Ichinose A, Horii S, Yoshida Y and Mukaida M 2005 *Jpn. J. Appl. Phys.* **44** 246
[8] Kursumovic A, Tomov R I, Hühne R, MacManus-Driscoll J L, Glowacki B A and Evetts J E 2004 *Supercond. Sci. Technol.* **17** 1215
[9] Kursumovic A, Evetts J E, MacManus-Driscoll J L, Maiorov B, Civale L, Wang H, Jia Q X and Foltyn S R 2005 *Appl. Phys. Lett.* **87** 252507
[10] Hengstberger F, Eisterer M, Weber H W, Kursumovic A and MacManus-Driscoll J L 2006 *IEEE Trans. Appl. Supercond.* **17** 3549–3552
[11] Yamada H, Yamasaki H, Develos-Bagarinao K, Nakagawa Y, Matawari Y and Obara H 2003 *Physica C* **392–396** 1068–1072
[12] Horide T, Matsumoto K, Yoshida Y, Horii S, Mukaida M and Osamura K 2003 *IEEE Trans. Appl. Supercond.* **15** 3734
[13] Diaz A, Mechin L, Berghuis P and Evetts J E 1998 *Phys. Rev. Lett.* **80** 3855
[14] Civale L, Maiorov B, Serquis A, Willis J O, Coulter J Y, Wang H, Jia Q X, Arendt P N, MacManus-Driscoll J L, Maley M P and Foltyn S R 2004 *Appl. Phys. Lett.* **84** 2121
[15] Gömöry F and Klincok B 2006 *Supercond. Sci. Technol.* **19** 732–737
[16] Rostila L, Lehtonen J and Mikkonen R 2007 *Physica C* **451** 66–70