Magnetic pinning in YBCO

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Abstract — **We demonstrate the successful incorporation of nanoscale ferromagnetic pinning centres within YBCO thin films. For sufficiently low dopant concentrations, the suppression of transition temperature due to poisoning of the YBCO is overcome. Even at these low dopant levels, the resultant films exhibit a coexistence of superconductivity and ferromagnetism, and a consequent absolute enhancement of the critical current density up to a factor two under all applied fields and field orientations, including self field.**

I. Introduction

The practical introduction of effective flux pinning sites into high-temperature superconductors is of paramount importance for their eventual widespread application[1]. The search for suitable processes for the generation of nanoscale defects to act as core pinning sites in the superconductor matrix has been extensive and highly fruitful, yielding improvements in the critical current density J_c under specific experimental conditions approaching an order of magnitude[2]. At the same time, many fundamental experiments have been performed on the formation of magnetic pinning sites in both low and high temperature superconductors, and their influence on the vortex lattice[3]. However, to date no practical and effective approach to the formation of magnetic pinning centres for critical current enhancement in the high-temperature materials has been proposed. Here, we present the results of one such approach, in the form of a ferromagnetic nanoparticle dispersion, and show that the superconducting properties of a YBCO thin film can be enhanced by this method.

II. Experimental

Thin film YBCO samples (0.5 μm thick) were deposited onto single crystal $SrTiO_3$ substrates by pulsed laser deposition (KrF: $\lambda = 248$ nm, 10 Hz, ~2 Jcm^{-2}) from composite targets formed from high-purity precursor powders by standard ceramic processing techniques (mixing, pressing and sintering). The substrates were held at 765°C in an atmosphere of 30 Pa flowing oxygen during deposition, and annealed *in situ* for one hour post-deposition at 520°C in 0.5 bar oxygen. A range of samples was prepared containing different amounts (0 at.%, 1 at.%, 3 at.%, 5 at.%) of a ferromagnetic dopant.

The prepared samples were photolithographically patterned into bridge structures suited to standard four-point electrical transport measurements, which were performed in an 8T cryogenic superconducting magnet.

III. Results and Discussion

X-ray diffraction performed on the samples (not shown) yields a clear indication of epitaxially grown YBCO, as expected, but does not reveal any additional peaks clearly relating to the dopant phase. We attribute this to the low concentration of the dopant additives, as well as their presence within the sample in the form of nanoparticles. Both of these properties conspire to reduce the intensity and expand the broadness of the peaks to the point where they are undetectable. This supposition is supported by TEM work (not shown) that reveals a dispersion of very fine particles (down to a few nm in size) throughout the YBCO matrix.

That these particles are ferromagnetic is evidenced by low temperature VSM measurements (figure 1) which confirm the existence of a ferromagnetic hysteresis loop arising from the particles at room temperature and persisting down to T_c, where the ferromagnetic signal is swamped by the superconducting response. It is expected, however, that the particles remain ferromagnetic also below T_c.

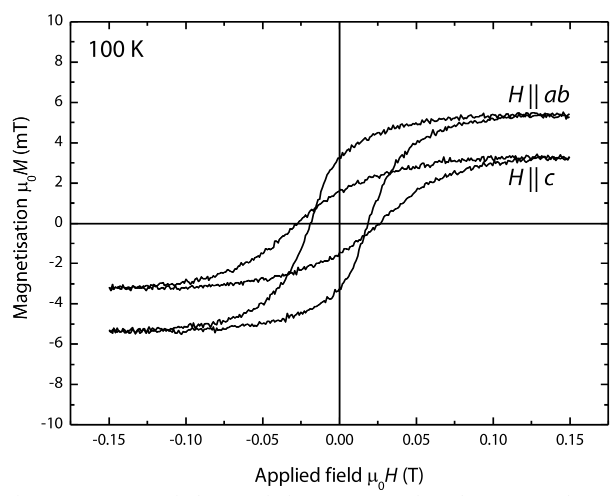

Fig. 1. Ferromagnetic hysteresis loops measured on the 1% sample at 100 K. The ferromagnetic response persists from room temperature down to T_c.

Measurements of the resistive superconducting transitions of the samples (figure 2) reveal a gradual depression of T_c with increasing dopant concentration, from 91 K for the 1% doping to 88 K for the 5% doping. This is likely due to poisoning of the YBCO by incorporation of the dopant material. Nonetheless, at low dopant concentrations, the T_c remains as high as that of the pure YBCO control sample, suggesting that the degree of poisoning in this case is negligible.

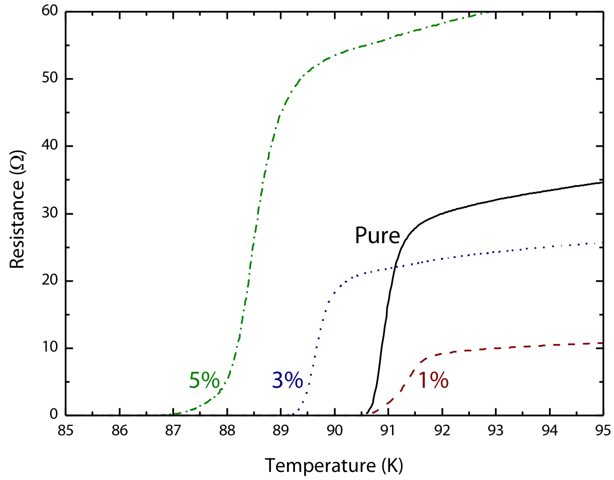

Fig. 2. Resistive superconducting transitions of the series of ferromagnetically doped YBCO samples, compared to the pure control sample.

The transport critical current of the samples was measured as a function of the applied field at 77 K, for fields $H \parallel c$ (figure 3). The self-field J_c of the doped samples was strongly enhanced, reaching a value in excess of 5 $MAcm^{-2}$ in the case of the 1% sample. The 3% and 5% samples exhibited a smaller enhancement in self-field J_c, but their values of around 4 $MAcm^{-2}$ still exceeded that of the pure YBCO at 3 $MAcm^{-2}$. The enhanced J_c persists throughout the entire accessible applied field range except for the highest fields in the more highly doped samples, where the depressed T_c acts to bring down the irreversibility line, causing a more rapid decay in J_c at the higher fields.

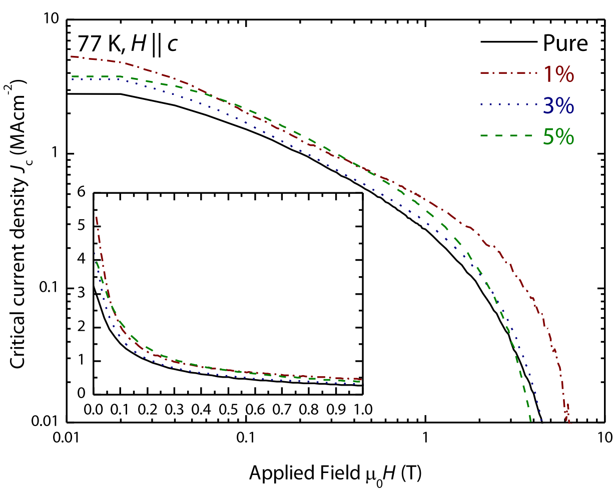

Fig. 3. Field dependence of the transport critical current at 77 K, $H \parallel c$ of the series of ferromagnetically doped YBCO samples, compared to the pure control sample.

Considering the angular dependence of J_c, as measured at 77 K, 1 T (figure 4), where the peak value in the 1% doped sample (for in-plane fields) is in excess of 1 $MAcm^{-2}$, the J_c enhancement of the 1% sample compared to the pure sample

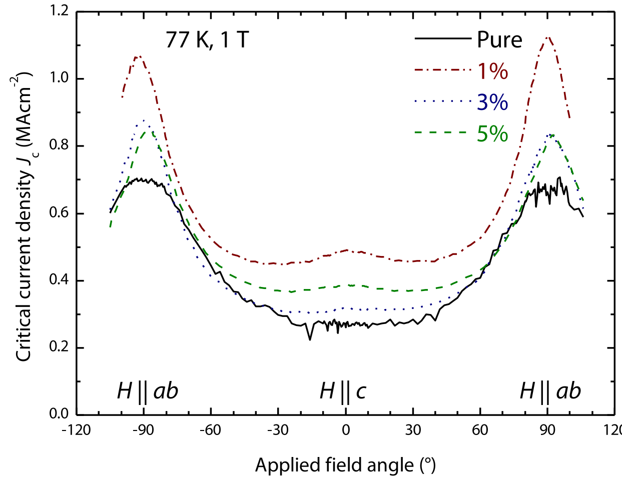

Fig. 4. Angular dependence of the transport critical current at 77 K, 1 T of the series of ferromagnetically doped YBCO samples, compared to the pure control sample.

is seen to be around 1.5 times for all field angles, with the 3% and 5% samples yielding intermediate values.

IV. Conclusions

We have demonstrated an absolute enhancement in the critical current density of a YBCO sample doped with ferromagnetic nanoparticles for all applied fields and field angles, suggesting a random pinning process. Although the form of the enhancement might not be as initially expected for a magnetic pinning process, we have suggested a mechanism by which such an enhancement might arise[4]. The technique lends itself to the possibility of combination with other well-known approaches for directed enhancement of pinning.

Acknowledgment

This work is funded by the UK Engineering and Physical Sciences Research Council as part of the project 'Novel materials nanoengineering for enhanced performance of superconductor coated conductors and functional oxides.'

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