Structure, pinning and supercurrent in YBa$_2$Cu$_3$O$_7$ films and ReBa$_2$Cu$_3$O$_7$ multilayers

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Abstract. High quality YBa$_2$Cu$_3$O$_7$ (YBCO) films and multilayers of ReBa$_2$Cu$_3$O$_7$ superconductors, where Re is rare earth elements (Y and Nd), have been prepared by pulsed laser deposition. Pinning characteristics of the structures obtained have been analysed and attributed to growth conditions and corresponding structural peculiarities. Relatively thick (∼1 µm) multilayers exhibit better performance than mono-layer YBCO films having arbitrary thickness. Differences in the films and multilayers are discussed in terms of their structure homogeneity and defects induced by the growth of the layers.

1. Introduction

An enormous effort has been made to establish a technology for growth of high quality YBa$_2$Cu$_3$O$_7$ (YBCO) films with a single-crystal structure. Various applications demand different forms of the high temperature superconducting (HTS) films in terms of thickness, composition (e.g. multi-layers), properties and performance. In this work, we show that films with relatively large thicknesses ∼1 µm can exhibit electromagnetic and structural properties, which outperform thinner films with “optimal” thicknesses. It is well known that superconducting films generally exhibit the inverse dependency of the critical current density ($J_c$) on their thickness ($d_p$): $J_c \propto 1/d_p$ [1, 2, 3, 4]. This dependence is usually valid starting from a certain optimal thickness. At thicknesses smaller than this optimal thickness, $J_c$ also drops much more rapidly than at larger thicknesses. This $J_c$-$d_p$ relation is slightly technique dependent. For example, in the case of pulsed laser deposition (PLD) the optimal thickness may vary approximately from 50 to 300 nm, depending on a certain set of deposition parameters (e.g. deposition rate) [4]. In any case, the $J_c$-$d_p$ dependence usually has a maximum at the optimal thickness.

It is also well established that the surface roughness and single-crystalline structure of the films degrade as the thickness of the films increases [5]. Gain in smoothening of the surface roughness is minimal for films deposited at slower rates [4, 5].

It has been shown [6, 7, 8] that introducing various multilayered structures with alternating ReBCO superconducting layers, where Re is a rare earth element, can positively influence superconducting performance. However, only relatively thin films < 1 µm have been investigated. No influence on the surface morphology has been shown.

In this work, we show that if YBCO films are deposited in the form of ReBCO multilayers, the film properties are significantly improved in terms of the $J_c(B_a)$ performance, as well as surface roughness and overall homogeneity of the films. In fact, we have found that YBCO/ReBCO
The distance between YBCO target and substrates was about 2 cm. The atmosphere of the chamber was oxygen at 40 Pa. High quality YBCO films and YBCO/NBCO multilayers have been grown by pulsed-laser deposition with the help of FEP Excimer Laser (248 nm) on (100) SrTiO$_3$ substrates in oxygen atmosphere.

2. Experimental Details

High quality YBCO/NBCO multilayers (with Re = Nd-element) of about 1 µm thick can outperform not only YBCO mono-multilayers at the same thickness, but also YBCO films with optimal thicknesses. The arrows point at some hole positions.

![SEM micrographs](image)

Figure 2. SEM micrographs of the surface morphology of (a) a 1 µm thick YBCO film and YBCO films of (b) 0.1 µm, (c) 0.4 µm and (d) 0.1 µm thick. The arrows point at some hole positions.

Figure 1. Critical current density $J_c$ dependence on the film thickness ($d_p$) at 10 K. The dotted line shows a $d_p^{-1}$ fit. The stars show $J_c$ values for the multilayers at 10 K in the corresponding fields (0 T, 0.2 T, 1 T from top to bottom).
Figure 3. Critical current density as a function of applied magnetic field. YBCO mono-layer films of different thicknesses and YBCO/NBCO multilayers grown at different temperatures are shown.
of the films. The resultant surface appears to be very rough. Smoother surfaces are obtained for 0.1 and 0.4 \( \mu m \) YBCO thick films (Fig. 2). Notably, the holes are also visible on the surface of the thinnest (0.1 \( \mu m \)) sample presented, being of a much smaller diameter than for thicker films (the arrows in Fig. 2(d)). By comparison, the multilayer exhibits extremely smooth surface with no sign of the slight “bumpiness”, which is observed for the 0.1 \( \mu m \) film. Only very few droplets and holes (of a smaller diameter than for YBCO films \( > 0.1 \mu m \)) can be seen. The surface structure presented for the multilayers is independent of their deposition temperature range presented in this work.

The \( J_c(B_a) \) dependences for some above-discussed samples are provided in Fig. 3. Two YBCO films: one of nearly optimal thickness of 0.4 \( \mu m \) and the other being 1 \( \mu m \) thick are presented for comparison. The 0.4 \( \mu m \) thick YBCO film shows \( J_c(0) = 3.2 \times 10^{10} \) A/m\(^2\) in self-field at \( T = 77 \) K. Strikingly, the multilayers outperform both YBCO films in the nearly entire field range. The only exception, where \( J_c \) of the 0.4 \( \mu m \) thick film is slightly larger than that for the 1 \( \mu m \) multilayer film, is for \( B_a < 0.3 \) T at \( T = 77 \) K.

The effect of larger surface supercurrent contribution compared to the bulk supercurrents, producing larger overall \( J_c \) in the thinner films [9] is expected to be stronger at lower temperatures, which contradicts to our observations. Therefore, we presume that the effect in the multilayers is twofold. On one hand, the filling factor determined from SEM observation is about 10 to 18\% larger than for YBCO films, which produces the higher \( J_c \) at low fields. On the other hand, due to different ionic radii of Y and Nd, YBCO and NdBCO systems have a mismatch between crystal lattice parameters. This results in additional stress near the YBCO/NdBCO interfaces, leading to formation of additional pinning sites, which, in turn, enhance \( J_c \) at large fields (\( > 0.5 \) T).

4. Conclusion
The YBCO/NdBCO multilayers of 1 \( \mu m \) thick have been shown to outperform YBCO monolayer films with any thickness \( \leq 1 \mu m \) in terms of \( J_c(B_a) \) dependence. Possible reasons for the observed performance are a larger filling factor (less holes, smooth surface) and more defects created in the multilayers due to the additional stress induced near the interfaces of YBCO and NdBCO layers as a result of their crystal lattice mismatch.

5. Acknowledgments
We would like to thank R. Kinnel for valuable technical assistance. This work was financially supported by the Australian Research Council.

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