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Structure, pinning and supercurrent in $YBa_2Cu_3O_7$ films and $ReBa_2Cu_3O_7$ multilayers

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Abstract. High quality $YBa_2Cu_3O_7$ (YBCO) films and multilayers of $ReBa_2Cu_3O_7$ 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 ($\sim 1\ \mu$m) 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 $YBa_2Cu_3O_7$ (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 $\sim 1\ \mu$m 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 $< 1\,\mu$m 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

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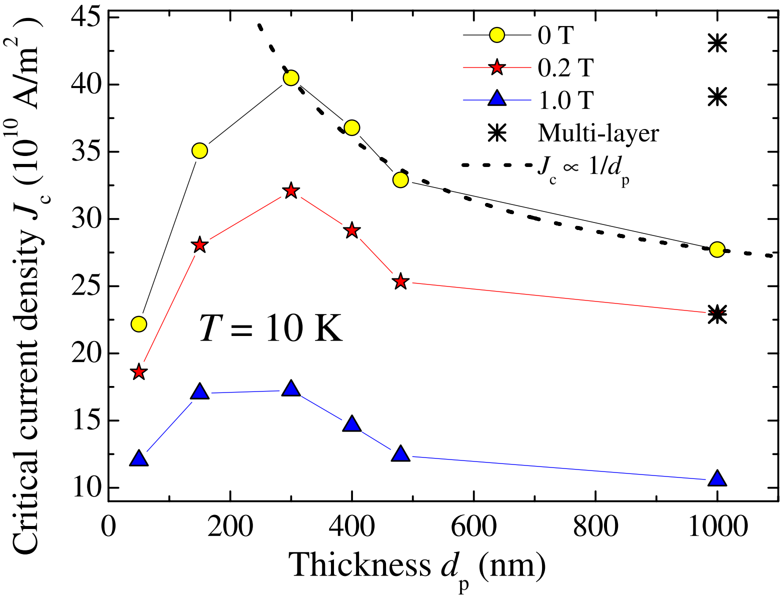

Figure 1. J_c dependence on the film thickness (d_p) at 10 K. The dotted line shows a $J_c \propto d_p^{-1}$ fit. The stars show J_c values for the multi-layers at 10 K in the corresponding fields (0 T, 0.2 T and 1 T from top to bottom).

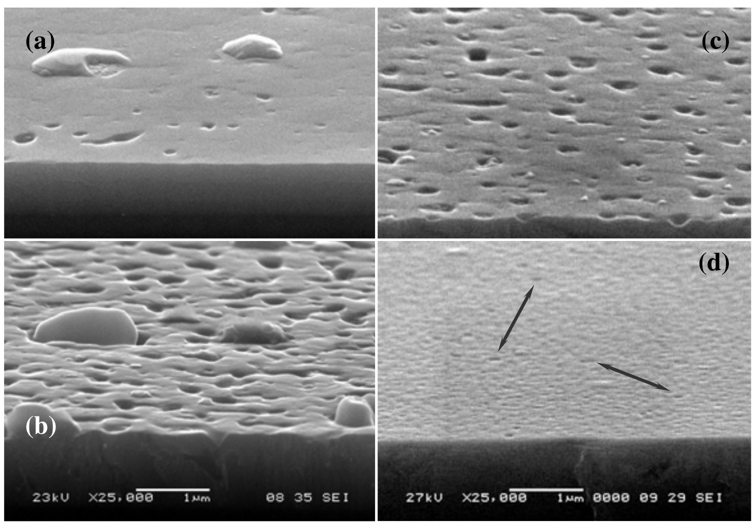

Figure 2. SEM micrographs of the surface morphology of (a) a 1 μm thick YBCO/NBCO multi-layer; and YBCO films of (b) 1 μm, (c) 0.4 μm and (d) 0.1 μm thick. The arrows point at some hole positions.

multilayers (with Re = Nd-element) of about 1 μm thick can outperform not only YBCO mono-layer films of the similar thickness, but also YBCO films with optimal thicknesses.

2. Experimental Details

High quality YBCO films and YBCO/NBCO multilayers have been grown by pulsed-laser deposition with the help of KrF Excimer Laser (248 nm) on (100) $SrTiO_3$ substrates in oxygen atmosphere of 40 Pa. The distance between YBCO target and substrates was about 5 cm. The

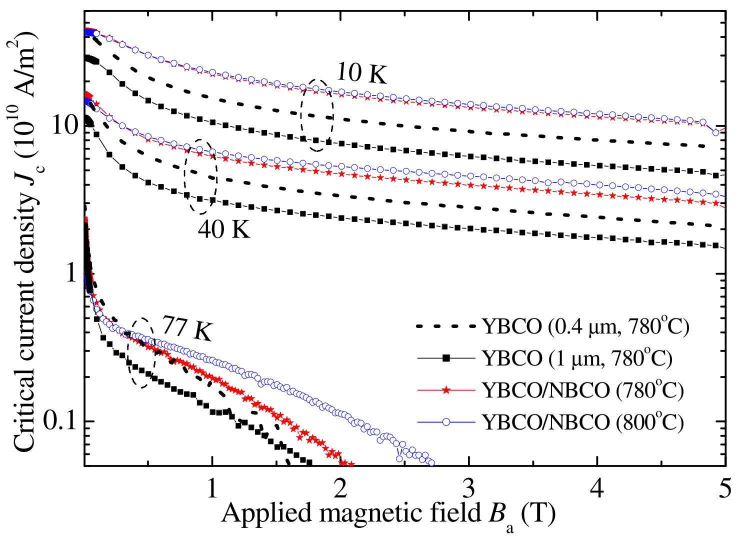

Figure 3. Critical current density as a function of applied magnetic field. YBCO mono-layer films of different thicknesses and YBCO/NBCO multilayers grown at different temperatures are shown.

optimal deposition temperature (at which the highest $J_c(0, 77\,\mathrm{K})$ is obtained) for the YBCO films was found to be 780°C. The optimal thickness (with the same criterion as for deposition temperature) was found to vary from 0.15 to 0.4 μm Fig. 1. Our main interest was to improve characteristics of thicker YBCO films of about 1 μm thick by introducing alternating layered structure. Therefore, we have prepared a series of YBCO/NBCO multilayers with the resultant thickness equal to the thickness of 1 μm thick YBCO film. The multilayered structure considered in this work is as follows. A 300 nm thick YBCO layer is deposited directly on the substrate, then a 50 nm thick NBCO film is deposited, followed by a 300 nm YBCO layer, a 50 nm NBCO, and a 300 nm YBCO layers. The optimal deposition temperature for NBCO films was established to be about 50°C higher than that for YBCO films. Therefore, we varied the deposition temperature to find the optimal, compromising temperature for the entire multilayered structure [4]. The critical temperature (T_c) of YBCO films is of about 89.6 K. The multi-layers presented in this work have $T_c = 89.3$ K.

The surfaces of the films have been observed by scanning electron microscopy (SEM) at a rather small angle ($\sim 10°$ to $20°$) to the surface plane. Electromagnetic properties of the films have been investigated by magnetization measurements over a wide applied field ($|B_a| \leq 5$ T) and temperature (5 K $\leq T \leq$ 95 K) ranges. The DC magnetic field was applied always perpendicular to the film plane. $J_c(B_a, T)$ dependences have been obtained from the width of the magnetization loops, using the critical state model: $J_c = 2\Delta M/[w_p(1 - w_p/3l_p)]$ in A/m^2, where $\Delta M = |M^+| + |M^-|$ taken from magnetization loops measured at different temperatures versus the applied field, w_p and l_p are respectively width and length of the films measured.

3. Results and Discussions

In Fig. 2, we show the surfaces of a 1 μm thick YBCO/NBCO multi-layer, as well as YBCO films having thicknesses of 1 μm, 0.4 μm and 0.1 μm. It is obvious that the multilayer exhibits a much smoother surface that the YBCO film with the same thickness (1 μm). The YBCO film is covered with holes characteristic for the spiral growth of this composition. The holes (~ 0.2 μm diameter) and corresponding structural inhomogenities extend throughout the entire thickness of the film. In addition, some droplets up to 1 μm large can be found on the surface of the films. The resultant surface appears to be very rough. Smoother surfaces are obtained for 0.1 and 0.4 μm YBCO thick films (Fig. 2). Notably, the holes are also visible on the surface of the thinnest (0.1 μm) 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 μm film. Only very few droplets and holes (of a smaller diameter than for YBCO films > 0.1 μm thick) 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 μm and the other being 1 μm thick are presented for comparison. The 0.4 μm 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 μm thick film is slightly larger than that for the 1 μm 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/NBCO multilayers of 1 μm 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.

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