The Role of Multilayering in the Significant Improvement of Structural and Superconducting Properties in High-T_c Films

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By introducing multilayered structures to $YBa_2Cu_3O_7$ (YBCO) films, significant improvement of superconducting and structural properties in the obtained multilayers has been obtained. A sandwich-like system with three main YBCO layers of ~300 nm thick and two additional NdBCO layers of about ~50 nm thick in between the YBCO layers exhibits much smoother surface compared to the YBCO films of the same thickness. It has critical current density (J_c) which is not only significantly larger (by a factor > 3) than that obtained in YBCO films with the same thickness (1 μm), but also larger than J_c in mono-layer YBCO films of any smaller thickness. The J_c enhancement is observed in both low field and high field regions, which attributed to a larger filling factor of the multilayer, better grain alignment and additional formation of dislocations at the interfaces between the layers.

1. Introduction

A tremendous attention has been paid for establishing a technology for growth of high quality YBaCuO films (and coatings) with a single-crystal structure. In the case of coated conductors (so-called the second generation of high-temperature superconducting wires), the ultimate goal is to obtain YBCO coatings with high total critical current $I_c = J_cA$, where $A = w_pd_p$ is the area through which current flows, w_p is the width, d_p is the thickness of the YBCO coating. The critical current density (J_c) of high quality YBCO films is very high, reaching about $0.3J_0$, where J_0 is the depairing current density. This makes it very difficult for further enhancement. A larger width is not technologically favourable. Therefore, the easiest approach would be to increase the thickness of the layers. However, superconducting films generally exhibit the following J_c dependence as a function of thickness: $J_c \propto 1/d_p$ [1-4]. In this work, we show that films with relatively large thicknesses ~1-2 μm can exhibit electromagnetic and structural properties, which outperform thinner films with "optimal" thicknesses, which is defined at the thickness with the maximum J_c at zero applied magnetic field (B_a). This dependence is usually technique, as well as measurement condition dependent [4]. For example, in the case of pulsed laser deposition the optimal thickness could vary from 100 to 400 nm, depending on a certain set of deposition parameters. In addition, the surface roughness and single-crystalline structure of the films degrade as the thickness of the films increases [4,5].

Introducing various multi-layered structure to the ReBCO superconducting films, where Re is a rare earth element, can positively influence superconducting performance [6-8]. However, only relatively thin films < 1 μm or non-superconducting intermediate layers have been investigated. No influence on the surface morphology has been shown.

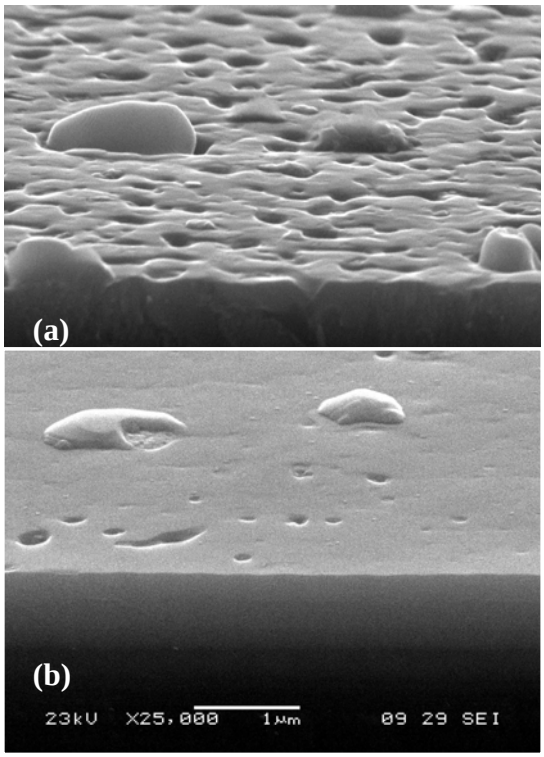

Fig. 1. SEM micrographs of the surface morphology of (a) a 1 μm thick YBCO film and (b) a YBCO/NdBCO multi-layer with a similar thickness.

In this work, we show that if YBCO films are deposited in the form of (Y/Nd)BCO multi-layers, the properties of such structure are significantly improved in terms of the $J_c(B_a)$ performance, as well as surface roughness and overall evenness of the films. In fact, we have found that the multilayers of about 1 μm thick can outperform not only YBCO mono-layer films of the similar thickness, but also mono-layer YBCO films having the optimal thickness.

2. Experimental details

High quality YBCO films and YBCO/NdBCO multilayers have been grown by pulsed-laser deposition (PLD) 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 optimal deposition temperature (at which the highest J_c(0, 77 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 0.25 to 0.4 μm [4]. 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/NdBCO multi-layers with three 100 to 300 mn thick layers of YBCO and two 25 to 50 mn thick intermediate NdBCO layers. The optimal deposition temperature for NdBCO 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 multi-layered structure. The critical temperature (T_c) for both YBCO films and the multilayers varies slightly from 89.1 to 91.5 K.

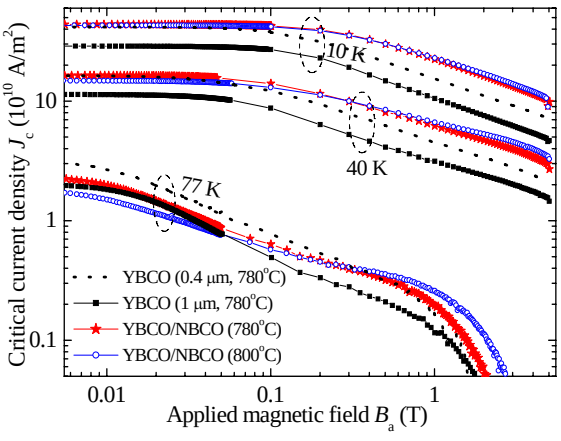

Fig. 2. Critical current density as a function of applied magnetic field. YBCO mono-layer films of different thicknesses and YBCO/NdBCO multi-layers grown at different temperatures are shown.

The surfaces of the films have been observed by scanning electron microscopy (SEM). The interfaces between the layers have been investigated with the help of Rutherford Backscattering Spectroscopy (RBS) technique. Electromagnetic properties of the films have been investigated by magnetization measurements at different fields and temperatures. 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 ΔM taken from magnetization loops measured at different temperatures versus the applied field, l_p is the length of the films measured.

3. Results and discussion

In Fig. 1, we show the surfaces of a YBCO film and a YBCO/NdBCO multi-layer for 1 μm thick samples with 300/50/300/50/300 nm layer thicknesses, i.e. NdBCo comprises 10% of the entire film. The multi-layer exhibits a much smoother surface that the YBCO film. The YBCO film is covered with holes characteristic for the spiral growth of this composition. The holes (~0.2 μm diameter) and corresponding structural inhomogenity 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. In contrast, the multilayers exhibit extremely smooth surfaces with only very few (smaller diameter) holes and much fewer number of droplets. The improved surface could result from local defect (dislocation) formation and corresponding strain release of the overall crystal structure in the multilayers. The surface structure presented has been nearly independent of deposition temperature range and layer thicknesses presented in this paper.

The analysis of the RBS results suggests that the surface roughness improves from the bottom to the top layers. The roughest interface is estimated for the first interface between the substrate and the YBCO layer, the smoothest for the surface. Therefore, the interchanging of the layers removes the crystal lattice stress gradually, improving the structural order.

The $J_c(B_a)$ dependences for the above-discussed samples are provided in Fig. 2. Two YBCO films of optimal (0.4 μm) and 1 μm thick are presented for comparison. The 0.4 μm thick YBCO film shows $J_c(0) = 3.2\times10^{10}$ A/m^2 in zero-field at $T = 77$ K. Strikingly, the multi-layers outperform both YBCO films in the nearly entire field range. The only obvious exception, where J_c of the 0.4 μm thick film is slightly larger than that for the 1 μm multi-layers film, is for $B_a < 0.3$ T at $T = 77$ K. The faster J_c degradation with increasing T is due to non-optimal deposition temperature for NdBCO, whose superconductivity, hence, weakens with increasing T [9]. The significant enhancement of J_c (i) at higher fields can imply that more dislocations are created in the multilayers due to the additional stress induced at the interfaces between YBCO and NdBCO layers as a result of their crystal lattice mismatch; (ii) at lower fields - a larger filling factor (less holes, smoother surface).

Acknowledgments

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