Influence of thickness and deposition rate on superconducting properties of $YBa_2Cu_3O_7$ films

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High temperature superconducting $YBa_2Cu_3O_7$ films with various thicknesses have been prepared by pulsed laser deposition method with different deposition rates. The thickness dependence of critical current density J_c evolves with magnetic field, temperature and deposition rate. Changes in J_c behaviour observed are explained on the basis of monitoring the surface morphology transformation for samples with different thicknesses. The surface microstructure is shown to degrade significantly with increasing thickness.

1. Introduction

High temperature superconductor (HTS) wires, so-called coated conductors, exhibit the best opportunity to improve the electric power grids, motors, generators, transportation and many other industries, with a new generation of highly efficient, compact and environmentally friendly wires and corresponding electrical equipment. $YBa_2Cu_3O_7$ (YBCO) superconducting films (the current-carrying component of the coated conductors) generally exhibit the inverse dependence of the critical current density J_c on their thickness (d_p) measured at zero applied field and most often at 77 K [1-3]. However, there is no comprehensive analysis of critical current density as a function of d_p at different temperatures and magnetic fields. This analysis may shed light on particular pinning mechanism leading to the d_p^{-1} dependence of J_c in the films, since vortex pinning is strongly affected by temperature and magnetic field. In this work, we show that YBCO films obtained by pulsed laser deposition (PLD) exhibit a maximum J_c at a certain optimal thickness. This optimal thickness range migrates to larger thicknesses as applied magnetic field and temperature increase. We discuss reasons leading to this behaviour.

2. Experiment

YBCO thin films were deposited on $SrTiO_3$ substrates using the pulsed laser deposition (PLD) technique with a KrF excimer laser having the wave-length of 248 nm. Two series of YBCO thin films having different thicknesses deposited at different deposition rates (2 Hz and 6 Hz) were prepared with identical conditions. The thickness of the films investigated has been varied form 50nm to 2 μm. The thickness has been accurately verified by scanning electron microscopy (SEM) for every sample. The substrate-to-target distance was fixed at 46 mm. During deposition the substrate temperature and oxygen pressure were 780° C and 300 mbar, respectively. The $J_c(B_a)$ curves were obtained from magnetization hysteresis loops measured by a Quantum Design MPMS SQUID magnetometer.

3. Results and discussion

Fig. 1 shows the influence of the deposition rate and the film thickness on the surface microstructure of the YBCO films. Both sets of the films exhibit that the surface roughness and the number of holes increases as their thickness is enlarged. The films deposited at the lower rate (2 Hz) have more holes than the films deposited at 6 Hz rate. Moreover, the average diameter of the holes in 2 Hz films is approximately by a factor of 1.5 larger than that for 6 Hz films (200 nm and 300 nm, respectively).

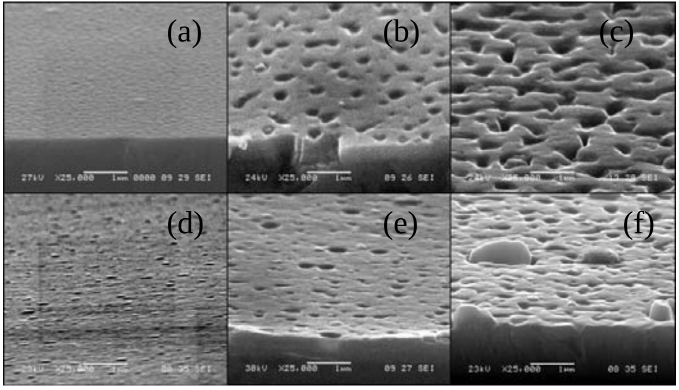

Fig. 1 SEM images of the surface morphology for YBCO films deposited at 2 Hz with thicknesses: (a) 100nm, (b) 345nm, (c) 1820nm and at 6 Hz with thicknesses (d) 50nm, (e) 480nm, (f) 1000nm.

Generally, the holes result from incomplete coalescence of the films [4]. In our case, the incomplete coalescence is the most pronounced in thick (>300 nm) 2 Hz films due to a slower, ordered growth mode. This implies that the larger holes (rougher surface) would create larger obstacles to current flow in the upper layers of YBCO, decreasing the effective cross-sectional area and thus lowering the total J_c [3]. Moreover, in the thickest films deposited at 2 Hz (Fig.1(c)), the holes combine, forming extended valleys. This indicates a strongly percolated current flow in the upper layers of the films, in contrast to the lower layers, which exhibit rather continuous and smooth structure (Fig. 1(a)).

Figs. 2 and 3 present $J_c(T,B_a)$ dependence as a function of the thickness for the films deposited at 2 and 6 Hz deposition rate, respectively. The curves are presented for different applied fields from 0 to 5 T. For films deposited at 2 Hz (Fig.2), the common $1/d_p$-like trend is modified at 40 K and 77 K at high fields (> 1 T and 0.1 T, respectively). In contrast, for the fast deposition rate (Fig. 3), $J_c(d_p)$ is notably modified only at 77 K and 0.05 T. Generally, the modifications exhibit the shift of the optimal thickness towards thicker films. This implies that films with intermediate thicknesses have stronger pinning properties at larger fields and higher temperatures. Presumably, these films have a larger defect number with the slightly larger dimensions to accommodate for the vortex diameter ($2\xi(T)$) increase with temperature. This shift of the optimal thickness is more pronounced for 2 Hz deposited films, indicating generally weaker pinning for films deposited at the slower rate. It is also important to note that the large holes >> $2\xi(T)$ observed in thick films cannot pin vortices effectively.

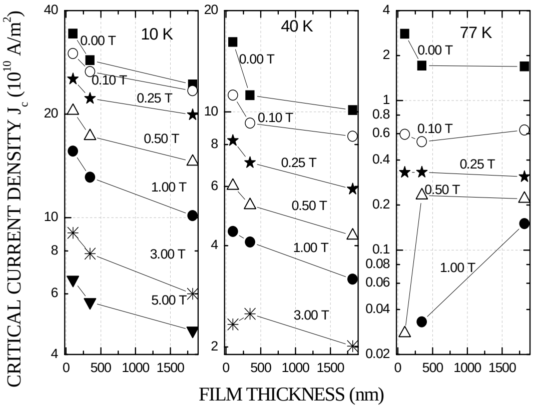

Fig. 2 $J_c(d_p)$ dependencies at different fields and temperatures for YBCO films deposited at 2Hz.

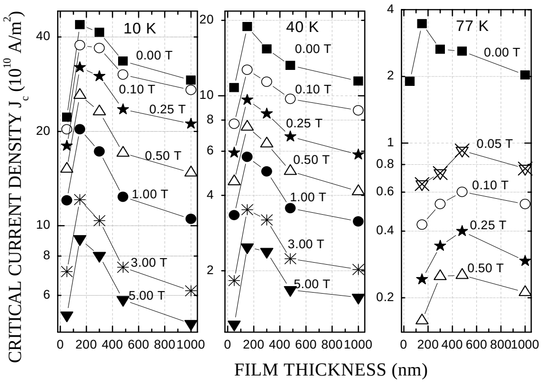

Fig. 3. $J_c(d_p)$ dependencies at different fields and temperatures for YBCO films deposited at 6Hz.

The comparison of the $J_c(T,B_a)$ curves for two films of the optimal thickness (~ 300 nm) deposited at the different rates is shown in Fig. 4. J_c is larger for the 6 Hz deposited samples over the entire field range, which again can be explained by a larger number of defects created in the 6 Hz film. A similar behaviour is observed for the thickest samples investigated. However the difference between the curves at large fields diminishes, which indicates a lesser difference between pinning defects in thick films. At small fields, at which largest currents flow through the films, the 6 Hz film has still larger J_c values. This could be due to smaller percolation in the upper layers in agreement with Fig. 1 and, accordingly, a larger effective cross section for the current flow in the 6 Hz films. In contrast, the behaviour at smallest measured thicknesses (< 100 nm) changes qualitatively. J_c at small fields is larger for the 2 Hz films (Figs. 2 and 3). Apparently, the percolation and effective cross section have negligible influence on the current-carrying capacity of the films at these thicknesses. However, the more ordered crystal structure, formed for the slowly deposited films, has fewer defects, so that quasi-particles are scattered to a lesser degree, rendering larger transparency of the structure than in the 6 Hz film. Hence, larger currents can be achieved for the slowly deposited films especially in small fields.

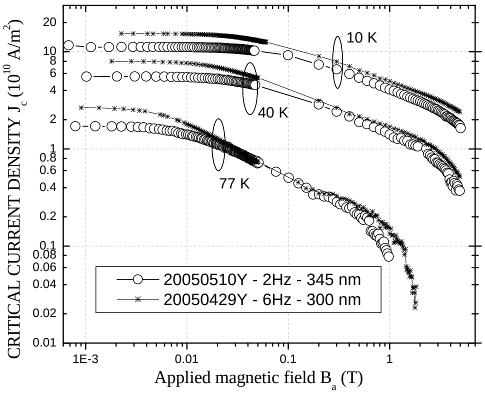

Fig. 4. $J_c(T,B_a)$ dependencies for two samples deposited at 2Hz and 6Hz.

The features of the J_c behaviour observed are in general consistent with pinning in YBCO films on out-of-plane dislocations (dominantly edge dislocations) which form at the film-substrate interface due to the crystal-lattice mismatch between them [5]. The structure degradation with increasing thickness indicates that the influence of dislocation for large thicknesses reduces only slightly. On the other hand, the upper layers of the film, starting from about 600 nm thickness, are shown to not considerably influence the vortex pinning mechanism in the films, in spite of the significant structural changes observed. Indeed, the optimal film thickness with the largest J_c is varying from ~50 to 600 nm. The role of the upper layers in the current-carrying capacity can be considered from the point of view of how quickly it deteriorates, so that the increase in the total cross section of the films (in order to increase the total I_c) is counteracted by the microstructure deterioration, reducing the effective cross section. In addition, the thickness behaviour observed points out at the important role of the structural transparency for the current flow in the films [6], which is in particular pronounced for low fields and large currents.

In conclusion, the J_c behavior variation in films of different thicknesses grown with different speeds is explained by changing (degrading) microstructure from the bottom layers to the top ones. The vortex pinning is shown to be governed in films of arbitrary thicknesses mainly by the layers which are situated below about 600 nm. In the thicker films, J_c is mostly affected by the competition between microstructure degradation and the enlargement of the effective cross section for the current flow.

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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