Critical Current of Superconducting $YBa_2Cu_3O_{7-\delta}$ Films With Different In-Plane Orientations

P. A. Lin, C. C. Chi, and B. Rosenstein

***Abstract*—By using a pulsed-laser deposition (PLD) technique, we grow high quality $YBa_2Cu_3O_{7-\delta}$ films on YSZ (Yt-stabilized Zr) substrates with 0-degree and 45-degree in-plane orientations at 810 °C and 690 °C respectively. Surprisingly, despite the large difference in growth temperature the qualities of the films are almost the same. To study the subtle differences between these two types of films, we measured both the temperature and magnetic field dependencies of the critical current. Although there is very little difference in their magnetic field dependence, there is a distinct temperature dependence, i. e. $J_c(1 - T/T_c)$ proportional to $(1 - T/T_c)^{5/4}$ for 0 degree in-plane orientation and proportional to $(1 - T/T_c)^{3/2}$ for 45 degree in-plane orientation at temperatures near T_c. We also studied the critical current densities with different fractions of mixed orientations, and found an empirical formula $J_c \propto e^{5\alpha}$ where α is the fraction of the majority domain.**

***Index Terms*—In-plane orientations, low angle grain boundaries, vortex.**

I. Introduction

SINCE THE discovery of high T_c superconductors, the critical current density has become an important issue for both basic research and device applications. It has been found that the critical current density is mainly controlled by the pinning of the Abrikosov vortices and material inhomogeneities [1], [2].

It was discovered early on that the pinning of vortices in thin epitaxial films is much stronger than that of single crystals. After many years of research, it has become clear that this difference between films and single crystals is due to the existence of extended c-oriented linear defects, such as dislocations, which are present in great numbers in films but not in single crystals [3]–[6].

On the other hand, it is well known that the critical current density also depends on the grain boundary structures [2]. The defect structure is reflected in temperature, magnetic field and angle dependence of the critical current dependencies.

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The temperature dependence in the vicinity of T_c obeys the relation $J_c(T) \sim (1-t)^\beta$, where $t = T/T_c$. This type of $J_c(T)$ temperature dependence can follow from models of different kinds: e.g., vortex depinning models of different sort, as well as models of electron transparency of grain boundaries providing a range of values of from 1 to 2 [1], [7], [8].

The theoretical models based on the superconductor-normal metal-superconductor(SNS),superconductor-insulator-superconductor(SIS),and superconductor-normal-insulator-superconductor (SNIS) give $\beta = 2, 1\ 3/2$ respectively. The last value was often observed experimentally for high T_c films [9], [10]. The value of $\beta = 5/4$ was also observed by Fedotov *et al.* [9]. The same group (the Kiev group) provided a theoretical model, based on a specific consideration of grain boundary electron transparency, to derive this β value [10], [11]. This model supposes a high J_c value ($> 10^6$ A/cm^2 at 77 K) for the quasi-single-crystalline YBCO films. The low-angle grain boundaries for this case are considered ordered rows of c-oriented edge dislocations (dislocation walls).

The magnetic field dependence of critical current density can be characterized by two main features, namely: plateau at low fields (H $\leq$ about 100 G) and subsequent drop at higher fields, which may be described approximately as $H^{-1/2}$ [10], [11]. At high fields this drop of j_c with H becomes stronger as shown by the experiments of the Kiev group [10], [11] as well as from the work of the Holland group [12]–[14].

There are many published reports on the temperature, magnetic field and angle dependence of the critical current dependencies. Almost of all these studies are based on $YB_2Cu_3O_{7-\delta}$(YBCO) thin films grown on matching substrates such as STO (3.83 A°).

In our group, we fabricated YBCO thin films on YSZ (5.14 A°), which has high misfits at about 6%. Although the mismatch is large, we can obtain two different pure in-plane orientations. Despite the difference of the in-plane orientations, the T_C and J_C of the two kinds of thin films are almost the same. The critical temperature (onset) was about $T_c^{onset} = 91$ K and the critical current density about $J_c = 4 \times 10^6$ Acm^{-2} at 77 K [14]. Using the AFM technique, it was established that there were many low angle grain boundaries formed when the films were grown.

For this paper we studied the YBCO films with magnetic fields perpendicular to the thin films surface, finding the temperature and magnetic field dependence of critical current density [12]–[19].We found the exponent $\beta = 5/4$ to be consistent with the results of the Kiev group. In addition, we studied the dependence of the critical current density on different mixed orientations of the film and found an empirical formula to describe the data.

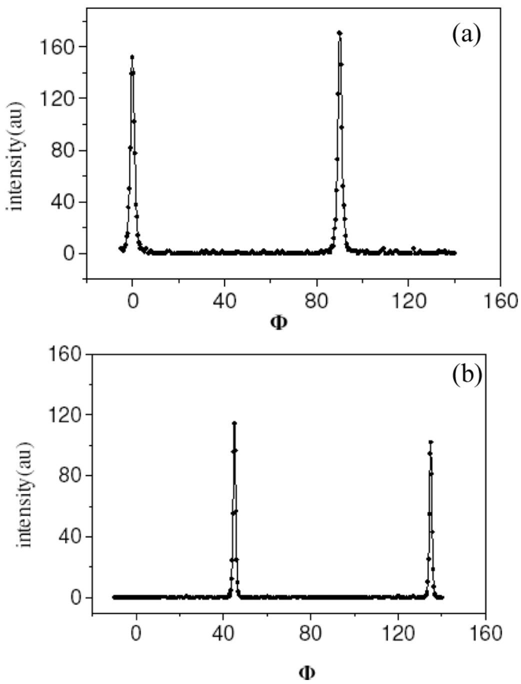

Fig. 1. (a) The film deposited on YSZ substrate at temperature 810 °C with pure 0-degree orientation; (b) the film deposited on YSZ substrate at temperature 690 °C with pure 45-degree orientation.

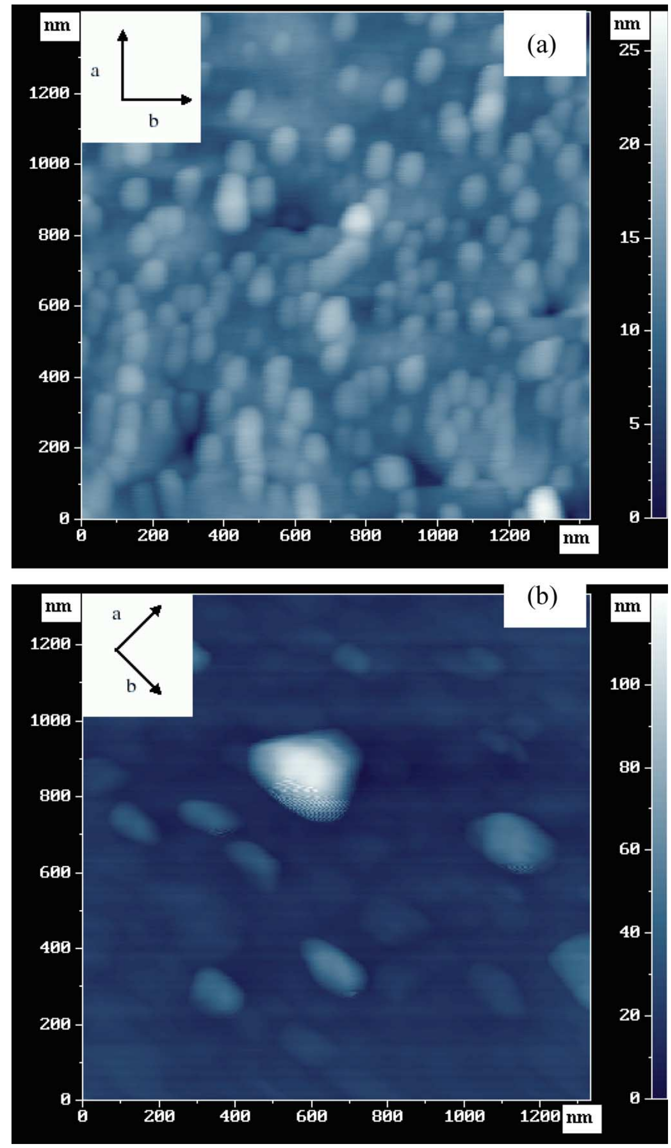

Fig. 2. (a) The surface structure of 0-degree orientation; (b) surface structure of 45-degree orientation from AFM.

II. Structural Properties of 0-Degree and 45-Degree In-Plane Orientation YBCO Films

A Lamda Physik LPX 100 excimer laser with pulse width of 30 ns wavelength of 248 nm was used to grow the YBCO thin films on YSZ [14], [15]. We varied laser energy density, oxygen pressure, and the distance between target and holder to optimize the YBCO superconducting properties on YSZ substrates. We found that the optimized conditions are roughly independent of deposition temperatures [16]–[19].

We obtained pure 0-degree in-plane orientation films grown at 810 °C and pure 45-degree in-plane orientation films grown at 690 °C. All other parameters were fixed at their optimized values, with the oxygen pressure at 320 mTorr, the distance between target and holder at 39 mm, and laser energy density at 1.5 J cm^{-2}. In the temperature range of 690 °C to 810 °C, we can grow films with different proportions of orientations. In this temperature region, all films are c-axis films [19].

A. X-Ray Characterization of the 0-Degree and 45-Degree In-Plane Orientations of the YBCO Films

To characterize the different in-plane orientations between YBCO and YSZ, we detected peaks of YBCO {103} YSZ {202} by using a four-circle x-ray diffractometer with Cu $K\alpha$ source. We first detected YSZ {202} peak, and used it as a reference point of the Φ-scan for YBCO {103} as shown Fig. 1. We observed purely 0-degree orientation of the film with respect to the substrate at 810 °C and the 45-degree orientation at 690 °C.

B. Surface Properties of 0-Degree and 45-Degree In-Plane Orientations of the YBCO Films

We also studied the surface structure of the films by using AFM and SEM. The AFM pictures of thin films, i.e. 50 nm, show the individual grains much more clearly. Figs. 2(a) and 2(b) show that the grain orientations of the 0-degree oriented film and of the 45-degree oriented film are consistent with the X-ray Φ-scan data of the previous subsection. The SEM pictures show the films are generally smooth except for a few adhered particles. Typical examples of the 300 nm films are shown in Figs. 3(a) and 3(b) for the 0-degree oriented film and the 45-degree oriented film respectively.

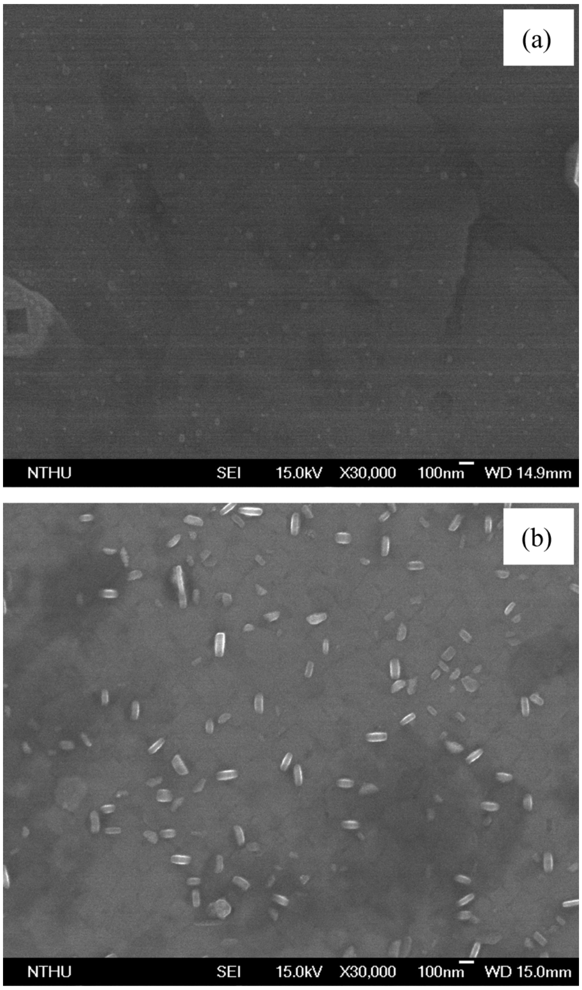

Fig. 3. (a) The surface structure of 0-degree orientation; (b) the surface structure of 45-degree orientation from SEM.

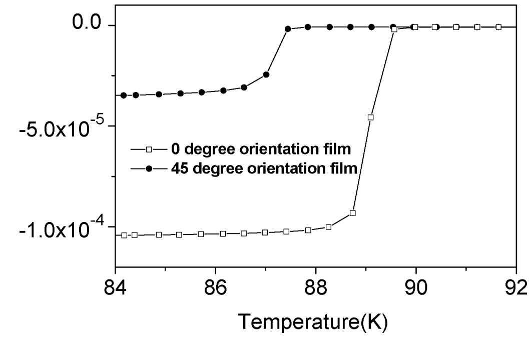

Fig. 4. The M-T diagram of 0 and 45 degree orientation film.

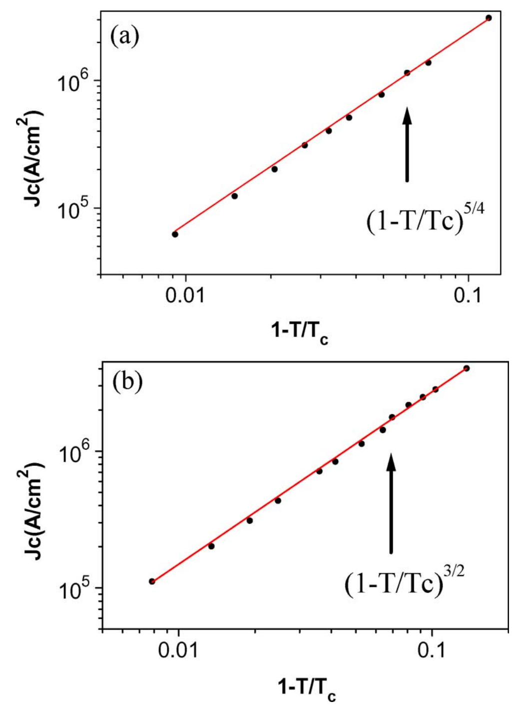

Fig. 5. (a) The temperature dependence near Tc for 0 degree orientation; (b) the temperature dependence near Tc for 45 degree orientation.

III. Critical Current Density Properties of 0-Degree and 45-Degree In-Plane Orientations of the YBCO Films

A. Determination of T_c

Using the (SQUID) Superconducting Quantum Device Interference Magnetometer, we deduced T_c from the M-T curve obtained by applying a 0.1 Gauss field (Fig. 4). Since thermal fluctuation in YBCO is relatively small, sufficient precision (0.1 K) was achieved at the onset of negative magnetization. These procedures resulted in Tc values of 89.2±0.1 K in the pure 0-degree orientation and 87±0.1 K in 45-degree orientation. The M-T curve for the 0-degree film is sharper than that for the 45-degree film. It implies that the coupling between aligned gains for the former is stronger.

B. Temperature Dependence

We used the SQUID Magnetometer to obtain the M-H curves and Bean's model [27]–[29] to estimate J_c for different temperatures. The thicknesses of the films used are about 300 nm. The temperature dependence of J_c is shown in Figs. 5(a) and 5(b). We fitted the data using $J_c = J_{co}(1-t)\beta, t = T/T_c$ [10], [11]. For the pure 0-degree orientation $(T_c = 89.2 \pm 0.1\ K)$ we found a β value of 5/4 and a J_{co} value of $4.94 \pm 004 \times 10^7\ Acm^{-2}$ in the region of $1 - t \leqq 0.12$. For the 45-degree orientation $(T_c = 87 \pm 0.1\ K)$, we found that the dependence is fitted best with $\beta = 3/2$ and $J_{co} = 4.9 \pm 0.3 \times 10^6\ Acm^{-2}$ in the range of $0.01 \leqq 1 - T/T_c \leqq 0.12$,. High precision of T_c is required for the demonstration of the power law behavior.

C. Magnetic Field Dependence

The magnetic field dependence in the intermediate range of 100 G (of order of Hc1) to 2 kG can be described by the single parameter formula [30]:

$$J_c = J_o e^{-H/H^*} \tag{1}$$

J_o is the critical current at zero magnetic field. This is demonstrated for the 0 degree domain orientation in Figs. 6(a) and 6(b) for temperatures $T/T_c = 0.73$ and 0.86 respectively. Similarly, magnetic field dependence of the critical current for the 45 degree oriented sample is shown in Figs. 7(a) and 7(b) for temperatures $T/T_c = 0.74$ and 0.87 respectively. One observes that

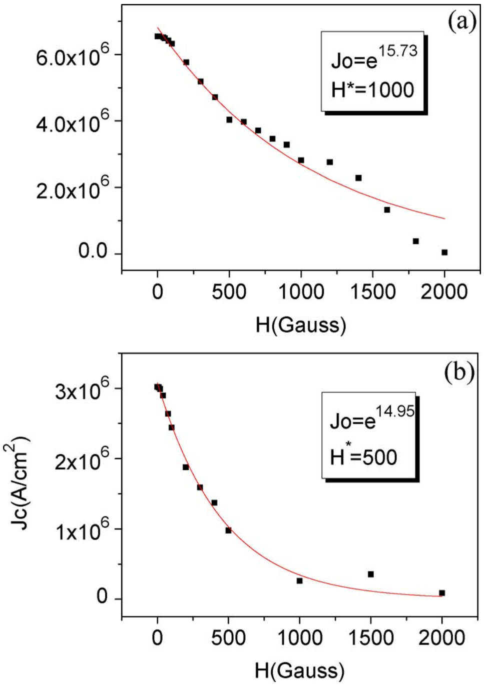

Fig. 6. The magnetic field dependence of 0 degree orientation at (a) $T/Tc = 0.73$ and (b) $T/Tc = 0.86$ respectively.

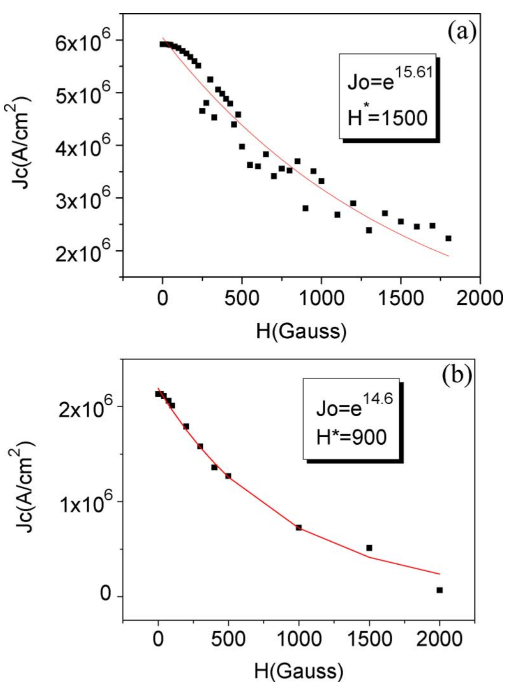

Fig. 7. The magnetic field dependence of 45 degree orientation at (a) $T/Tc = 0.74$ and (b) $T/Tc = 0.87$ respectively.

the value of the field H^* is rather insensitive to the domain orientation but increases with temperature.

IV. Critical Current With Different Mixed Orientations at 5 K

We studied the critical current for different orientation mixtures by deviating the deposition parameters from their optimized conditions [20]–[25]. A four-circle x-ray diffractometer

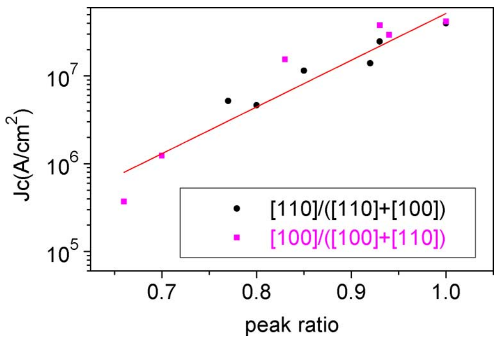

Fig. 8. The Jc with different in-plane orientations.

with a Cu Kα source was used to detect the YBCO {103} and YSZ {202} and distinguish different in-plane orientations. We used the peak height to define the ratio of the two domains. Fig. 8 shows that an empirical formula $Jc \propto e^{5\alpha}$, where α is the fraction of the majority domain, describes our data reasonably well.

V. Discussion and Conclusion

A. Temperature Dependence 0-Degree and 45-Degree In-Plane Orientations

In our experiments, we found that $J_c \sim (T_c - T)^{5/4}$ in the pure 0-degree orientation, and $J_c \sim (1 - T_c/T)^{3/2}$ in the pure 45-degree orientation. The only obvious difference between these two kinds of films is the surface structure, which might be related to the coupling between grains. Figs. 2 and 3 provide evidence that the 0-degree orientation is smoother than the 45-degree orientation.

The exponent in the 0-degree orientation sample is 5/4, right in Several unanswered questions remain. It is not clear why between the predicted values of the SIS and the SNIS models. In the case of the pure 45-degree orientation, one can infer that it is likely to be the SNIS contact.

The experimental data were obtained from magnetization measurements and the critical state model was used in order to extract the J_c value. Generally, such a procedure is applied at low temperatures. Thus, it is not clear that the critical state model is really applicable at high temperatures because of the rather low activation energy values and correspondingly high creep rates as T approaches T_c.

B. Magnetic Field Dependence of 0-Degree and 45-Degree In-Plane Orientations

Concerning the magnetic field dependence of the critical current, the generally accepted simple theoretical expectation [1], [12] is that the electromagnetic vortex-vortex interactions lead to the following power law: $j_c(H) \sim H^{-1/2}$. However, more complex models [11] provide more sophisticated dependencies. In our case, we used a single parameter exponential formula, (1), to fit our data. Although no model exists for the exponential dependence, the fit is reasonably well in the intermediate range of 100 G to 2 kG.

C. Dependence of Mixed Orientations

The current density dependence with different mixed orientations has been seldom discussed in literature. Perhaps the only past reference is described by Dong, Kim, and Kwok [26]. Their data is described by a formula similar to ours. There is no theory for this phenomenon. This feature is perhaps related to the fact that Jc drastically decreases at the grain boundary with tilt angle of 45 degree [36], which is due to the d-wave nature of superconductivity in YBCO [37].

To conclude, we fabricated a high quality YBCO film on YSZ and studied its x-ray and surface structure. We found that the magnetic field dependence of the 0-degree and the 45-degree orientations has similar feature. However the temperature dependence reveals a difference in power law. We do not have a good explanation at the moment. Finally, we studied the critical current density with different mixed orientations, and propose an empirical formula to describe the data.

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