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著者	渡辺　和雄
journal or publication title	Applied Physics Letters
volume	56
number	15
page range	1490-1492
year	1990
URL	http://hdl.handle.net/10097/46969

doi: 10.1063/1.103211

Strong flux pinning centers in Y-Ba-Cu-O films prepared by chemical vapor deposition

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(Received 18 December 1989; accepted for publication 9 February 1990)

The Y-Ba-Cu-O film prepared by chemical vapor deposition showed $T_c = 91.5$ K and B_{c2} (77.3 K) = 60 T defined by zero resistance. The J_c values measured at 77.3 K were 7.8×10^5 A/cm^2 at $B = 0$ and 1.0×10^5 A/cm^2 at 16 T, magnetic fields perpendicular to the *c* axis. Small disk-shaped precipitates possibly regarded as strong flux pinning centers in the Y-Ba-Cu-O films were observed using transmission electron microscopy. The evaluation of J_c related to the concentration and configuration of the precipitates was in reasonable agreement with the measured J_c values.

A remarkable advance has recently been made for the techniques of preparation of high T_c superconducting oxides. $J_c > 10^6$ A/cm^2 at 77.3 K and $B = 0$ was obtained in the Y-Ba-Cu-O thin films prepared by various techniques such as chemical vapor deposition (CVD),[1] sputtering,[2] and laser ablation.[3] Ag-sheathed tapes in the Bi-Sr-Ca-Cu-O system showing $J_c > 10^4$ A/cm^2 at 77.3 K and $B = 0$ were also reported.[4]

In particular, the Y-Ba-Cu-O films prepared by CVD demonstrated the excellent performance of $J_c > 10^4$ A/cm^2 at 77.3 K in high fields up to 27 T.[5] It is very important to investigate the flux pinning mechanism related to the large J_c in high fields, from the aspect of the fabrication of practical oxide superconducting wires.

On the other hand, thermally activated flux creep[6] was observed in transport properties of high T_c oxide superconductors, because of the large thermal energy at liquid-nitrogen temperature. The CVD YBaCuO films showed the largest activation energy U_0 (2×10^4 K at 10 T) among superconducting oxides,[7] when electrical resistance measurements were used. An activation energy E_0 from magnetization measurements was about one order of magnitude smaller than the U_0 value.[7] These different results might be related to the motion of flux bundle.

Recently,the flux pinning centers due to lattice defects or the Ca- and Cu-rich impurity phase Ca_2CuO_3 were reported in the Bi-Sr-Ca-Cu-O system.[8] It has also been considered that intrinsic pinning,[9] twin boundaries,[10] or precipitates of the Y_2BaCuO_5 (211) phase[11] may be responsible for the flux pinning centers in the Y-Ba-Cu-O system.

Therefore, investigation on the flux pinning mechanism in the CVD films will offer powerful and fruitful information for application of high T_c superconductors. In this letter we report that small disk-shaped precipitates possibly regarded as the strong flux pinning centers were found in CVD YBaCuO films using transmission electron microscopy (TEM). We estimated the large J_c value in the CVD films by assuming the concentration and configuration of the precipitates.

The CVD films were deposited on the $SrTiO_3$ (100) substrates using β-diketone metal chelates.[11] The films showed the predominant orientation of the *c* axis perpendicular to the film surface. A small amount of the *a* axis oriented $Y_1Ba_2Cu_3O_{7-\delta}$ grains and CuO grains were included in the films.[12] Superconducting properties of the films, patterned with a narrow bridge that was 0.3 mm wide, 1 mm long, and 0.3 μm thick, were measured by a four-terminal resistive measurement. Magnetic fields were applied parallel to the *ab* plane and perpendicular to the transport current.

The temperature dependence of the resistance under magnetic fields for the CVD YBaCuO film (H-11) was investigated. The resistive transitions defined by zero resistance were at 91.5 K and $B = 0$, and at 86.0 K and 21 T. The upper critical fields B_{c2} at 77.3 K and $T = 0$ were estimated by the slope of the temperature dependent B_{c2} using the GLAG theory in the dirty limit, and the results are listed in Table I including the B_{c2} values determined by the midpoint (50% *R*) and the onset (90% *R*) of resistive transition curves. The $B_{c2}(0)$ values, which were given by $0.69T_c(-dB_{c2}/dT)_{T_c}$, varied from 3200 *T* at the 90% point to 630 T at the midpoint. It is unclear whether such the extremely large B_{c2} is meaningful or not. However, the slope of $(-dB_{c2}/dT)_{T_c} = 10$ T/K at the midpoint was in good agreement with the result of magnetization measurements performed by Welp *et al.*[13] From the practical standpoint, the slope of 4.2 T/K derived from $R = 0$ is useful, and in fact the large $B_{c2} = 60$ T at 77.3 K plays an important role to measure J_c in high fields up to 27 T.

TABLE I. Temperature dependence of B_{c2} in the Y-Ba-Cu-O film (H-11) prepared by chemical vapor deposition.

T_c (K)	$-(dB_{c2}/dT)_{T_c}$ (T/K)	B_{c2} (77.3 K) (T)	B_{c2} (0) (T)	
	4.2	60	270	0% *R*
91.5	10	140	630	50% *R*
	50	710	3200	90% *R*

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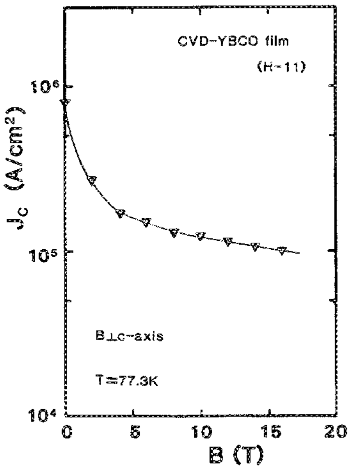

FIG. 1. Resistive J_c properties in magnetic fields at 77.3 K.

Figure 1 shows the J_c properties at 77.3 K in fields up to 16 T. These data were obtained by a pulsed current method. It was confirmed that the pulsed method with sweep time durations from 0.5 to 1.0 s yielded almost the same J_c values as those obtained by the dc method.[14] The J_c values obtained at 77.3 K were 7.8×10^5 A/cm^2 at $B=0$ and 1.0×10^5 A/cm^2 at 16 T.

As mentioned above, the CVD YBaCuO films demonstrated their excellent J_c values in high fields. It is, therefore, important to investigate what the strong pinning mechanism in the CVD films is. Great efforts were made to search a possible flux pinning center by means of TEM. In our plan-view observation by TEM,[12] we found a certain amount of strain contrasts in the c-axis oriented grains as shown in Fig. 2(a). Small disk-shaped precipitates embedded in the ab planes of $Y_1Ba_2Cu_3O_{7-\delta}$ were also observed in the a-axis oriented grains as shown in Fig. 2(b). The relationship between the strain contrasts and the precipitates is under investigation. However, if the strain contrasts are derived from the disk-shaped precipitates which can be considered to be the small plates, the dimensions of the small plates are approximately 25 nm long, 25 nm wide, and 1 nm thick. We guess that the small plates may be related to the precipitates of CuO.

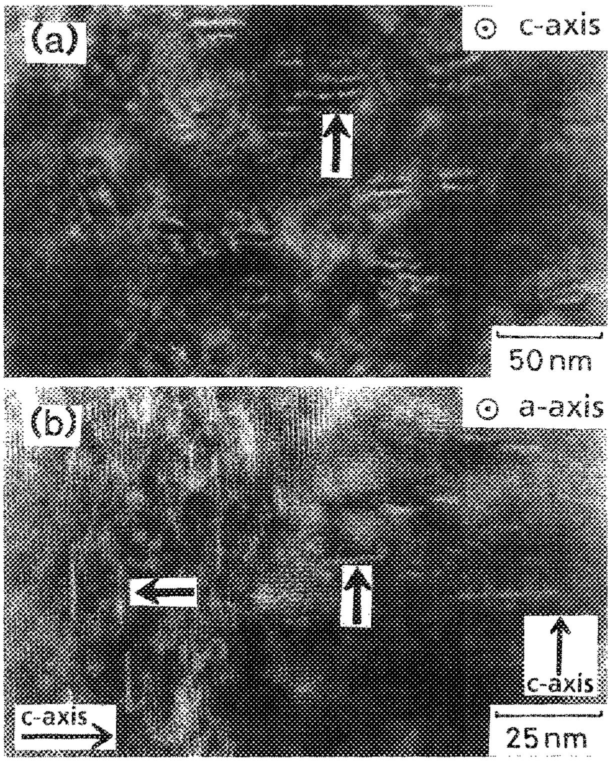

FIG. 2. High-resolution transmission electron micrographs of the CVD YBaCuO film. Arrows point to precipitates embedded in the ab planes. (a) Micrograph of the c-axis direction and (b) micrograph of the a-axis direction.

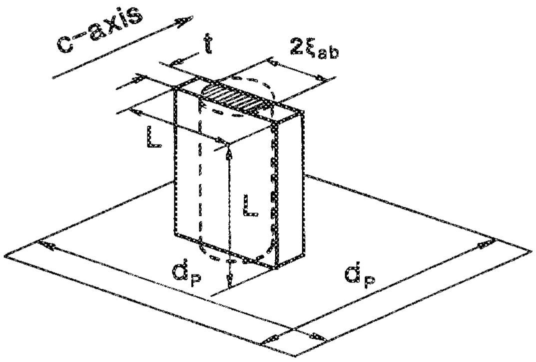

FIG. 3. Schematic illustration of the relationship between a flux line and a pinning center.

One can evaluate the global pinning force F_p by regarding the small plates as the pinning centers of the CVD Y-Ba-Cu-O films. The concentration N_p of the small plates was $\sim 1\times10^{22}$ m^{-3}, estimated from the TEM photographs. We assume the isotropic distribution of the pinning centers, so that the average spacing of the pinning center is $d_p = N_p^{-1/3} = 4.7\times10^{-8}$ m. Let us suppose that a flux line comes across the pinning center with a size of $L\times L\times t$ (see Fig. 3). Then at this point,the pinning energy is

$$U_p = \frac{B_c^2}{2\mu_0}\left(1-\frac{B}{B_{c2}}\right)2\xi_{ab}Lt, \qquad (1)$$

and the elementary pinning force is

$$f_p = \frac{U_p}{\xi_c} = \frac{B_c^2}{\mu_0}\left(1-\frac{B}{B_{c2}}\right)\frac{\xi_{ab}}{\xi_c}Lt, \qquad (2)$$

where the thermodynamic critical field is B_c and coherence lengths are ξ_{ab} in the ab plane and ξ_c in the c axis direction. The factor $(1-B/B_{c2})$ is a correction to the condensation energy at high fields. The probability P in which the flux lines come across the pinning center is given by

$$P = \frac{Lt}{d_p^2}\left(\frac{d_p}{a_f}\right)^2 = \frac{LtB}{\Phi_0}, \qquad (3)$$

where the flux line spacing is $a_f = (\Phi_0/B)^{1/2}$ with Φ_0 denoting the flux quantum. Thus, one can write the global pinning force in high fields as

$$F_p \approx N_p f_p P$$
$$= N_p\left(\frac{B_c}{\mu_0}\right)^2\frac{\xi_{ab}}{\xi_c}(Lt)^2\frac{B}{\Phi_0}\left(1-\frac{B}{B_{c2}}\right), \qquad (4)$$

where we assume a linear summation of the elementary pinning forces which is fulfilled for strong pinning centers. For $B_{c2}(77.3\ \mathrm{K}) = 60\ \mathrm{T}$, $B_c(77.3\ \mathrm{K}) \approx 0.5\ \mathrm{T}$, $B = 16\ \mathrm{T}$, and $\xi_{ab}/\xi_c = 4$,[15] we have approximately $J_c = 2\times 10^5\ \mathrm{A/cm^2}$ at 16 T and 77.3 K. This is in reasonable agreement with the experimental result, although the detailed field dependence of J_c should be corrected theoretically.

In conclusion, we found small disk-shaped precipitates in the *ab* planes of the CVD YBaCuO films by the transmission electron microscopy (TEM) observation. It was postulated that the precipitates of CuO dispersed in the *ab* planes might be responsible for the flux pinning centers. The evaluation of J_c based on the concentration and configuration of the precipitates was in reasonable agreement with the measured J_c values.

The authors would like to thank the staff members of HFLSM at Tohoku University for assistance. They also acknowledge the support of Grant-in Aid for Scientific Research on Priority Areas from The Ministry of Education, Science and Culture, Japan.

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