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Hysteresis in the $I_c(H)$ Characteristics of High-Temperature Superconducting Ceramics and Thin Films

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The experimental hysteretic behavior of the transport critical current observed in ceramic Y-Ba-Cu-O and (Bi-Pb)-Sr-Ca-Cu-O, as well as thin film Y-Ba-Cu-O, are presented. The data are analyzed semiqualitatively. The results show certain similarities among the ceramic samples and the films.

KEY WORDS: High-T_c superconductivity; critical currents; magnetic hysteresis.

The hysteresis of the transport $I_c(H)$ characteristics has been studied at some length for $YBa_2Cu_3O_{7-\delta}$ ceramics [1–4], but only very rarely in the (Bi-Pb)-Sr-Ca-O ceramic system [5]. In the case of thin film samples such property has not been reported up to date (at least in a systematic way), as far as we know. Here, we present $I_c(H)$ curves in increasing and decreasing applied fields for $YBa_2Cu_3O_{7-\delta}$ and (Bi-Pb)$Sr_2Ca_2Cu_3O_\delta$ ceramics, and for $YBa_2Cu_3O_{7-\delta}$ epitaxial thin films, in order to demonstrate the presence of hysteresis in all the cases, and to compare their basic features.

The samples were selected and fabricated as shown in Table I. The $I_c(H)$ curves were measured at liquid nitrogen temperature using $10 \times 1 \times 0.3$ mm^3 slabs in the case of the ceramics, and 0.5 μm thickness and 10×10 mm^2 area films. The $I_c(H)$ increasing-field curves (*virgin* ones) were measured from zero field cooling. The $I_c(H)$ decreasing-field curves (*returning* ones) were measured by lowering the applied field, H, to zero from a certain maximum field, H_m, previously reached from zero field cooling. The critical currents were extracted from the *I-V* curves using a 10^{-5} V/cm criterion.

If we regard the material as a random assembly of type II superconducting grains interconnected by SIS Josephson junctions, the $I_c(H)$ curves can be modelled as a superposition of the Fraunhofer-like patterns of each junction, $i_c = i_c(L, \varphi, H_i)$, where L is the length of the junction, φ is the angle relative to the applied field, and H_i is the intergranular field "felt" by the junction. H_i, in turn, depends on two factors: the local demagnetization, G, and the field-history-dependent magnetization of the surrounding grains, thus provoking the i_c hysteresis. The $I_c(H)$ behavior is then theoretically obtained by averaging i_c taking into account the statistical distributions of L, φ, and G inside the sample [2–4]. If the magnetization of the grains is calculated through Bean's model, three features of the returning $I_c(H)$ curves are predicted: (a) a maximum is displayed for some $H \geq 0$ if H_m surpasses some critical value, (b) as H_m increases, the maximum moves to higher field values up to saturation at some critical H_m, and (c) as H_m increases, the

Table I. Sample Preparation Details

Sample type	No.	Nominal composition	Preparation procedure
Ceramic	1	$YBa_2Cu_3O_{7-\delta}$	Standard ceramic [4]
	2	$GdBa_2Cu_3O_{7-\delta}$	Standard ceramic (long sintering) [4]
	3	$(Bi_{1.64}Pb_{0.36})$ $Sr_2Ca_2Cu_3O_\delta$	Standard ceramic [5]
Thin film (epitaxial)	4	$YBa_2Cu_3O_{7-\delta}$	Standard laser ablation [6]

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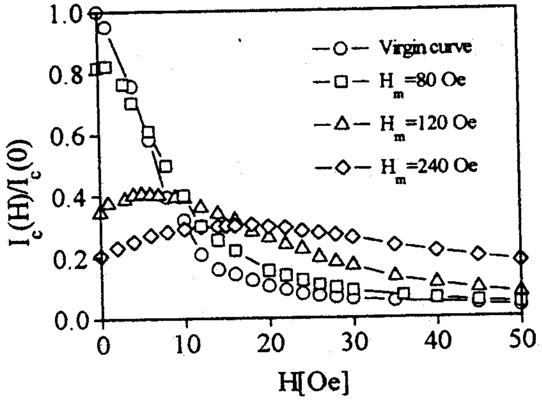

Fig. 1. $I_c(H)$ curves for sample 1.

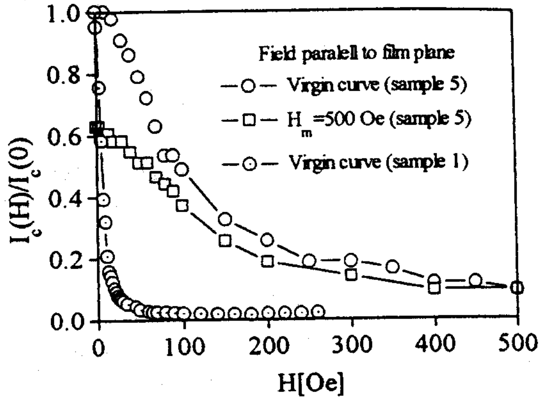

Fig. 3. $I_c(H)$ curves for samples 4 and 1.

maximum intensity is depressed down to saturation at the same critical value of H_m.

Figure 1 shows a set of $I_c(H)$ curves for sample 1. As can be seen, the virgin curve displays a clear Fraunhofer character, while the main features predicted by the theory are fulfilled. The maxima of the returning curves of sample 2, however, are closer to $H=0$.

Figure 2 displays the curves for sample 3. Although the Fraunhofer-like behavior of the virgin curve exists as in the preceding cases, and hysteresis is also present, all the returning maxima are located at $H=0$. It can be shown that this is connected to a large weight of negative values in the distribution of G [5].

Figure 3 presents the $I_c(H)$ curves for sample 4 with the applied field parallel to the plane of the film. Once more, a clear Fraunhofer-like behavior is displayed by the virgin curve. However, the effective junction length connected to granularity in this case can be roughly calculated to be 0.8 μm from the curve by estimating the position of the first minimum of the "dominant" Fraunhofer pattern, smaller than the 5 μm calculated for sample 1 (which corresponds to the mean grain size in that case). But, if we assume that the film is made of columnar "grains" with the approximate height of the film thickness, this becomes a plausible value.

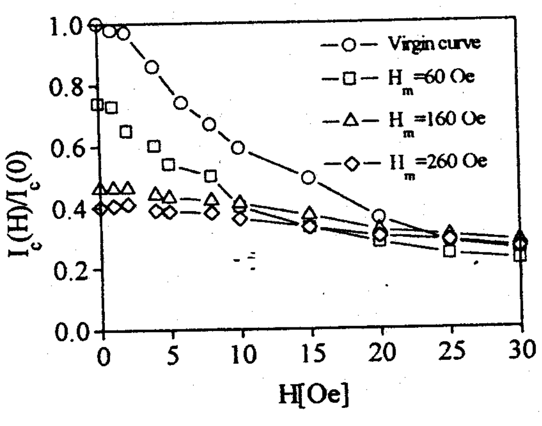

Fig. 2. $I_c(H)$ curves for sample 3.

A hysteretic behavior roughly analogous to the one reported for ceramics is observed, with the maxima located at $H=0$. If we take into account the epitaxiality of sample 4 and that both samples 2 and 3 are likely to have some degree of texturation, it can be concluded that this feature is somehow connected to anisotropy. Finally, although the virgin curve for sample 4 with the field applied perpendicular to the film plane does not show a very obvious Fraunhofer-like character, a junction length of about 40 nm can be estimated following the method used above. This can be associated to the dimensions of the columnar "grains" on the plane of the film. Then, the $I_c(H)$ response of the films might be interpreted, at low fields, in terms of some sort of "anisotropic granularity."

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