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Critical Current Density in $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{1-x} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_x$
Melt-Textured Composites

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Highlights

- Melt-textured $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ sample successfully produced.
- Tiny reduction in critical temperature.
- Strong reduction of critical current density.

ACCEPTED MANUSCRIPT

Critical Current Density in $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{1-x} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_x$ Melt-Textured Composites

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ABSTRACT

Melt textured $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{1-x} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_x$ composites ($x = 0.00$ and $x = 0.05$) were grown using the top seeding method. The effect of the $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ phase on the growth process and the modification of the microstructure as well as on the physical properties was analyzed. X-ray

analyses indicated that both pure and Pr-doped samples present an orthorhombic superconducting phase. From resistivity measurements for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ samples, the T_c^{ab} did not change and was around 90.5 K. However, from magnetic measurements, the superconductivity was observed in critical temperatures $T_c = 92.9$ K and 92.4 K for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ samples, respectively. The $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ sample showed higher critical current densities than those shown by the $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ sample, with values of $J_c = 5.85 \times 10^5$ A/cm² and 4.72×10^5 A/cm², respectively. This paper also discusses the importance of Pr substitution on nano- and micron-metre scales to enhance $J_c(H)$.

1. Introduction

The $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y-123) superconductor is considered one of the most interesting materials for presenting high critical temperature T_c and critical current density J_c . In $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ polycrystalline samples, very low critical current density is observed, usually in the range 10^3 A/cm². This low J_c value has been attributed to the anisotropic superconducting properties and the presence of grain boundaries [1]. On the other hand, melt growth process has enabled us to fabricate large single grain bulk $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ superconductors in which, with addition of the fine dispersed Y_2BaCuO_5 (Y-211) particles in the matrix, critical current density values in the order of 10^5 A/cm² at 77 K were easily obtained [2]. The high J_c value observed in melt textured Y-123 has made this material highly attractive for technological applications.

$\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Pr-123) is also very interesting since it exhibits the same orthorhombic structure as the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and other similar rare-earth (RE) compounds. Pr has a large size ion radius and also a big spin magnetic moment when compared to other rare-earth element [3]. In $\text{Y}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ compound, a transition occurs from superconductor to an antiferromagnetic insulator at $x \cong 0.56$ [4], and this is largely affected by the RE ionic size in $\text{RE}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$. The x critical value decreases with increasing RE ionic size. Some theories are used to explain critical temperature T_c versus x relation in this system: hole filling [5], pair breaking [6], hole location [7] and percolation [8-10].

The ionic size effect is coupled with the problem of how Pr doping deteriorates the superconductor state and consequently the superconductor/insulator transition [8-10]. It is believed that the deterioration is produced with the localization of holes around the Pr ion, occurring due to the hybridization between Pr-4f orbital and neighboring O-2p in the CuO_2 plane. Yoshida *et al.* studied the transport properties of $\text{Y}_{1-x}\text{Pr}_x\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ polycrystalline samples and composites consisting of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ [8-10]. The results were described as a mixed crystalline solid solution consisting of two kinds of crystal unit cells Y-123 and Pr-123. In this model, the system is regarded as a 2D site-percolation structure built along the ab -plane with structural resolutions on nano- and micron-metre scales [8-10].

The aim of this paper is to investigate the microstructure and physical properties of melt textured $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{1-x} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_x$ composites ($x = 0.00$ and $x = 0.05$). As a transition occurs from superconductor to an antiferromagnetic insulator state at $x \cong 0.56$, then we decided to produce a sample with low Pr concentration (around 5 %) to avoid undesired effects. The samples were prepared by employing the top-seeding method and characterized using optical microscopy, scanning electron microscopy, X-ray

diffraction, transport and magnetization measurements. The effect of $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ phase on the critical temperature and critical current density was studied.

2. Experimental Details

The melt textured samples were obtained using a top-seeding method. The seed used in this study was an $\text{NdBa}_2\text{Cu}_3\text{O}_{7-\delta}$ single crystal. The same thermal procedure was used for the preparation of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (Y - 123) and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ ((Y - Pr) - 123) composites. The $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ phases were prepared separately but using the same thermal route. High purity Y_2O_3 , Pr_6O_{11} , BaCO_3 and CuO powders were used. For $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}/\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$ composite, our seeded melt growth method employed a precursor material containing 75 wt. % $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and 25 wt. % Y_2BaCuO_5 (commercial powder). Also, each sample received the addition of 1 wt. % CeO_2 to limit particle-coarsening effects and to increase liquid capillarity [11]. The temperature was increased with a 40°C/h ramp rate up to 920°C and held there for 24 h. Then, the temperature was increased with a 0.5°C/h ramp rate up to 1040°C (melt temperature) and held there for 3 h. It was then cooled at 0.5°C/h to 980°C . Finally, the temperature was reduced to room temperature at the rate of 40°C/h . For $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ composites, the melt temperature used was 1050°C . Finally, for both samples, oxygen annealing was carried out at 420°C for 120 h in O_2 flow.

The microstructure of the composites was investigated using scanning electron microscopy (Shimadzu SSX 550 model). The phases formed were analyzed through powder-ray diffraction using CuK_{α} radiation (Shimadzu XRD 6000 model). Rietveld refinements of crystal structures were performed using GSAS and EXPGUI [12-13] software. Transport measurements were carried out by the four-probe method and with a low-frequency-low-current AC technique. Magnetization measurements were carried out in 15 K using a Quantum Design PPMS magnetometer in magnetic fields up to $\mu_0 H = 8$ T. Critical current densities were determined by the Bean model from the hysteresis loops.

3. Results and Discussion

The structure of all samples was investigated using X-ray diffraction. Patterns for melt textured $YBa_2Cu_3O_{7-\delta}$ and $(YBa_2Cu_3O_{7-\delta})_{0.95} - (PrBa_2Cu_3O_{7-\delta})_{0.05}$ composites are presented in Figure 1. The measurements demonstrate that the pattern for the melt textured $(YBa_2Cu_3O_{7-\delta})_{0.95} - (PrBa_2Cu_3O_{7-\delta})_{0.05}$ was very similar to that of the $YBa_2Cu_3O_{7-\delta}$ composite. However, the peaks corresponding to Y-123 and Pr-123 were not separately observed in the experimental XRD patterns. Using the GSAS and EXPGUI software, the lattice parameters a , b , c and V for melt textured $YBa_2Cu_3O_{7-\delta}$ and $(YBa_2Cu_3O_{7-\delta})_{0.95} - (PrBa_2Cu_3O_{7-\delta})_{0.05}$ composites were calculated. They are shown in Table I and are in agreement with the published results from other studies [14]. Also, the agreement factors and goodness-of-fit (S) are small and therefore reliable.

Table I: Lattice parameters a , b , c and V for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites.

$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$				
Phases	a (Å)	b (Å)	c (Å)	V (Å³)
$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$	3.81873(6)	3.88722(8)	11.6820(1)	173.410(5)
Y_2BaCuO_5	12.1816(2)	5.6603(1)	7.1327(2)	491.81(2)
$R_{wp} = 5.4 \%$ $R_{exp} = 4.3 \%$ $S = 1.2$ $R_f = 10 \%$				

$(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$				
Phases	a (Å)	b (Å)	c (Å)	V (Å³)
$\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$	3.8203(1)	3.8890(2)	11.6886(5)	173.66(1)
Y_2BaCuO_5	12.191(1)	5.6609(5)	7.1376(7)	492.59(9)

$$R_{wp} = 8.1 \%$$

$$R_{exp} = 6.3 \%$$

$$S = 1.1$$

$$R_F = 19 \%$$

SEM images of $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ (a-b) and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ (c-d) melt textured composite for ab – and $a(b)c$ – plane are shown in Figure 2. A typical microstructure is seen in this figure, which is consistent with the high density of grains embedded in a matrix Y(Pr)-123. Typical small and large Y-211 particles are also present. Y-211 particles are trapped in the interior of the domains and some residual phase is observed in the boundary region. This might indicate an incomplete peritectic reaction. A detailed image of the BaCeO_3 particles dispersed regardless of the plane in the phase matrix can be also observed in the figure. The composition of these inclusions is not homogeneous and there are significant differences in size.

In general, great changes were not observed in the microstructure of the (Y – Pr) – 123 sample, when compared with the sample Y – 123. And also, as expected, from the SEM images, it was not possible to observe individual grains based on Y - 123 and Pr – 123 (only 5 % of the grains). Also, the presence and the distribution of BaCeO_3 particles was the same for both samples, not showing dependence with Pr doping. On the other hand, a great increase in porosity was observed in the Pr-doped sample. Moreover, for samples (Y – Pr) – 123, it was possible to observe a great increase in microcracks parallel to (001) planes, which is clearly shown in Figure 2(d).

Figure 1: Representative X-ray diffraction patterns for melt textured $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ composites.

Figure 2: SEM images of $\text{YBa}_2\text{Cu}_3\text{O}_{7-d}$ (a-b) and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ (c-d) melt textured composite for ab - and $a(b)c$ - plane.

Figure 3(a-b) shows the temperature dependence on the resistivity for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ composite superconductor. The measurements were performed for $I//ab$ - and $I//a(b)c$ -plane with current $I = 10$ mA. The results indicate that the sample showed a metallic-like behavior at higher temperatures, and also as expected, the room-temperature resistivity for in-plane measurement was lower than that out-of-plane. For the sake of clarity, the presented curves in Figure (b) were normalized to unity at 100 K. The T_{c0} values are 93.0 K and 91.0 K for $I//ab$ and $I//a(b)c$ configurations, respectively. In Figure (c), the corresponding $d\rho/dT$ versus temperature is shown. The plot of $d\rho/dT$ is a simple procedure for magnifying details of the transition. This plot shows clearly that the transitions occurred at different temperatures. The width of transition for this sample, ΔT , defined between 5 % and 95 % of the transition height, were approximately 0.7 K and 0.9 K for $I//ab$ and $I//a(b)c$ configurations, respectively. Figure 3 also shows the maximum $d\rho/dT$, that corresponds approximately to the bulk critical temperature, T_c^{ab} and $T_c^{a(b)c}$, with the values 93.5 K and 91.7 K for both configurations.

Figure 3: (a) and (b) Temperature dependence on the resistivity for YBa₂Cu₃O_{7-δ} melt textured for $I // ab$ - and $I // a(b)c$ -plane; and in (c), $d\rho/dT$ versus temperature for YBa₂Cu₃O_{7-δ} melt textured for both planes. The current was 10 mA. In panel (c), the critical temperature T_c is shown.

Figure 4(a) and (c) presents the temperature dependence on the resistivity for the melt textured (YBa₂Cu₃O_{7-δ})_{0.95} - (PrBa₂Cu₃O_{7-δ})_{0.05} composite for $I // ab$ - and $I // a(b)c$ -plane with current $I = 5, 10, 15$ and 50 mA. The results (not shown) obtained for this sample also revealed a metallic-like behavior at higher temperatures. And also, the room-temperature resistivity for in-plane was lower than that out-of-plane. The T_{c0} values were approximately 89.5 K and 90.3 K for configurations $I // ab$ and $I // a(b)c$, respectively. Also, as expected, the values were similar regardless of the current. In figures (b) and

(d) the corresponding $d\rho/dT$ versus temperature are shown. The transitions width were approximately 0.9 K and 0.7 K for $I//ab$ and $I//a(b)c$ configurations, respectively. The bulk critical temperature for this sample was $T_c^{ab} = 90.5$ K and $T_c^{a(b)c} = 90.6$ K for $I//ab$ and $I//a(b)c$, respectively.

Figure 4: (a) and (c) Temperature dependence on the resistivity for melt textured $(YBa_2Cu_3O_{7-\delta})_{0.95} - (PrBa_2Cu_3O_{7-\delta})_{0.05}$ composite for $I//ab$ - and $I//a(b)c$ -plane; and in (b) and (d), the corresponding $d\rho/dT$ versus temperature.

Figure 5 shows DC magnetization measurements performed as a function of temperature in low-field under zero-field-cooling (ZFC) and field-cooling (FC) conditions for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. The measurements were carried out in 20 Oe and with the field applied parallel to ab -plane. Great difference between the ZFC and FC magnetizations curves could be observed. One characteristic temperature is noteworthy in the curves for both samples. The inflection of the magnetization with lowering temperature denotes T_c , a temperature below which rapid decrease in magnetization occurs as the result of super-current-induced diamagnetism. Below T_c , the ZFC and FC curves strongly split apart with the ZFC magnetization increasing with temperature reduction. The behavior is stronger for the Y – 123 sample. Magnetization curves for only ZFC for both samples are shown in detail around the critical temperature in Fig. 5(b). As expected, the curves revealed that the value of the magnetic moment for the Y – 123 sample was higher than that for the (Y – Pr) – 123 sample. The same curves were seen in temperatures between 90 and 94 K. Superconductivity was observed as a sharp diamagnetic transition at critical temperatures $T_c = 92.9$ K and 92.4 K for Y – 123 and (Y – Pr) – 123 samples, respectively. The curves also showed that the critical temperature was weakly affected by Pr.

Figure 6 shows the magnetization as a function of the applied magnetic field for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. The measurements were performed at 15 K, with $H // c$ -axis and the magnetization was measured after initially cooling in zero field to 15 K. The sample Y – 123 had approximately the same hysteresis compared to that of (Y – Pr) – 123 sample. This will be later correlated with the microstructure of the two samples. And also, it is interesting to note that in both samples the M - H curves were asymmetric (for field increasing and decreasing branches) with respect to the magnetic field axis.

In Fig 6(c), we observed the critical current density measured as a function of the applied magnetic field (up to $\mu_0 H = 5$ T) for the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. We could also observe that the samples exhibited a similar functional variation of J_c with applied field. The values were obtained from magnetization measurements such as Figure 6(a-b). These samples presented identical geometry and orientation and were cut from a larger single grain. Also, the critical current density was determined through application of Bean model (as in the usual way) from the width of the positive-field branch of the loop [15-16]. As observed in Figure 6, sample Y – 123 showed higher critical current densities than that for the (Y – Pr) – 123 sample: at $\mu_0 H(T) = 0$ T, we obtained $J_c = 5.85 \times 10^5$ A/cm² for Y – 123 sample, while for (Y – Pr) – 123 sample, $J_c = 4.72 \times 10^5$ A/cm² was observed, a 20 % decrease.

Figure 5: Low-field magnetization ZFC and FC in 20 Oe // *ab*-plane versus temperature for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. In Figure (b), magnetization for both samples is shown in more detail around the critical temperature.

For the sake of comparison, the result of J_c for $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ (YPr – 123) melt-textured composite sample prepared using same thermal route [17] is also shown in Figure 6(c). The critical current density for this sample was also determined by applying the Bean model. This curve also exhibited the same functional variation as J_c with the applied field observed in other samples. As observed from that figure, sample YPr – 123 showed higher critical current densities than that for Y – 123 and (Y – Pr) – 123 samples. The value observed for J_c in 0 T for YPr – 123 sample is $J_c = 7.48 \times 10^5 \text{ A/cm}^2$, an increase of 22 % in relation to the Y – 123 sample.

It is important to point out that the depression of superconductivity by Pr ion for (Y – Pr) – 123 and YPr – 123 samples occurred at different scales, with structural resolutions on nano- and micron-metre scales [8-10], when considering the percolation model proposed by Yoshida *et al.* In this model, the system is regarded as a 2D site-percolation structure built along the *ab*-plane with structural elements of Y-sited and Pr-sited crystal unit cells. Therefore, for the $Y_{0.95}Pr_{0.05}Ba_2Cu_3O_{7-\delta}$ sample, the depression must have occurred at a nano-metre scale while for the $(YBa_2Cu_3O_{7-\delta})_{0.95} - (PrBa_2Cu_3O_{7-\delta})_{0.05}$ sample, it must have occurred at a micron-metre scale.

Substitutional studies were carried out by Huhtinen *et al.* on sintered bulk samples of $YBa_2Cu_3O_{7-\delta}$ to determine the effect of Pr doping on the formation of effective pinning centers for J_c enhancement [18]. The results showed that Pr substitutions are effective, forming rows of oxygen vacancies with pronounced strain fields in CuO_2 planes. These defects are analogous to arrays of normal nanodots in CuO_2 planes and, therefore, have strong intragrain pinning interactions with pancake vortices of CuO_2 planes forming the mixed state structure. They observed that for 8 % Pr, the increase in J_c was almost by a factor of 10, whereas for 10 % doping, the critical current density was seen to get degraded to the level of 2-4 % Pr.

Figure 6: (a-b) Magnetization as a function of the applied magnetic field for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. Data was taken after zero field cooling. (c) Critical current density measured as a function of the applied magnetic field for the $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ melt textured composites. For the sake of comparison, the result of J_c for $\text{Y}_{0.95}\text{Pr}_{0.05}\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$ ((YPr) – 123) sample is also shown. The measurements were performed at 15 K with $H // c$ -axis.

4. Conclusions

In this study, melt textured $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{1-x} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_x$ ($x = 0.00$ and $x = 0.05$) samples were prepared using the top seeding growth technique. The samples were characterized using scanning electron microscopy, X-ray diffraction, magnetization and electrical resistivity. SEM images revealed that the microstructure is consisted of a highly density of grains embedded in a matrix Y(Pr)-123. The X-ray patterns revealed that the samples correspond to the orthorhombic $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ phase. From resistivity measurements, the critical temperature was determined to be around 90.5 K for both samples, however from the magnetic characterization, the superconductivity was observed at critical temperatures $T_c = 92.9$ K and 92.4 K for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and $(\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.95} - (\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta})_{0.05}$ samples, respectively. The critical current densities for the two samples were different, being 20 % lower for the Pr-doped sample.

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