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ENHANCED LEVITATION FORCE OF PARTIAL MELTED $(Y,Er)Ba_2Cu_3O_{7-\delta}$ SUPERCONDUCTORS WITH FORMATION OF MINOR 211 PHASE

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ABSTRACT

$Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ superconductors with Er_2O_3 addition were prepared by partial melting and the effects of excess Er_2O_3 addition on the magnetic levitation force (MLF) of the partial-melted samples have been investigated. A non-linear relationship was observed between the MLF measured at 77 K and the amount of Er_2O_3. It was found that the optimum amount of excess Er_2O_3 for enhanced MLF is 10 wt.%. X-ray powder diffraction analysis showed formation of major 123 phase with minor 211 non-superconducting phase for all samples. The results were discussed in detail and the presence of 211 impurities is suggested to act as pinning centers in the 123 samples.

Keywords: $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ superconductors, magnetic levitation force, 211 phase

1. INTRODUCTION

Bulk high-temperature superconductors have significant potential for various magnetic levitation applications as they produce stable levitation over permanent magnets or vice versa without active control. Well-textured Y123 bulk superconductors have been widely used for various applications such as magnetic bearing, flywheel, no-contact magnetic levitation transport system and motors. The magnetic levitation can be enhanced by introducing certain impurities which act as flux pinning centers in bulk superconducting materials. Structural defects such as dislocations, twins, 211 precipitates or chemical dopants play an important role in improvement of pinning capabilities of bulk melt-processed Y123[1-3].

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The critical current (J_c) of a Y123 sample rich in 211 particles was found to be higher than that of the standard sample that was free of Y211 phase[4]. The reason for the high J_c value in melt processed Y123 has been attributed to the absence of weak links and the strong pinning of non-superconducting Y211 fine particles as a result of the partially molten state. It is generally believed that Y123/Y211 interfaces or microstructure defects associated with Y123/Y211 interfaces acting as effective pinning centers[5,6].

On the other hand, addition of excess Y_2O_3 was observed to influence the mechanism of melt texturing[7] and the magnetic levitation force (MLF) of Y123[8]. The chemical reaction for Y123 at high temperature was suggested to involve the following two-stage reaction:

$$2YBa_2Cu_3O_x + 3Y_2O_3 \rightarrow 4Y_2BaCuO_5 + 2CuO \quad \text{eq. (1)}$$

$$YBa_2Cu_3O_x + CuO \rightarrow Y_2BaCuO_5 + L \quad \text{eq. (2)}$$

where L is a liquid phase consisting of $BaCuO_2$, CuO etc.

The equations above indicate that 211 impurities may be introduced in RE123 (RE-rare earth) matrix by reacting it with excess RE_2O_3. Recent studies on Er123 showed MLF enhancement as a result of excess Er_2O_3 in the preparation process. However, the MLF was negative at very close separation distance between magnet and superconductor indicating attraction instead of repulsion[9].

It is interesting to see the effect of Er substitution at the Y-site in $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ as well as the use of excess Er_2O_3 on MLF. Furthermore, studies of magnetic levitation of RE123 are not as extensive as that of Y123. This paper reports on MLF measurements of $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with excess Er_2O_3 to determine whether there is any difference in the behavior of MLF to Y123 and Er123. Powder X-ray diffraction was performed to determine the structure and phases of the samples.

2. EXPERIMENTAL METHODS

The 123 samples were prepared by conventional solid state reaction method from $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ starting composition using high purity oxides ($\geq$ 99.95 %). Appropriate amounts of Y_2O_3, Er_2O_3, $BaCO_3$ and CuO powders were mixed and ground in an agate mortar. The mixture was then calcined in air at around 900 °C for 48 hours with an intermittent grinding and pressed into 2.5 g pellets with sizes of 13 mm diameter and 3 mm thick using a hydraulic press. The pellets were sintered for 24 hours at 930 °C in air followed by controlled cooling to room temperature. The superconducting pellets were then crushed and ground before mixing with appropriate amounts of Er_2O_3 powder in different proportions (0 to 20 wt. %). The powders were repressed into pellets and heated in a tube furnace at 1100 °C. The partially melted samples were reground and repressed into pellets before final sintering at 930 °C in air for 24 hours

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followed by controlled cooling to room temperature.

Electrical resistance (dc) measurements of the samples were carried out using the four-point-probe technique with silver paint contacts in conjunction with a closed cycle refrigerator from Janis Model CCS-350ST. MLF was measured at 77 K on a Sartorius BP3100S Pan Balance by using a magnet of dimensions (6.4 x 6.4 x 6.4) mm^3. The magnetic field at the surface of the magnet was around 0.2 Tesla. The samples were examined by X-ray powder diffraction with Cu-K_α radiation using Philips Model PW1830 diffractometer. The volume ratio of 123 to 211 phases in the samples was estimated by assuming that the amounts of 123 phase and 211 phases are proportional to the intensity of their strongest diffraction line.

3. RESULTS AND DISCUSSION

XRD patterns showed formation of major 123 phase and minor 211 phase for all samples. Figure 1 shows XRD diffraction patterns for $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ samples with 0 wt. % and 20 wt. % excess Er_2O_3. $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 0 wt. % excess Er_2O_3 has the lowest percentage of 211 phase (~10%). The samples containing 5 wt.% to 20 wt.% excess Er_2O_3 showed existence of minor 211 phase between 25% to 37% by volume (Table 1). Among the Er-added samples, $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 5 wt % and 10 wt % Er_2O_3 produced the highest (37%) and the lowest (25%) percentage of 211 phase, respectively. Table 1 shows values of $T_{c\ zero}$, $T_{c\ onset}$, room temperature resistivity, percentage of weight loss due to partial melting and 123:211 volume ratio for all samples. Room-temperature resistivity measurements (Table 1) of the samples showed that the resistivity values are in the range of 0.04 to 0.45 mΩ cm.

Weight loss data (Table 1) shows that the melt loss of 32.4 % observed for 5 wt.% excess Er_2O_3 during partial melting process was the highest among the samples. However, further addition of Er_2O_3 leads to lower weight loss. The lowest weight loss was 10.4 % which was observed for the sample with 15 wt. % excess Er_2O_3. The data also shows that the weight losses for samples with 10 to 20 wt. % excess Er_2O_3 is less than that of 0 wt. % excess Er_2O_3. From the data in Table 1 it can be seen that there is no clear relationship between the percentage of 211 formed and the amount of excess Er_2O_3. Although chemical reaction of the constituents is similar to that of eq. (1) the end results have been complicated by partial melting. As such, it is suggested that the amount of 211 depends not only on the amount of Er_2O_3 but also on the extent of partial melting of the samples.

The temperature dependence of the electrical resistance of $ErBa_2Cu_2O_{7-\delta}$ with 0-20 wt. % excess Er_2O_3 is shown in Figure 2. $Y_{0.5}Er_{0.5}Ba_2Cu_2O_{7-\delta}$ with 0 wt. % excess Er_2O_3 superconducts with $T_{c\ zero}$ of 81 K while samples with 5 wt.% to 20 wt.% excess Er_2O_3 showed slightly lower $T_{c\ zero}$ between 65 K and 72 K (Table 1).

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The lower $T_{c\ zero}$ values are probably due to larger percentage of 211 of the samples compared to the 0 wt. % sample. $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 5 wt. % excess Er_2O_3 showed semimetallic normal state behavior while $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 10 wt.% and 15 wt.% excess Er_2O_3 showed metallic normal state behavior. $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 20 wt. % excess Er_2O_3 showed semi-metallic semiconductor-like normal state behavior. Electrical resistivity measurements for the samples at room temperature using Van der Pauw method showed the lowest value for 0 wt. % sample (~0.04 mΩ cm). The higher values of resistivity for the 5 wt. % and 15 wt. % samples may be caused by the higher percentage of 211 phase.

Figure 3 shows the variation of magnetic levitation force (MLF) at 77 K for all the samples as the separation distance (*d*) between the samples and the permanent magnet are reduced. Positive MLF was observed for all samples and this indicates the existence of bulk superconductivity. This is supported by XRD data which shows the existence of orthorhombic 123 phase for all the samples. For samples with excess Er_2O_3, it is clear that as *d* is reduced, the MLF increase and reach maximum values at *d* = 0.18 cm. The fact that only a monotonic behavior was observed for the sample with 0 wt. % Er_2O_3 indicates that the drop in MLF for $d < 0.18$ cm for samples with excess Er_2O_3 must be due to the presence of 211 phase. A similar behavior of MLF with *d* was observed for Er123 prepared with excess Er_2O_3[9].

Table 1. $T_{c\ onset}$, $T_{c\ zero}$, resistivity (at 300 K), percentage of weight loss during partial melting and ratio of 123: 211 for all samples.

Sample (excess Er_2O_3)	$T_{c\ zero}$ (±1 K)	$T_{c\ onset}$ (±1 K)	Resistivity at 300 K (± 0.3 mΩ cm)	**Weight Loss During Partial Melting** (±0.1 %)	123:211 Volume Ratio (±1 %)
0 wt. %	81	91	0.04	19.2	90:10
5 wt. %	**65**	**85**	0.37	32.4	63:37
10 wt. %	65	77	0.08	14.7	75:25
15 wt. %	70	85	0.45	10.4	67:33
20 wt. %	**72**	**95**	0.21	12.8	73:27

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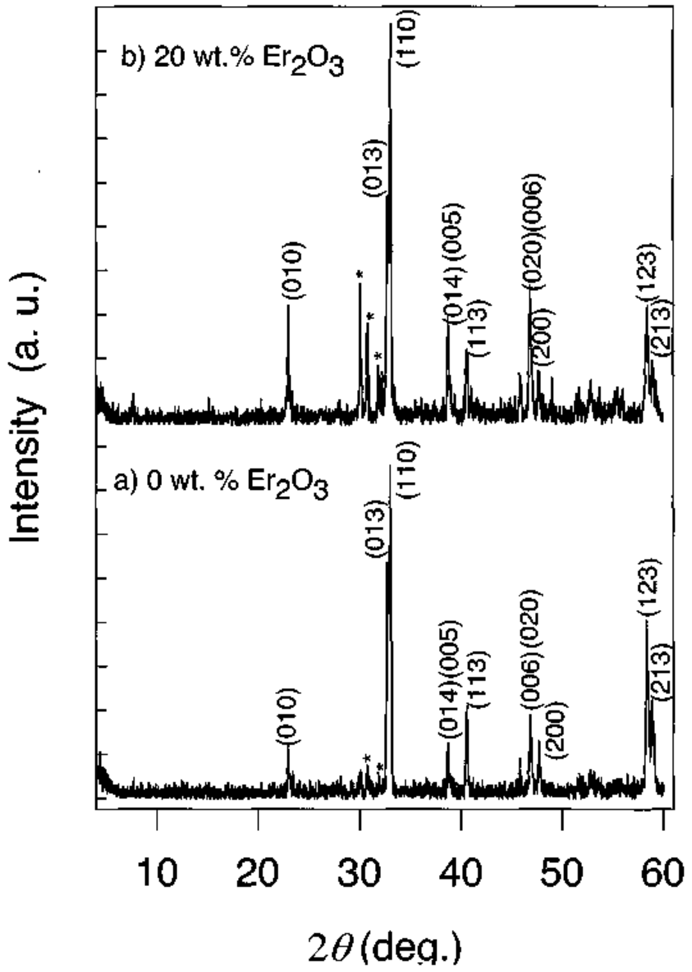

Figure 1: X-ray diffraction pattern for $(Y,Er)Ba_2Cu_2O_{7-\delta}$ with (a) 0 wt. % and (b) 20 wt. % excess Er_2O_3. 211 peaks are indicated by (*).

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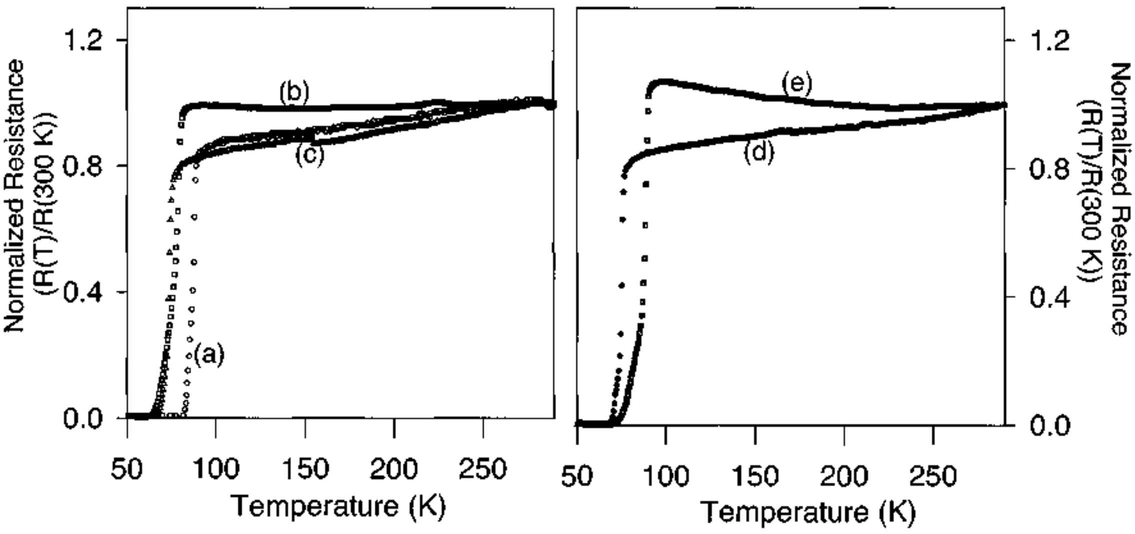

Figure 2: Normalized resistance versus temperature for samples with (a) 0 wt. % (b) 5 wt. % (c) 10 wt. % (d) 15 wt. % and (e) 20 wt. % excess Er_2O_3

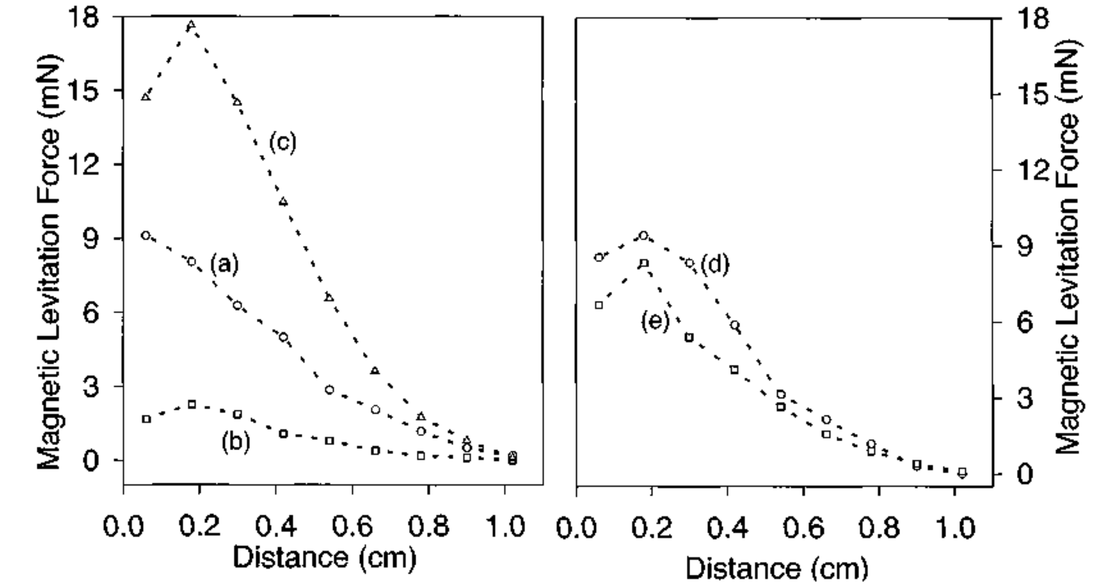

Figure 3: Magnetic levitation force (MLF) versus distance (*d*) for samples with (a) 0 wt. % (b) 5 wt. % (c) 10 wt. % (d) 15 wt. % and (e) 20 wt. % excess Er_2O_3

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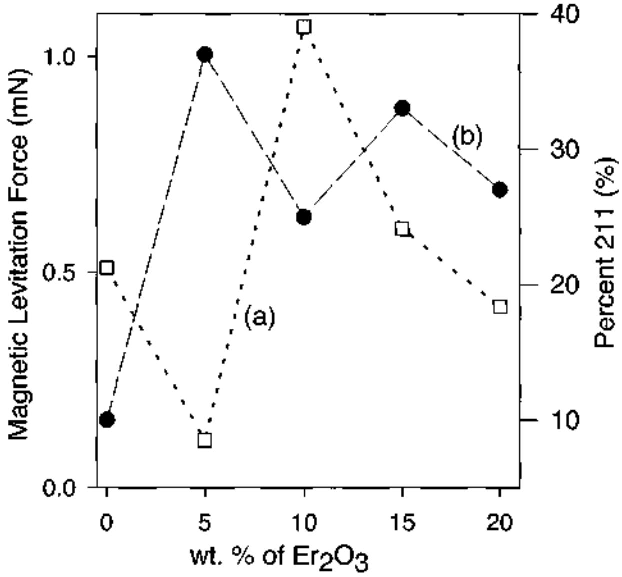

Figure 4: (a) Magnetic levitation force (MLF) at $d = 0.42$ cm and (b) percentage of 211 versus wt. % of excess Er_2O_3

However, for $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ negative MLF was not observed in any of the samples. As such, our result for $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ showed significant improvement compared to the previous work on $ErBa_2Cu_3O_{7-\delta}$[9] where negative MLF was observed for samples with excess Er_2O_3.

It can be observed from further analysis of the MLF behavior as shown in Figure 3 that for a particular value of $d > 0.18$ cm, the levitation force is not a linear function of the amount of excess Er_2O_3. For example, Figure 4 shows MLF at separation distance of 0.42 cm versus wt. % excess Er_2O_3 for all samples. $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 5 wt. % excess Er_2O_3 showed the lowest value of MLF among all Er_2O_3 added samples probably because of excessive partial melting which reduced the percentage of the 123 phase. $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ with 10 wt. % excess Er_2O_3 gives the highest maximum MLF value among all samples at $d = 0.42$ cm. More importantly, Figures 3 and 4 show enhanced MLF for the 10 wt. % Er_2O_3 sample compared to the 0 wt % Er_2O_3 sample for all separation distance. As a comparison, previous report on Er123 showed enhanced MLF only at 20 wt. % Er_2O_3[9].

This study shows that the percentage of 211 content may be crucial for enhanced levitation. The fact that 211 content of 25 wt. % sample produced enhanced MLF but higher 211 content caused MLF to drop indicates that although the 211 phase acts as flux pinning centers in the 123 matrix, excessive amount of non-superconducting 211 content will cause

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MLF to drop. For the sample with 10 wt. % excess Er_2O_3, the significant reduction in weight loss may have introduced more 123-211 interfaces in the 123 matrix and produced a higher MLF. Comparison between samples seems complicated due to partial melting of all the samples during heating. However, since the starting superconducting volume is the same for all samples and a comparable weight loss was observed for samples with 0 wt. % and 10 wt. % excess Er_2O_3, it can be suggested that the enhanced MLF observed for the latter may be due to flux pinning by the 211 phase. This is further supported by the fact that the enhanced MLF is not purely due to the superconducting volume as the sample with the 0 wt. % excess Er_2O_3 that has the highest superconducting volume did not show the highest MLF.

4. CONCLUSION

The effect of excess Er_2O_3 on superconducting properties and MLF of $Y_{0.5}Er_{0.5}Ba_2Cu_3O_{7-\delta}$ was studied. Er_2O_3 addition promotes formation of non-superconducting 211 phase which acts as flux pinning centers in the superconducting 123 matrix. A remarkable enhancement of the levitation force was observed for the sample with 10 wt % excess Er_2O_3 which contains 25% of 211 phase by volume. The result is a marked improvement over previous work on Er123 which showed optimum MLF for a much higher wt. % excess Er_2O_3 [9].

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