Enhancement of Critical Current Density and Flux Pinning in Bi-2212 Thick Films Due to MgO Addition

Baorong Ni, Masaru Kiuchi, and Edmund Soji Otabe

***Abstract*—In order to substitute cheaper sheath materials for Ag, Bi-2212 superconducting thick films grown on oxidized Ni substrates were prepared by using a normal partial melt process. 0–5 vol% of fine MgO particles were doped in Bi-2212 phase during the fabrication for the purpose of enhancement of the critical current density (J_c) in Bi-2212. The samples were analyzed with the assistances of X-ray diffractometer (XRD) and electron probe microanalyzer (EPMA). The critical temperature and J_c were measured by using the conventional resistive method (4-probe method). An apparent improvement in J_c characteristic was observed in the samples with fine MgO particles doped. The J_c value in the 5 vol% MgO doped sample reached to the level comparable with that in other Ag-sheathed samples. Furthermore, the irreversibility field was confirmed to be largely enhanced by the addition of MgO particles. The pin parameters derived from the scaling behavior of pinning force density turned out to be similar to those predicted in the case of normal precipitate flux pinning, indicating that MgO particles in Bi-2212 act as effective pinning centers.**

***Index Terms*—Bi-2212 thick film, critical current density, flux pinning, Ni substrate.**

I. INTRODUCTION

FOR the most part, the industrial and scientific applications for high- T_c superconductors (HTS) requires the low-cost production of long lengths of wire or tape with sufficient mechanical flexibility as well as superior critical current characteristic. Although Bi-2212 superconducting material is considered as one of the promising candidates for applications, one of the serious obstacles to the industrial progress is the high manufacturing cost, since a large amount of Ag is required for the sheath of wire or tape. Furthermore, the critical current characteristic in Bi-2212 still remains relatively low level, comparing with that in other HTS. Therefore, it is important to reduce the manufacturing cost by substituting other cheaper sheath materials for Ag, as well as to improve the critical current characteristic by enhancing the flux pinning in Bi-2212.

Recently, some studies on substituting other cheaper sheath materials, e.g., Ni, for Ag have been reported [1], [2], [4]. In these studies, it was clarified that the NiO buffer layer formed on the surface of Ni tape prevents the Bi-2212 phase from Ni contamination and brings a certain quality in superconducting characteristics. On the other hand, we demonstrated in our previous studies [3], [4] that the addition of fine MgO particles into Bi-2212 phase enhances the critical current density (J_c) in bulk and thick film samples. The enhancement was considered as the result of the improved flux pinning interaction due to MgO particles.

In this study, we prepared several kinds of Bi-2212 superconducting thick films grown on oxidized Ni substrates. Several vol% of fine MgO particles were introduced into Bi-2212 phase for the purpose of enhancing the critical current characteristic in Bi-2212. The structures and superconducting properties were investigated. A discussion based on the flux pinning due to normal particles and the scaling of the global pinning force density was given.

II. EXPERIMENTAL

A. Sample Preparations

The samples ware prepared using a normal partial melt process. Ni substrate with oxidized NiO on its surface was prepared. The oxidation was carried out at 600°C for 20 hours in the air, and the thickness of NiO was about 15 μm. Several vol% of fine MgO particles of about 200 nm in diameter were added into previously compounded Bi-2212 powders. The mixture was dissolved in a solvent consisting of an organic binder. Then, the resulting slurry was cast on the oxidized Ni substrate. Finally, a heat treatment of normal partial melt process was applied, with a variation of melt temperature according to the amount of doped MgO. The sample preparations were described in further detail elsewhere [4].

B. Analyzes and Measurements

The crystallinity and microstructure of samples were identified and analyzed with the assistances of X-ray diffractometer (XRD) and electron probe microanalyzer (EPMA). The crystalline phase was identified as Bi-2212 for the most part, while a trace of Ni was also detected in all samples. It was found that the majority of the flake-shaped Bi-2212 crystals are along the Ni/NiO substrate with the c-axis perpendicular to the substrate surface.

Fig. 1 shows an example of SEM image of the polished cross-section of Bi-2212 samples. The average of the thickness of Bi-2212 phase was obtained as about 18–30 μm. The whitish particles uniformly dispersing in the Bi-2212 phase were observed in the samples with MgO doped, while no such whitish particles were observed in the MgO-free sample. These particles were confirmed to be MgO by element mapping analysis and additional qualitative analysis of EPMA.

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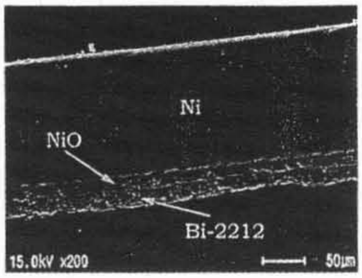

Fig. 1. SEM image of the polished cross-section of Bi-2212. The thicknesses of Bi-2212 phase and NiO are about 25 μm and 15 μm, respectively.

TABLE I
CRITICAL TEMPERATURES IN VARIOUS SAMPLES

MgO addition (vol%)	0	3	5
T_c (K)	86	85	89

The critical temperature (T_c) and critical current density were measured using a conventional four-probe resistive method. The temperature and applied magnetic field were varied from 4.2 K to 100 K and from 0T to 10T, respectively. The maximum of transport current flowing in samples was limited to about 150 A, which causes a temperature rising of several degrees in samples. The temperature of samples was monitored and recorded in real-time. The directions of transport current and magnetic field are within the *ab*-plane of Bi-2212 crystal and perpendicular each other.

III. RESULTS

Table I gives the measured critical temperatures in various samples. Although there is a certain dispersion of T_c values between the samples with different addition of MgO, no distribution in T_c was observed in these samples.

Fig. 2(a) and (b) show the critical current densities in the samples with 3 and 5 vol% MgO doped respectively, at various magnetic fields and temperatures. The critical current density in the MgO-free sample at 30K was also plotted for comparison. Large enhancements of critical current densities in the samples doped with MgO were obtained. Especially for the 5 vol% MgO doped sample, even in the temperature region beyond 50K, the values of J_c are still one order of magnitude larger than in the MgO-free sample, and reached the same level as in other Ag-sheathed Bi-2212 films. Fig. 3 shows the temperature dependence of J_c at 1.0 T in the samples with and without MgO doping. In conventional flux pinning theory [5], the critical current density due to normal particles is given by

$$J_c = \frac{\pi B_c^2 S \xi}{4\mu_0 B a_f}\left(1 - \frac{B}{B_{c2}}\right) \tag{1}$$

where B_c and B_{c2} are the thermodynamic and upper critical field, respectively, ξ the coherence length, a_f the fluxoid spacing, and S the total surface area of normal particles. If we suppose that all the Bi-2212 samples have the same electromagnetic characteristics such as B_c, B_{c2} and ξ, and neglect the difference in irreversibility field (B_{irr}), which will

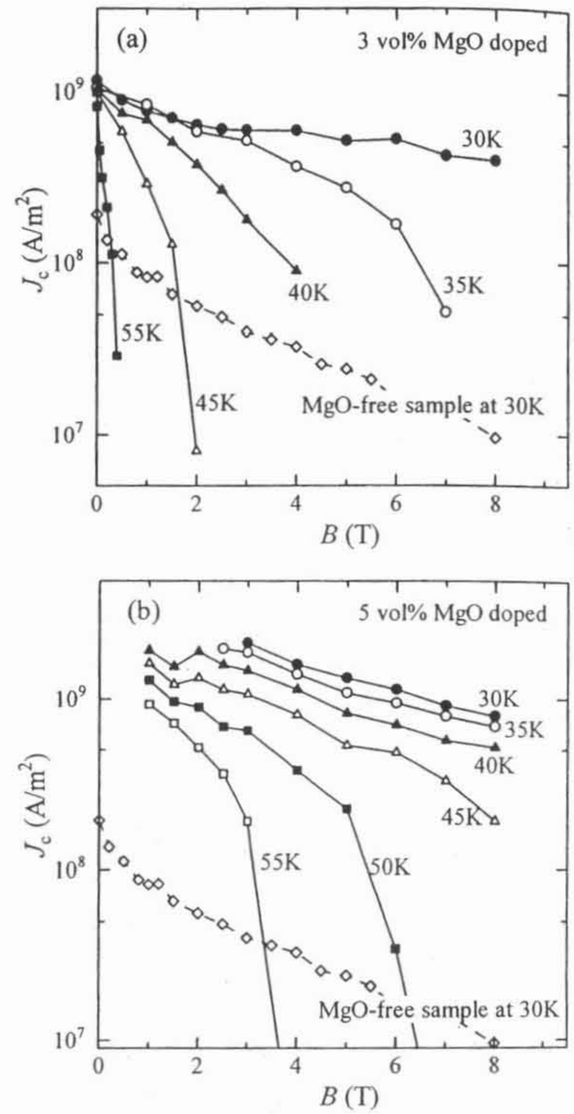

Fig. 2. Critical current densities in the samples with (a) 3 vol% and (b) 5 vol% MgO doped at various magnetic fields and temperatures. The magnetic field dependence of critical current density in the MgO-free sample at 30K was also plotted for comparison.

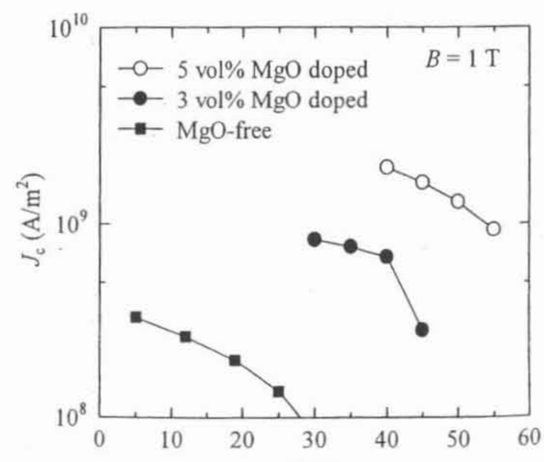

Fig. 3. Temperature dependence of critical current densities at 1T in the samples with and without MgO doping.

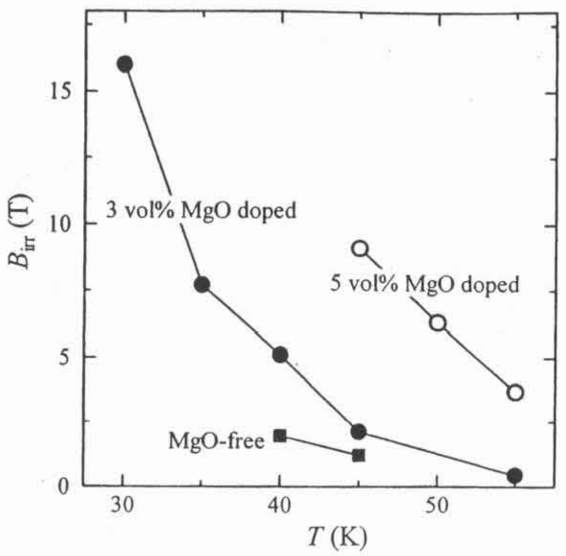

Fig. 4. Temperature dependence of irreversibility field. The open and filled circles denote the values in samples with 3 and 5 vol% MgO doped, respectively. B_{irr} in the MgO-free sample are also plotted for comparison.

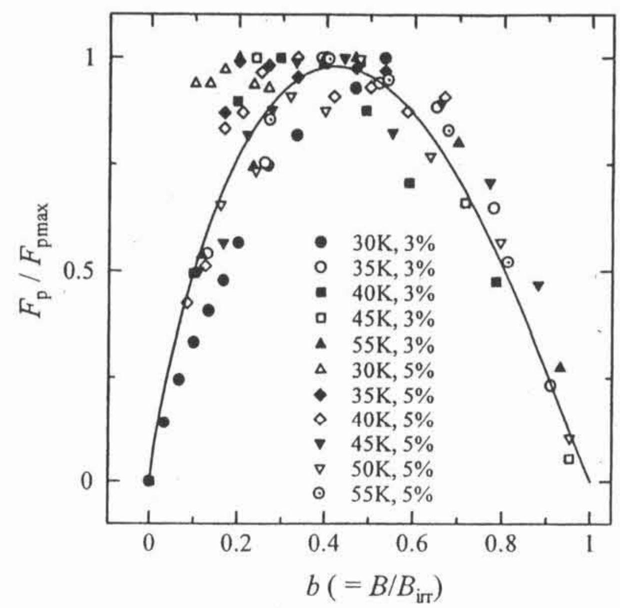

Fig. 5. Scaling behavior of the pinning force density. The magnetic field is normalized by the experimental B_{irr}. The solid-line is fitting curve given by (2).

be mentioned later, the ratio of J_c between the samples with 5 and 3 vol% MgO doped under a certain dc field can be considered to be simply proportional to the total surface area of MgO particles, i.e., the ratio of volume percent. Meanwhile, the experimental values of the J_c ratio are given from Fig. 3 as 5.0 for $B = 1$ T and $T = 45$ K, which is quite larger than the expected value of 5/3. This quantitative discrepancy may be caused by the difference of the irreversibility field in the 2 samples, since a large enhancement of B_{irr} was obtained in the 5 vol% MgO doped sample as shown below.

On the other hand, the peak effect in J_c was observed in the sample with 5 vol% MgO doped as shown in Fig. 2(b), while no such phenomenon could be recognized in other samples that have less MgO addition and lower critical characteristic. The peak field of about 2T seems to be much larger than that observed in a Bi-2212 single crystal [6]. This difference may have some relation with the enhanced irreversibility field. As so far, there has been no consensus about the origin of the peak effect, although some interpretations, such as 2D-3D dimensional crossover in the vortex structure [6] or matching effect [7], were proposed. Further investigation is proceeding.

The irreversibility field was defined by the magnetic field at which the critical current density is reduced to 10^6 A/m^2. At lower temperatures, because the critical current exceeded the maximum current output of our dc power supply, this value was determined by extrapolating the experimental J_c. Fig. 4 shows the temperature dependence of the irreversibility fields in the samples with 3 and 5 vol% MgO doped. Comparing with that in the MgO-free sample (denoted by filled rectangle), B_{irr} was sufficiently improved by several times.

Fig. 5 shows the temperature-scaling of the global pinning force densities (F_p's) in the samples with 3 and 5 vol% MgO doped, where magnetic field and pinning force density are normalized by B_{irr} and the maximum of $F_p(F_{pmax})$, respectively. The disordered scaling behavior in lower magnetic field and lower temperature regions may be caused by the coexistence of multiple flux pinning mechanisms in these temperature and magnetic field regions.

According to the conventional flux pinning theory [8], [9], the flux pinning force density is represented by the following scaling law:

$$F_p(b) \propto b^{\gamma}(1-b)^{\delta} \quad (2)$$

where $b = B/B_{irr}$, γ and δ are scaling (or pin) parameters. It is well known that the scaling parameters are affected by the flux pinning mechanism in the superconductor. In our case, γ and δ are obtained by fitting the scaling shown in Fig. 5 as 0.8 and 1.1, respectively. These values are similar to those predicted in the case of strong flux pinning due to normal precipitates [10], e.g., $\gamma = 1/2 - 1$ and $\delta = 1$, indicating that the fine MgO particles doped in Bi-2212 phase act as effective pinning centers and enhance the critical current characteristic in high magnetic field and high temperature regions.

IV. Conclusion

Bi-2212 superconducting thick films grown on oxidized Ni substrates were prepared using a normal partial melt process. Several vol% of fine MgO particles were doped into Bi-2212 phase. The critical temperature was confirmed to be uninfluenced by the addition of MgO particles. The critical current densities in the samples with 0, 3 and 5 vol% MgO doped were measured. It was found that the addition of MgO particles sufficiently enhances the critical current density and the irreversibility field, especially for the sample with 5 vol% MgO doped, since the J_c value in this sample reached the level of Ag-sheathed Bi-2212 films. A peak effect in J_c vs. B was observed in the sample with higher critical current density. The pin parameters of γ and δ were derived by fitting the scaling of the pinning force densities. These parameters turned out to be similar to those predicted in the case of normal precipitate flux pinning. The result can be considered as evidence that MgO particles in Bi-2212 act as effective pinning centers.

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