Critical current density distribution in superconducting oxide layer of Bi$_2$Sr$_2$CaCu$_2$O$_x$/Ag composite tapes

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Received 9 February 1998; accepted 23 February 1998

Abstract

The relationship between $J_c$ and the thickness of the oxide layer of Bi$_2$Sr$_2$CaCu$_2$O$_x$/Ag composite superconductor is studied to clarify the critical current distribution in the oxide layer. $J_c$ of the oxide layer within 5 $\mu$m from the oxide/silver interface exceeds 3 $\times$ 10$^5$ A/cm$^2$ at 4.2 K, 10 T, while $J_c$ for the whole part of oxide (25 $\mu$m in thickness) stays at 1.2 $\times$ 10$^5$ A/cm$^2$. The results indicate that the superconducting current is carried by thin and highly aligned oxide part along the oxide/silver interface. The results also suggest that the higher $J_c$ can be expected with decreasing thickness of the oxide layer and with increasing the oxide/silver interface. © 1998 Elsevier Science B.V. All rights reserved.

PACS: 74.72.Hs; 85.25.K

Keywords: Bi-2212; Critical current density; Critical current; Thickness dependence

1. Introduction

Bi–Sr–Ca–Cu–O (BSCCO) high $T_c$ superconductors (HTS) are promising and expected for practical applications such as magnets, cables, etc. In most cases, the conductors are fabricated in the form of BSCCO/silver composite tapes to obtain uniform and long conductors that can be expected to carry high critical current ($I_c$). In order to optimize and establish fabrication processes, basic knowledge on the distribution of critical current density ($J_c$) inside the oxide layer is essential. Much effort has been performed on this matter for Bi$_2$Sr$_2$Ca$_2$Cu$_2$O$_y$(Bi-2223)/Ag tapes [1–8] and critical current dependence on the thickness of Bi-2223 filament is well known. However, the information stays insufficient for Bi$_2$Sr$_2$CaCu$_2$O$_y$(Bi-2212)/Ag tapes that are fabricated by using melt-solidification technique and are expected to have stronger electrical coupling between grains than Bi-2223. In the melt-solidification process, a well-aligned microstructure can be obtained because Bi-2212 particle crystallizes from the partially molten state and aligns along the oxide/silver interface and/or free surface. Because of the excellent grain alignment and intergrain cou-
pling of Bi-2212, slight attention has been paid for critical current distribution inside Bi-2212 part. No systematic study and/or direct measurement on this issue has been reported so far. In this study, \( J_c \) distribution in the oxide layer for Bi-2212/Ag tapes has been investigated by examining the relationship between \( J_c \) and the thickness of the oxide layer.

2. Experimental

Bi-2212 powder with the nominal composition of \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x \) was synthesized from precursor powder mixture of \( \text{Bi}_2\text{Sr}_2\text{CuO}_x \) (Bi-2201) phase and submicron-sized \( \text{CaCuO}_3 \) [9]. The Bi-2212 powder was mixed with organic binders and solvent to prepare a slurry. Bi-2212/Ag tapes were fabricated by using the dip-coating technique [10,11] with this slurry and 50 \( \mu \text{m} \) thick silver substrate tapes. The samples obtained in this way were cut into pieces of 30–35 mm in length before the heat treatment. After removing organic materials at 500°C, melt-solidification process [10,11] was performed in pure oxygen (1 atm, flow rate: 100 cm\(^3\)/min) with the maximum temperature around 890°C. By this treatment, the oxide layer of 4.0 mm in width and 25 \( \mu \text{m} \) in thickness was obtained. To examine the thickness dependence of \( J_c \), the thickness of the oxide layer was decreased to several levels between 2 and 20 \( \mu \text{m} \) by mechanical polishing. In order to minimize mechanical damage on the oxide, the following method was employed: after mounting the specimen on a brass mechanical support with a two-sided adhesive tape, polishing was performed carefully using No. 600 grade polishing paper to make a groove at the middle part of the oxide layer. Sample configuration is illustrated in Fig. 1. Two series of samples (No. 1 and No. 2) were prepared in exactly the same way in order to determine the reproducibility and/or the mechanical damages induced in the samples during the polishing process. Transport critical current was measured by using a four-probe resistive technique at 4.2 K in the magnetic field of 10 T parallel to the tape surface. Thickness of the oxide layer was measured by using scanning electron microscope (SEM) for all the samples after \( I_c \) measurement. Fig. 2 shows the typical micrograph for the cross section along the groove (i.e., across the current direction) of a sample. The thickness of the sample was determined by averaging at least five measured values for each sample (e.g., the thickness
was determined to be 2.6 μm for the sample shown in Fig. 2). $J_c$ was calculated from $I_c$, thickness, and width of the oxide layer.

3. Results and discussion

Fig. 3 shows the thickness dependence of (a) $I_c$ and (b) $J_c$ for the sample series No. 1 and No. 2. $I_c$ decreases with decreasing thickness of oxide layer. For both series, $J_c$ of the samples without polishing (i.e., as heat treated) is around $1.25 \times 10^5$ A/cm², which is the same as that typically reported for the oxide layer in Bi-2212/Ag tape prepared with the melt-solidification process [12]. $J_c$ shows no significant difference in the thickness range between 25 and 15 μm. However, $J_c$ increases significantly with decreasing thickness below 15 μm and exceeds $3 \times 10^5$ A/cm² below 5 μm. $J_c$ for the oxide layer with the thickness of 2 μm reaches $3.8 \times 10^5$ A/cm². Results for the two series show good agreement in the whole range of thicknesses. In SEM observation, no obvious mechanical damage such as cracks and voids can be seen even for the sample with the smallest thickness. SEM observation and the good agreement between series No. 1 and No. 2 in thickness dependence of $I_c$ indicate that the polishing process to reduce the thickness was performed successfully without damaging the samples.

Assuming that the local $J_c$ ($J_{c\text{local}}$) can be written as a function of $t$ (the distance from oxide/silver interface), measured $I_c$ at the thickness of $t$ can be expressed in the following equation, where $w$ is the width of oxide layers

$$I_c(t) = \int_0^t J_{c\text{local}}(t) w dt,$$

and

$$J_{c\text{local}}(t) = \frac{dI_c(t)}{wdt}. \tag{2}$$

Thus, the first derivative of the $I_c$--thickness function gives $J_{c\text{local}}$ as indicated in Eq. (2). Local $J_c$ calculated by using this equation and $I_c$ as a function of thickness of the oxide layer are shown in Fig. 4a and b. SEM micrograph for the cross section of the oxide layer is also shown in Fig. 4c to reveal the relationship between local $J_c$ and microstructure. The specimen for the micrograph was etched [13] in order to emphasize grain boundaries. Three regions (regions I, II, and III) can be distinguished in $I_c$--thickness relationship. $I_c$--thickness profile is fitted with a linear relation for each region as a simple approximation to calculate local $J_c$. Local $J_c$ for regions I, II, and III are $3.3 \times 10^5$, $0.45 \times 10^5$, and $1.1 \times 10^5$ A/cm², respectively. Differences observed in the microstructure give a good explanation for this distribution of $J_c$ for each region. Local $J_c$ is highly related to the grain alignment. In the middle region (region II), the oxide shows poor grain alignment and low local $J_c$ below $0.5 \times 10^5$ A/cm². On the contrary, highly oriented grains can be seen near the oxide/silver interface and the free surface (regions I and III), where platelike Bi-2212 grains align parallel to the interface or the surface. The thickness of each aligned part is 5 μm from the interface or
the surface, and shows good agreement with the thickness of the region with high local $J_c$. In order to give a detailed explanation for the difference of local $J_c$ in both aligned parts, further study is required. However, it is notable that the local $J_c$ exceeds $3 \times 10^5$ A/cm$^2$ near the oxide/silver interface. These results indicate that the major part of the current flows in the aligned part along the interface. The middle part with low grain alignment has no significant contribution to $I_c$, i.e., degrades $J_c$ for the whole oxide layer. These results suggest that the further improvement of $J_c$ in Bi-2212/Ag conductors for practical applications can be expected by reducing the thickness of the oxide layer from the oxide/silver interface below 5 $\mu$m. For example, in the case of silver sheathed tapes which have oxide/silver interface on both sides of the oxide filament, $J_c$ enhancement should be achieved with employing oxide filaments thinner than 10 $\mu$m. Another possible way to increase $J_c$ is to increase the thickness of well-aligned part along the oxide/silver interface which carries higher $J_c$.

4. Summary

$J_c$ distribution in the oxide layer of Bi-2212/Ag tapes prepared by using the dip-coating technique was studied. Local $J_c$ of 3.3 $\times$ $10^5$ A/cm$^2$ (4.2 K, 10 T) is obtained for the region near the oxide/silver interface where Bi-2212 grains align well. On the contrary, in the middle region of the oxide layer where the grain alignment is bad, local $J_c$ stays below 0.5 $\times$ $10^5$ A/cm$^2$. $I_c$ of the whole tape is mainly achieved by the contribution of the region within 5 $\mu$m from the oxide/silver interface with highly oriented microstructure. The results indicate possible and expecting ways that lead to large $J_c$ enhancement of Bi-2212/Ag HTS.

References