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Thermal conductivity of YBaCuO bulk superconductors under applied field: effect of content and size of Y211 phase

Hiroyuki Fujishiro [a,*], Hidekazu Teshima [b], Manabu Ikebe [a], Koshichi Noto [a]

[a] Faculty of Engineering, Iwate University, 4-3-5 Ueda, Morioka 020-8551, Japan
[b] Advanced Technology Research Laboratories, Nippon Steel Corporation, 20-1 Shintomi, Futtsu, Chiba 293-8511, Japan

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Abstract

The temperature and magnetic field dependence of the *a*-axis thermal conductivity κ_a of YBaCuO bulk superconductors has been measured as a function of the content and the size of Y_2BaCuO_5 (Y211) impurity phase particles. In the specimen with the high critical current density J_c the $\kappa_a(T)$ enhancement below the superconducting transition temperature T_c is drastically suppressed in comparison with that of the lower J_c specimens with smaller Y211 content or with larger Y211 particle size. In the YBaCuO bulk system, Y211 particles are efficient phonon scatterers as well as the main flux pinning centers and a clear correlation between the flux pinning and the phonon scattering strength has been confirmed.

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1. Introduction

In the melt-processed REBaCuO bulk superconductors (RE: rare earth ions), RE_2BaCuO_5 (RE211) impurity phase particles are dispersed finely and uniformly in the $REBa_2Cu_3O_7$ (RE123) matrix phase by addition of platinum (Pt) metal [1]. The critical current density J_c is increased by the dispersed RE211 particles which act as strong flux pinning centers. In this case, the number density and the size of the RE211 particles are essential to determine J_c. Recently, the higher J_c than that for RE = Y system, were realized for RE = Nd and Sm systems, where a part of the Nd and Sm ions substituted for the Ba ions and produce the non-superconducting (or low-T_c) phase [2]. Furthermore, new promising REBaCuO bulk superconductors using RE = Gd, (Sm,Gd) and (Nd,Eu,Gd) have been investigated, resulting in a drastic improvement of J_c caused by the extremely fine and uniform RE211 phase particles [3–5]. The REBaCuO bulks are promising materials from the view point of the superconductor application.

For the application of the bulk superconductors, thermal transport properties such as the thermal conductivity κ and thermal diffusivity α are important to estimate the thermal stability and the reliability as cryogenic apparatus. For example, the low thermal conductivity is desirable for

* Corresponding author. Tel./fax: +81-19-621-6363.
E-mail address: fujishiro@iwate-u.ac.jp (H. Fujishiro).

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the application to the power current leads of superconducting magnets. For the application as bulk magnets as high as ~2 T at 77 K, however, the high heat conduction is indispensable to prevent the exudation of the trapped flux caused by the temperature rise. We have already reported the thermal transport properties of the several REBaCuO bulk superconductors [6–8]. The effects of the content and the size of the RE211 phase particles on the thermal transport properties, however, have not been clarified.

In this paper, we investigate the a-axis thermal conductivity $\kappa_a(T)$ of the YBaCuO bulk superconductors by varying the volume fraction and size of the Y_2BaCuO_5 (Y211) impurity phase under the applied field of up to 10 T and discuss the interrelation between the critical current density J_c and the phonon scattering strength.

2. Experimental

The YBaCuO bulk crystals were fabricated by the modified quench and melt growth method [9,10] with various volume fractions and sizes of the Y211 phase particles. The three specimens were prepared with different volume fraction X (%) and average particle size Z (μm) of the Y211 phase. We abbreviate the name of the three specimens as #11(25%, 1 μm), #10(2%, 1μm) and #01(25%, 10 μm), respectively, where the X and Z values are given in the parenthesis. The specimens of #11 and #10 were fabricated by the addition of Pt metal (0.5 wt.%) and the #01 specimen was fabricated without the Pt addition. The specimens were cut into a rectangular parallelepiped with the a-axis directed along the longest edge. The typical sizes of the specimens were $3.0 \times 3.0 \times 12.5$ mm^3. The a-axis thermal conductivity $\kappa_a(T)$ was measured by a steady-state heat flow method in the temperature range of 10–300 K [11]. The $\kappa_a(T)$ measurement under the magnetic field of up to 10 T was performed using the cryocooler-cooled superconducting magnet. The magnetic field dependence of the critical current density J_c at 77 K was determined by the magnetization measurement ($B \perp ab$-plane) on the basis of the Bean-model.

3. Results and discussion

Fig. 1 shows the a-axis electrical resistivity ρ_a of the three specimens as a function of temperature T. The inset shows the normalized magnetization M. The superconducting transition temperature T_c determined by resistivity and magnetization depends on both the volume fraction and the size of Y211 phase and the specimen #11(25%, 1 μm), which is a standard product of Nippon Steel Corporation as a bulk superconductor, has the highest T_c. ρ_a of the specimen #10(2%, 1 μm) is the highest and that of #01(25%, 10 μm) is the lowest. These results suggest that the size of the Y211 particles may affect the electron transport more strongly rather than the net Y211 content.

Fig. 2 presents the magnetic field dependence of the critical current density J_c at 77 K as a function of the applied field B. In zero magnetic field, #11 specimen attained the highest J_c value of 6.07×10^4 A/cm^2 and #10 showed the lowest value of 1.05×10^4 A/cm^2, while that of #01(2.2×10^4 A/cm^2) was intermediate. The reduction in J_c in the applied field was somewhat consistent with the initial values of J_c i.e., the specimen with larger J_c showed gentler field dependence. In the applied field of 0.5 T, for example, the J_c values of the #11, #01 and #10 were about 55%, 45% and 11% of the respective zero field values. The large J_c values of #11 may reflect the strong flux pinning caused by

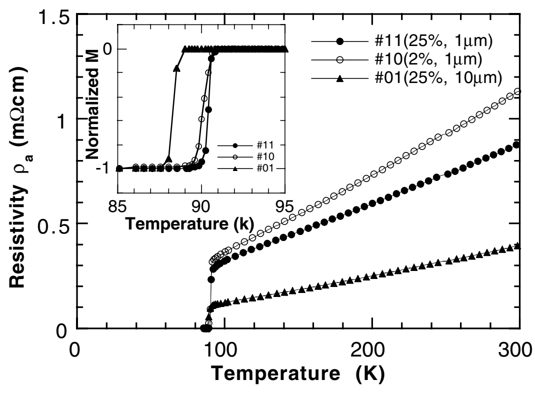

Fig. 1. The a-axis electrical resistivity ρ_a of the three specimens (#11(25%, 1 μm), #10(2%, 1 μm) and #01(25%, 10 μm)) as a function of temperature T. The normalized magnetization M is also shown in the inset.

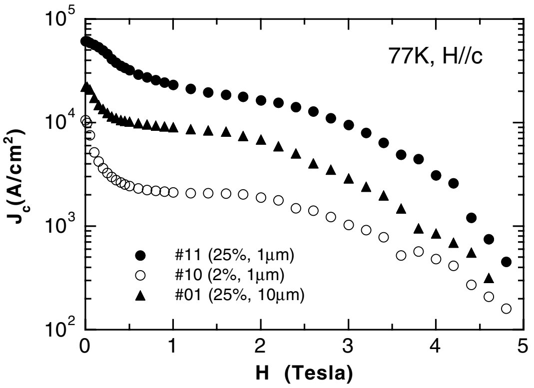

Fig. 2. The magnetic field dependence of the critical current density J_c at 77 K for three specimens.

the rich number of the Y211 flux pinning centers. In #01 specimen with larger Y211 particle size and in #10 with the smaller Y211 content, the number density of the Y211 pinning center is not large enough, which may deteriorate their J_c characteristics.

Fig. 3 shows the temperature dependence of the a-axis thermal conductivity $\kappa_a(T)$ in the zero field for three specimens. The electronic thermal conductivity κ_e is also shown, which is estimated by Wiedemann–Franz law above T_c using ρ_{ab} shown in Fig. 1. Below T_c, κ_e is estimated based on the formula derived by Kadanoff and Martin [12,13]. The contribution of the electronic part is relatively small and the heat transport is overwhelmingly due to phonons.

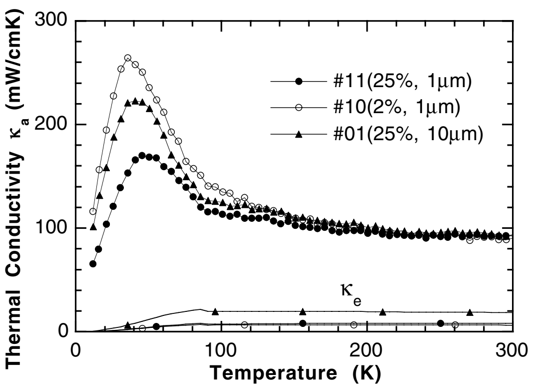

Fig. 3. The temperature dependence of the a-axis thermal conductivity $\kappa_a(T)$ under the zero field. The estimated electronic thermal conductivity κ_e is also shown.

In superconductors below T_c, κ_e is rapidly reduced with decreasing temperature, because the electrons condense into the Cooper pairs which do not carry entropy. On the other hand, the phonon thermal conductivity κ_{ph} is enhanced because the Cooper pairs are ineffective in phonon scattering. In Fig. 3, the $\kappa_a(T)$ enhancement in the #11 specimen below T_c is suppressed in comparison with those of #01 and #10. The specimen #01 contains the same amount of the Y211 impurity phase but the Y211 particle size ($\sim$10 μm) is 10 times larger in comparison with those ($\sim$1 μm) in #11. The number density n of the Y211 particles in #01 is smaller by 10^{-3} compared with that of #11. The phonon wavelength is by far smaller than the Y211 particle size of the present specimens. In such a case, the phonon scattering cross section S of a particle with radius r is πr^2 which is 100 times larger for the Y211 particles in #01. Then the total phonon scattering probability ($= nS$) due to Y211 particles in #01 should be about 1/10 of that of #11. In #10, of which Y211 content is 1/12.5 of #11, the total scattering probability is estimated to be also 1/12.5 of the #11 specimen. Thus the estimated phonon scattering probability due to the Y211 phase particles is the largest in #11 and is the smallest in #10. The thermal conductivity κ_a is the smallest for #11 and is the largest for #10, which strongly indicates that the variation of κ_a enhancement between three specimens is controlled by the phonon scattering strength by the Y211 particles. The κ_a values of the three specimens, in contrast, are in accord with each other in the high temperature region ($T \geqslant 140$ K), where the dominant phonon scattering mechanisms are due to electrons and phonon–phonon scattering (Umklapp process) and the scattering by the Y211 particles becomes relatively unimportant [13].

As we have seen, the Y211 impurity phase particles play an important role for both the flux pinning and the phonon scattering below T_c By comparing the J_c results in Fig. 2 and κ_a in Fig. 3, we notice that the κ_a enhancement is more strongly reduced in the specimen with higher J_c and this is not a mere coincidence. This fact directly supports that the Y211 pinning centers are strongly scattering phonons at the same time. Then it is expected that the both J_c and the phonon scattering

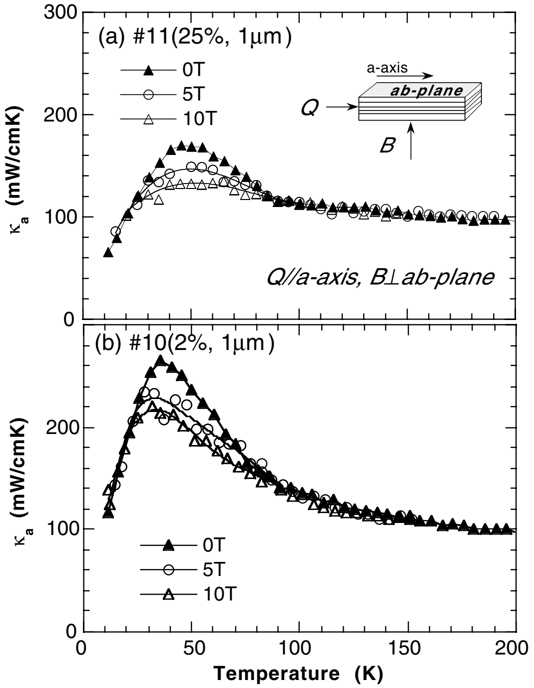

Fig. 4. Magnetic field dependence of $\kappa_a(T)$ for the (a) #11(25%, 1 μm) and (b) #10(2%, 1 μm) specimens.

strength of the YBaCuO bulk superconductors can be simultaneously enhanced if we can disperse more fine Y211 particles in the $YBa_2Cu_3O_7$ superconducting phase.

Fig. 4(a) and (b) presents $\kappa_a(T)$ of the #11(25%, 1 μm) and #10(2%, 1 μm) specimens in the applied fields. By application of fields, the phonon scattering by electrons partially recovers below T_c because of the normal-electron (= quasi-particle) revival in the vortex core regions. Then the thermal conductivity κ_a is reduced in the superconducting state. By comparing Fig. 4(a) and (b), the κ_a reduction effect due to the applied field seems to be smaller for the #11 specimen. For #11, the effect of the phonon scattering enhancement by quasi-particles is relatively small because of the stronger phonon scattering by the Y211 particles. Thus the behavior of κ_a in the magnetic field also supports that the heat conduction is mainly due to phonons and that the phonon scattering by the Y211 particles are important at low temperatures well below T_c.

In summary, we found that the Y211 impurity phase particles, which are the main flux pinning centers in the bulk YBaCuO superconductors, are also quite efficient phonon scattering centers at low temperatures below T_c. Then the low temperature phonon thermal conductivity can be a useful landmark for the flux pinning strength. The obtained results suggest that we can further enhance both phonon scattering and flux pinning by dispersing the finer (~0.1 μm) Y211 particles in the Y123 matrix phase.

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