Physica C 469 (2009) 1224–1228

Contents lists available at ScienceDirect

Physica C

journal homepage: www.elsevier.com/locate/physc

Superconducting characteristics of (Bi, Pb)-2223 single crystals with controlled oxygen-content

S. Kawai [a], E.S. Otabe [a], M. Kiuchi [a], T. Matsushita [a,*], T. Nomura [b,1], H. Yamauchi [b], T. Motohashi [c], S. Okayasu [d]

[a] Faculty of Computer Science and Systems Engineering, Kyushu Institute of Technology, 680–4 Kawazu, Iizuka, Fukuoka 820-8502, Japan
[b] Materials and Structures Laboratory, Tokyo Institute of Technology, 4259 Nagatsuda, Midori-ku, Yokohama 226-8503, Japan
[c] Faculty of Engineering, Hokkaido University, N13, W8 Kita-ku, Sapporo 060-8628, Japan
[d] Japan Atomic Energy Agency, 2–4 Shirane, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan

ARTICLE INFO

Article history:
Available online 31 May 2009

PACS:
74.25.Qt
74.72.Hs

Keywords:
Bi-2223 single crystal
Columnar defect
Critical current density
Irreversibility field
Condensation energy density

ABSTRACT

Critical current density was measured for oxygen-controlled (Bi, Pb)-2223 single crystals before and after the irradiation with gold ions in a magnetic field parallel to the irradiation-induced defects along the *c*-axis. Eleven specimens prepared in different annealing conditions were measured. The condensation energy density of each specimen was evaluated from the observed critical current density by using the summation theory of pinning forces of columnar defects and the flux creep theory. It was found that the specimen heat-treated at 1 atm in oxygen atmosphere has the highest condensation energy density among all specimens. Hence, it is speculated that the optimum oxygen pressure for the anneal is around 1 atm.

1. Introduction

Bi-2223 superconductor has advantages for application because of relatively high critical temperature about 110 K and easy grain alignment by mechanical treatment to achieve long wires. In fact, long silver-sheathed wires of order of several km have been fabricated by the powder in tube method. Recently, new pressurized sintering technique became available. The improvement by this process is mainly ascribed to the densification and the better *c*-axis orientation in Bi-2223 superconducting phase, which is important for the connectivity of grains. Thus, the critical current density of wires have been improved greatly compared with the normal pressure sintering process, and the critical current exceeded 200 A at 77 K in 2006 [1].

Further improvement of the critical current density is an essential problem for practical application of Bi-2223 wires, and for this purpose it is necessary to introduce strong pinning centers. Then, a question arises if Bi-2223 is a material with a sufficient potential for introduction of strong pinning centers. Since the flux pinning strength is directly related with the condensation energy density, the potential of Bi-2223 is expected to be clarified from estimating the condensation energy density. Recently, the condensation energy density of Bi-2223 [2] was estimated from the flux pinning strength of columnar defects nucleated in single crystals by heavy ion irradiation. It was found that the condensation energy density of an O_2 annealed Bi-2223 was very high at low temperatures [2]. This shows that Bi-2223 has a sufficient potential for application at low temperatures.

In this study, the influence of the oxygen-content on superconducting characteristic of (Bi, Pb)-2223 is investigated. For the purpose (Bi, Pb)-2223 single crystals were prepared and heat-treated in oxygen or nitrogen atmosphere. The annealing in nitrogen was done for deoxygenation of specimens. In addition, three batches of specimens were prepared and reproducibility was confirmed. Discussion is given on the influence by annealing condition and reproducibility.

2. Experiments

(Bi, Pb)-2223 single crystal specimens were prepared by the KCl flux method, in which 15% of Bi site was substituted by Pb [3]. The

* Corresponding author. Address: Department of Computer Science and Electronics, Kyushu Institute of Technology, 680–4 Kawazu, Iizuka, Fukuoka 820-8502, Japan. Tel.: +81 948 29 7663; fax: +81 948 29 7661.
E-mail address: matusita@cse.kyutech.ac.jp (T. Matsushita).
[1] Present address: The Furukawa Electric Co., Ltd., 2–3 Marunouchi 2-chome, Chiyoda-ku, Tokyo 100–8322, Japan.

0921-4534/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.physc.2009.05.108

size of the single crystals was typically 100–200 μm× 100–200 μm × 2.2 μm, and the *c*-axis is normal to the wide surface. 50–100 of specimen pieces were placed on an aluminum plate of size of 4 mm × 4 mm. The specifications of these specimens are listed in Table 1. The number of each specimen indicates the batch number. In this study, three batches of specimens were prepared. Two specimens were prepared as #1: one was post-annealed in oxygen atmosphere of 1 atm at 350 °C for 48 h and the other was not heat treated. Three specimens were parepared as #2: two specimens were post-annealed in oxygen atmosphere of 1 and 10 atm at 350 °C for 48 h and one was not heat treated. Six specimens were parepared as #3: three specimens were post-annealed in oxygen atmosphere of 1, 3 and 10 atm at 350 °C for 48 h, two specimens were heat treated only in nitrogen atmosphere of 1 atm at 350 and 450 °C for 48 h and one was not heat treated.

The columnar defects were nucleated parallel to the *c*-axis by irradiation of Au-ions with the energy of 200 MeV. The matching magnetic field of the dose, B_ϕ, was 1.0 T and the radius of the columnar was about 5.0 nm. The critical temperature decreased about 3 K after the irradiation.

Fig. 1 shows the critical temperature T_c of each specimen before and after the heavy ion irradiation. T_c of each batch, #1, #2 and #3, shows a similar tendency before the irradiation and monotonically decreases with increasing the oxygen doping. It is known that T_c and the length of the *c*-axis of (Bi, Pb)-2223 decreases with increasing oxygen partial pressure, carrier density increases [3]. The T_c of the present specimens prepared in the same condition also decreased with increasing oxygen partial pressure. Therefore, it is confirmed that the carrier density of each specimen increases with increasing oxygen partial pressure. The relationship between the carrier density and the condensation energy density of each specimen will be discussed later. The reproducibility of the specimen preparation is confirmed, since T_c of specimens prepared in the same oxygen annealing condition is the same in different batches. Therefore, this result shows that the amount of oxygen of the specimens could be changed well by the anneal in oxygen. T_c decreases generally after the irradiation independently of the doped condition of oxygen. Hence, the decrease in T_c seems to be caused by strains around nucleated columnar defects but not by deoxygenation through nucleated columnar defects. The difference of T_c between before and after the irradiation are different among the specimens of different batches. The reason for low T_c in specimen '#3 3 atm' seems to be ascribed to a trouble at irradiation. Therefore, we omit such specimens in discussion.

The critical current density, J_c, was estimated from the DC magnetization method using a SQUID magnetometer. A magnetic field was applied parallel to the *c*-axis, i.e., parallel to the columnar defects. For a single piece specimen, the hysteresis of the magnetic moment, Δm_i, is given by

$$\Delta m_i = \frac{(3l_i - w_i)w_i^2 t}{6} J_c \tag{1}$$

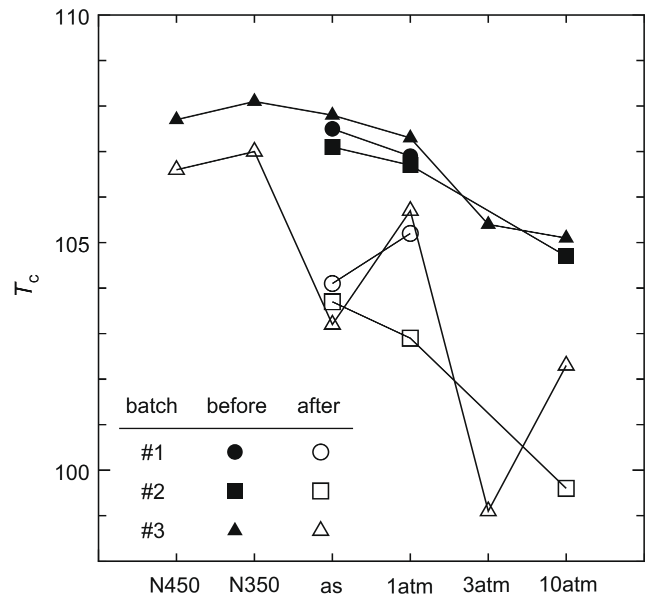

Fig. 1. Critical temperature of each specimen.

in terms of J_c, where l_i, w_i and t are the length and width of each piece ($l_i > w_i$) and the thickness of the specimen. In the present study, t and J_c are assumed to be constant in all single crystal pieces. The observed magnetic moment is:

$$\Delta m = \sum_{i=1}^{n} \Delta m_\mathrm{i} \tag{2}$$

The irreversibility field B_i is determined by the magnetic field at which J_c reduces to 1.0×10^8 A/m^2.

The condensation energy density, $B_c^2/2\mu_0$, of each specimen was estimated from the observed critical current density at low magnetic fields by using the summation theory of pinning forces of columnar defects and the flux creep theory [4,5]. The details of the analysis are published in Ref. [6].

3. Results and discussion

Fig. 2 shows the critical current density of each specimen at 5 K and 0.1 T. J_c increases by a factor of about 2 due to the columnar defect after the irradiation even at such low temperature and low magnetic field at which J_c before the irradiation is remarkably high. It was found that the specimen heat-treated at 1 atm in oxygen atmosphere has the highest critical current density in each batch. The reason for high J_c for the specimens heat-treated in nitrogen atmosphere is considered to be caused by improvement of CuO_2 planes.

Table 1
Specifications of specimens.

Specimen	Annealing condition	T_c (K) before irradiation	T_c (K) after irradiation
♯1 AS	Non-annealed	107.5	104.1
♯1 1 atm	350 °C 48 h 1 atm O_2	106.9	105.2
♯2 AS	Non-annealed	107.1	103.7
♯2 1 atm	350 °C 48 h 1 atm O_2	106.7	102.9
♯2 10 atm	350 °C 48 h 10 atm O_2	104.7	99.6
♯3 N450	450 °C 48 h 1 atm N_2	107.7	106.6
♯3 N350	350 °C 48 h 1 atm N_2	108.1	107.0
♯3 AS	Non-annealed	107.8	103.2
♯3 1 atm	350 °C 48 h 1 atm O_2	107.3	105.7
♯3 3 atm	350 °C 48 h 3 atm O_2	105.4	99.1
♯3 10 atm	350 °C 48 h 10 atm O_2	105.1	102.3