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CHANGE IN SUPERCONDUCTING PROPERTIES OF Bi-2212 SINGLE CRYSTAL DUE TO FAST NEUTRON IRRADIATION FOLLOWED BY THERMAL ANNEALING

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Change in superconducting properties due to thermal annealing was investigated on Bi-2212 single crystal specimens irradiated with fast neutrons. The Bi-2212 single crystal specimens (2 mm x 2 mm x 50-80 μm) prepared by the floating-zone method (FZ) were irradiated with the fast neutron fluence of 5x10^{14} cm^{-2} in JMTR, JAERI. After irradiation, the specimens were annealed in air at 673 K or 1073 K for 1 h to 3 d. Magnetization curves of the specimens before and after irradiation and annealing were measured with a VSM at 4.3 K, 20 K, 40 K and 60 K as a function of applied magnetic field. The critical current density \( J_c \) calculated from the magnetization hysteresis and the irreversibility field \( B_{irr} \) decreased due to the irradiation all over the range of temperature and magnetic field, and they were recovered by thermal annealing. In particular, the \( J_c \) values of the specimen annealed at 673 K for 1 to 3 h increased by 2 orders of magnitude larger than that of the specimen before irradiation. On the other hand, annealing at 1073 K showed only a partial recovery in the properties.

KEYWORDS: Bi_{2−x}Sr_{x}CaCu_{2}O_{y}, single crystal, neutron, irradiation, thermal annealing, critical current density

1. Introduction

Particle-beam irradiation is one of the most promising methods to introduce strong pinning centers into high-\( T_c \) superconductors. It has been reported that superconducting properties are affected by the irradiation of high-energy particles such as ions, neutrons and electrons\(^{[1][3]}\), which give different defect structures according to the mass, the energy and the fluence of incident particles, and their effects on superconducting properties have been investigated. Besides them, it is also expected that temperature during and after irradiation affects the defect structure and the superconducting properties of the irradiated specimens: For example, at high temperature all the defects disappear by the recombination of interstitial atoms and vacancies by thermal annealing, while at low temperature, no further structural change cannot occur after irradiation because of the quenching of produced defects. At middle temperature the behavior of atoms constituting radiation-induced defects is very interesting; in this case, they can move to construct some secondary defects such as stacking faults and dislocation loops, which may give great influence on the superconducting properties, including the enhancement of \( J_c \). Nevertheless, there have been few studies on this temperature effect carried out up to the present. In this study, we irradiated \( \text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_y \) (Bi-2212) single crystal specimens with fast neutrons and annealed them to understand the temperature effect on superconducting properties such as \( J_c \) and irreversibility field \( B_{irr} \). As a result, it was shown that the values of \( J_c \) and \( B_{irr} \) were enhanced in an appropriate annealing conditions of temperature and time.

2. Experimental

The Bi-2212 single crystal specimens used were prepared by the floating-zone method (FZ). Their size was 2 mm x 2 mm x 50-80 μm. The specimens were sealed in a quartz capsule with helium gas of 10^{7} Pa for the irradiation with fast neutrons in Japan Materials Testing Reactor (JMTR), Oarai Establishment, Japan Atomic Research Institute (JAERI). The irradiation temperature was about 330 K, and the neutron flux was 1.6x10^{13} cm^{-2}s^{-1}. The specimens were irradiated with the fluences of 5.0x10^{18} cm^{-2}, which is 5 times higher than that giving the maximum value in \( J_c \) enhancement ratio\(^{[4]}\). The irradiated specimens were heat-treated under flowing air at 673 K and 1073 K for 1 h, 3 h, 1 d and 3 d. The specimens were heated up to the prescribed temperature, kept for the prescribed time and rapidly cooled down to room temperature. For the specimens, magnetization was measured with a vibrating sample magnetometer (VSM) with a magnetic field applied up to 7.5T parallel to the c-axis with a sweep rate of 1 mT s^{-1} to 20 mT s^{-1} before and after neutron irradiation and thermal annealing, and \( J_c \) and \( B_{irr} \) were calculated from the magnetization curve.
3. Results and discussions

Figures 1 and 2 show magnetic field dependence of $J_c$ on the specimens before and after irradiation with the fluences of $5.0 \times 10^{18}$ cm$^{-2}$s$^{-1}$ and after annealing at 673 K and 1073 K, respectively. In all the cases, $J_c$ decreased due to irradiation, and increased again due to annealing. The enhancement ratio of $J_c$ is clearly seen from Fig. 3, where the $J_c$ value normalized by the initial one is plotted as a function of annealing time at 673 K and 1073 K. The $J_c$ decreased by the irradiation, and then increased up to the larger value than the one before irradiation by thermal annealing with time at 673 K. The final enhancement ratio was higher at relatively high temperatures of 40 K and 60 K. In case of annealing at 1023K, $J_c$ once increased by thermal annealing, and then decreased with time. The change of $B_{ni}$ at 40 K and 60 K is shown with annealing time in Fig. 4. The value of $B_{ni}$ also decreased by irradiation, and increased by thermal annealing with a maximum value at an appropriate annealing time on both cases. It should be noted that $B_{ni}$ became larger than the initial value before irradiation in case of annealing at 673 K, while at 1073 K the maximum value of $B_{ni}$ was lower than the initial value.

Fig. 1 Magnetic field dependence of $J_c$ on Bi-2212 single crystal before and after irradiation with the fluences of $5.0 \times 10^{18}$ cm$^{-2}$s$^{-1}$ and after annealing at 673 K.
Fig. 2 Magnetic field dependence of $J_c$ on Bi-2212 single crystal before and after irradiation with the fluences of $5.0 \times 10^{18}$ cm$^{-2}$s$^{-1}$ and after annealing at 1073 K.

Fig. 3 The change of $J_c$ due to neutron irradiation and thermal annealing.

Fig. 4 The change of $B_{an}$ due to neutron irradiation and thermal annealing.
There can been seen a relation in change by thermal annealing between $J_c$ and $B_{mr}$. Both took their maximum values by 24 h annealing at 673 K, and by 1 h annealing at 1073 K. For both parameters, the enhancement ratio was also larger by the lower temperature annealing than the higher temperature annealing. At the lower temperature of 673 K a portion of the atoms constituting radiation-induced defects can move to effectively form some secondary defects acting as pinning centers for fluxoids, while at the higher temperature of 1073 K, most of the atoms can move to annihilate the radiation-induced defects. What kinds of defects were produced by thermal annealing in the appropriate condition is still an open question, but these results suggest that post-annealing after irradiation can be a method for magnetic property change of Bi-2212.

References