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Section 8. Magnets and superconducting materials

Defect production and recovery in high-T_c superconductors irradiated with electrons and ions at low temperature

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Abstract

We have measured the fluence dependence of the electrical resistance at normal-state (100 K) and the critical temperature, T_c, in the high-T_c superconductor $EuBa_2Cu_3O_y$ irradiated with 2 MeV electrons and various ions (H, He, C, Ne, and Ar) with energies from 0.5 to 2 MeV. The defect production rate, which is obtained from the initial slope of the resistance–fluence curve, is almost proportional to the nuclear stopping power, S_n. The T_c depression due to irradiation is also nearly proportional to S_n. These results indicate that the defect production process is dominated by elastic displacement and does not depend strongly on the energy spectrum of primary knock-on atoms (PKA). Successive annealing up to 300 K after irradiation results in a significant recovery of normal-state resistance and T_c. This result suggests that low temperature irradiation is necessary for determining the nature of damage produced in high-T_c superconductors which will be used for application under superconducting state.

1. Introduction

When considering the application of high-T_c superconductors (HTSC) to magnets for fusion reactors, degradation of superconducting properties due to high energy irradiation fields is one of the problems to be solved. In order to estimate irradiation effects in HTSC, it is necessary to know which irradiation parameters dominate a damage production process. Electron- and ion-irradiations are useful methods to study irradiation effects. By changing the energy and mass of the incident particles, irradiation parameters such as nuclear stopping power and energy spectrum of primary knock-on atoms can be systematically controlled. Two kinds of damage production processes are usually considered; one is damage production through elastic collision and the other is that through electronic excitation. The former process is dominant for neutron irradiation which is one of the main causes of defect production for fusion reactor materials. It is known that both processes contribute to damage production in HTSC when the incident ion energy is relatively high ($\gtrsim$100 MeV) [1]. One of the purposes of our study is to clarify for low energy ($\sim$1 MeV) ion irradiation whether or not elastic displacement is a dominant damage production process.

Previously, depression of the critical temperature, T_c, in $YBa_2Cu_3O_y$ (YBCO) high-T_c superconductor has been investigated by changing particles and energies [2]. However, in that study, the samples were prepared in different ways, and the samples were irradiated at different temperatures. Therefore, in this work, $EuBa_2Cu_3O_y$ (EBCO) films prepared by the same procedure were used and the irradiation temperature was fixed at 100 K. As we shall see below, irradiation temperature is an important parameter when estimating irradiation effects in HTSC. The second purpose of our work is to clarify in HTSC whether or not there exists a primary knock-on atom (PKA) energy dependence of resistance change, T_c depression, and defect recovery

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due to temperature elevation. By using 2 MeV electrons and various ions from 0.5 MeV H to 2 MeV Ar, the average PKA energy can be changed over three orders of magnitude [3].

It is known that defect recovery occurs when the temperature of HTSC is increased above 150 K after low temperature (<150 K) ion-irradiation [4–6]. However, so far there has been no study of defect recovery systematically changing ions and energies. Based on the above recognition, we have measured the fluence dependence of normal-state resistance at 100 K and T_c while

Table 1
Irradiation parameters for electron- and ion-irradiations

Particles	Energy (MeV)	S_n (MeV/(mg/cm^2))	Range (μm)
Electron	2.0	2.3×10^{-8} [a]	~2000
^{1}H	0.5	1.5×10^{-4}	3.1
^{4}He	1.0	1.2×10^{-3}	2.1
^{12}C	1.0	2.4×10^{-2}	0.9
^{20}Ne	1.0	9.6×10^{-2}	0.8
^{40}Ar	2.0	2.7×10^{-1}	0.9

[a] For electron irradiation, the damage energy, S_d, is listed instead of S_n.

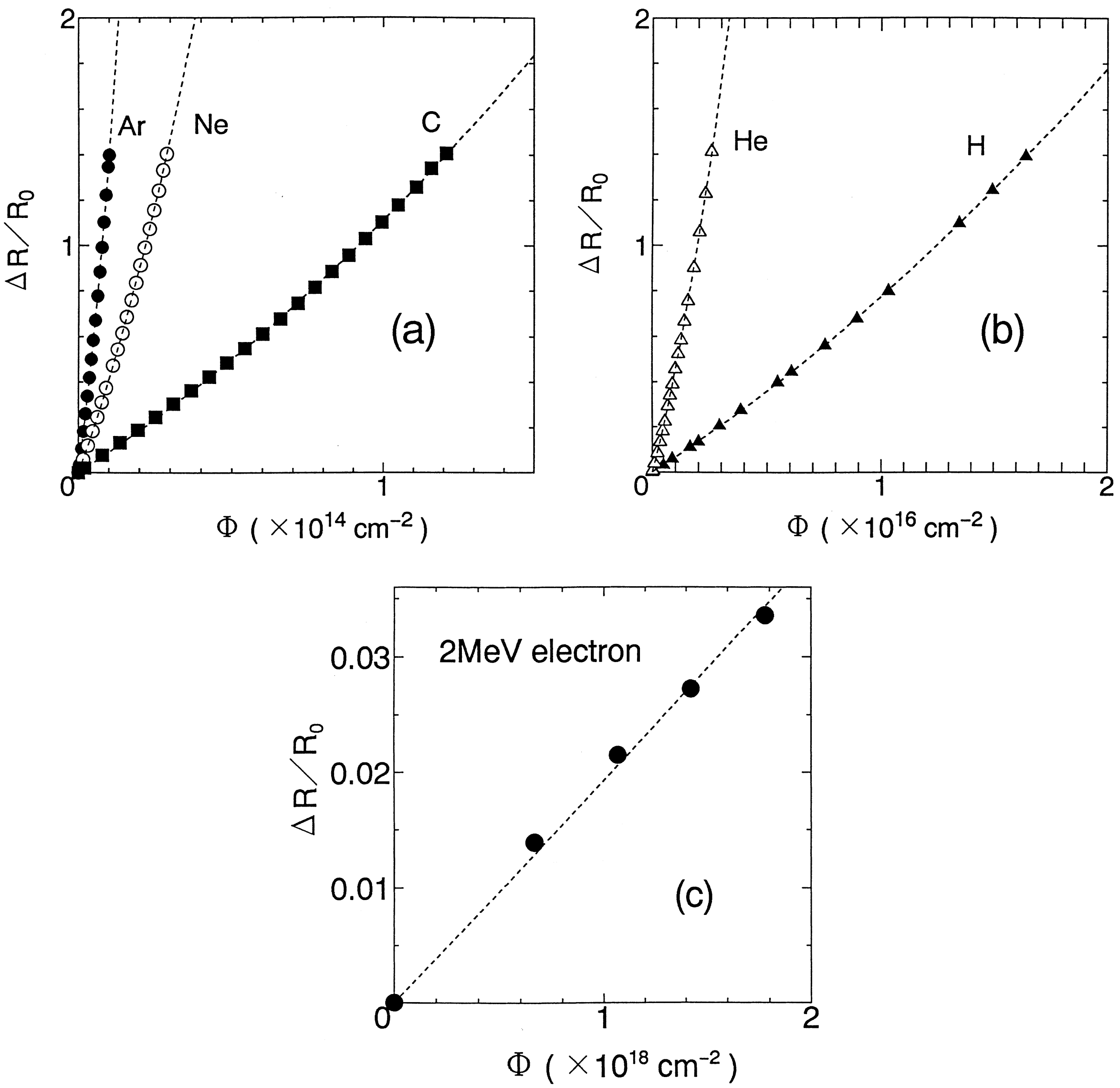

Fig. 1. (a)–(c): The fluence dependence of ΔR normalized by R_0 in EBCO irradiated with 2 MeV electrons and various ions listed in Table 1. The dotted lines are just to guide the eye.

systematically changing incident particles and energies in EBCO irradiated at 100 K. The effect of successive annealing up to 300 K after ion-irradiation has been investigated. The PKA energy dependence of irradiation effects and that of defect recovery are discussed.

2. Experimental procedure

The c-axis oriented films of EBCO high-T_c superconductor were prepared by rf magnetron sputtering [7]. The thickness of the films is about 300 nm. Before irradiation, the electrical resistance was measured as a function of temperature. The superconducting transition temperature before irradiation, T_{c0}, ranged from 80 to 89 K. EBCO films were irradiated with energetic electrons and ions. The irradiating particles and energies are listed in Table 1. The nuclear stopping power and the projected range for ion-irradiations were calculated by TRIM-92 [8]. For the electron irradiation, the value of the damage energy, S_d, which will be explained later, is listed instead of S_n. The range for electron irradiation was roughly estimated using the data calculated for iron irradiated with 2 MeV electrons [9]. For H ion irradiation, although the sample were irradiated by 1 MeV H_2, the value of S_n calculated for EBCO irradiated with 0.5 MeV H ions is listed. It is assumed that a H_2 molecule dissociates into two 0.5 MeV H ions immediately after the molecule enters the sample. In the following discussion, the fluence for H ions indicates the number of incoming H ions per unit cross section.

The range for all irradiations listed in the table is much larger than the sample thickness, meaning that the effect of ion-implantation can be excluded. Electron- and ion-irradiations were performed using a single-ended accelerator at JAERI (Japan Atomic Energy Research Institute)-Takasaki and a 2 MV Van de Graaff accelerator at JAERI-Tokai. The films were irradiated parallel to the c-axis under vacuum. In-situ measurement of the fluence dependence of electrical resistance was performed by a standard four probe method keeping the temperature at 100 K. The films were irradiated with ions until $\Delta R/R_0$ reaches about 1.4, where ΔR is the increment of electrical resistance at 100 K due to irradiation and R_0 is the electrical resistance at 100 K before irradiation. The critical temperature, T_c, was measured before and after the irradiation without warming above 100 K. The value of T_c is determined as the temperature where electrical resistance becomes one-half of normal-state resistance. After the ion-irradiation experiments, the temperature was elevated up to 300 K. The films were then cooled again in order to investigate the effect of defect recovery due to the annealing. The electrical resistance at 100 K and T_c before annealing the sample were compared with those after annealing.

3. Results and discussion

Fig. 1 (a)–(c) shows $\Delta R/R_0$ plotted as a function of fluence, Φ, in EBCO irradiated with electrons and ions. An increase in normal-state resistance is observed. For ion-irradiation the slope of the curves increases as fluence increases, indicating that there is an interaction

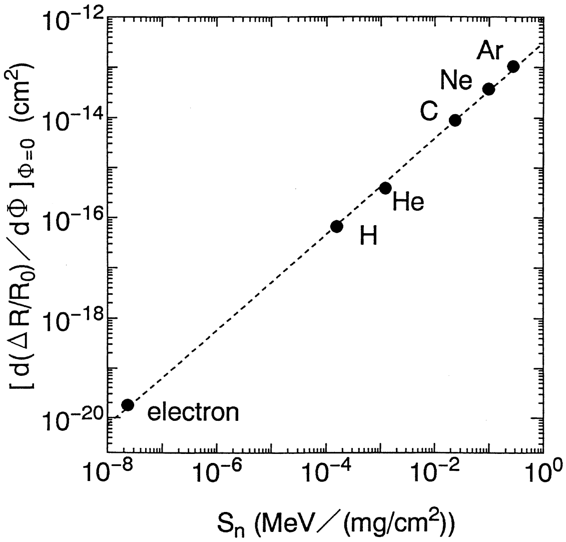

Fig. 2. The initial slope of $\Delta R/R_0$-Φ curve, $[(\Delta R/R_0)/\Phi]_{\Phi=0}$, plotted against S_n. The values listed in Table 1 are used for the value of S_n. The dotted line is a least square fit of the data with a slope of 0.96.

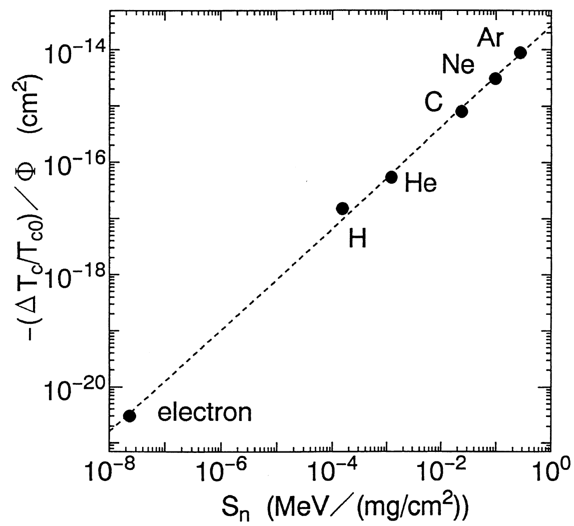

Fig. 3. The slope of $\Delta T_c/T_{c0}$-Φ curve, $-(\Delta T_c/T_{c0})/\Phi$, plotted against S_n. The values listed in Table 1 are used for the value of S_n. The dotted line is a least square fit of the data with a slope of 0.90.

between the created defects when the fluence is high. The resistance–fluence curves for HTSC is quite different from the curves for ion-irradiated metals. For ion-irradiated metals such as iron, the resistance tends to saturate as fluence increases [3]. The initial slope of fluence–resistance curves, $[(\Delta R/R_0)/\Phi]_{\Phi=0}$, is known to be proportional to defect production rate in ion-irradiated superconductors [10]. The value when $\Phi=0$ is used to extract the effect of the first incoming particle and to exclude the effect due to interaction between the created defects. The values of $[(\Delta R/R_0)/\Phi]_{\Phi=0}$ are different for each irradiations, reflecting different defect production rates. Since the ion energy is relatively low, defect production by energy transfer through elastic displacements is expected. In order to investigate the effect of energy transfer through elastic collisions, the values of $[(\Delta R/R_0)/\Phi]_{\Phi=0}$ were plotted as a function of the nuclear stopping power, S_n, in Fig. 2. For electron irradiation, the damage energy, S_d, was used instead of S_n. The damage energy, S_d, is defined as the energy used to cause

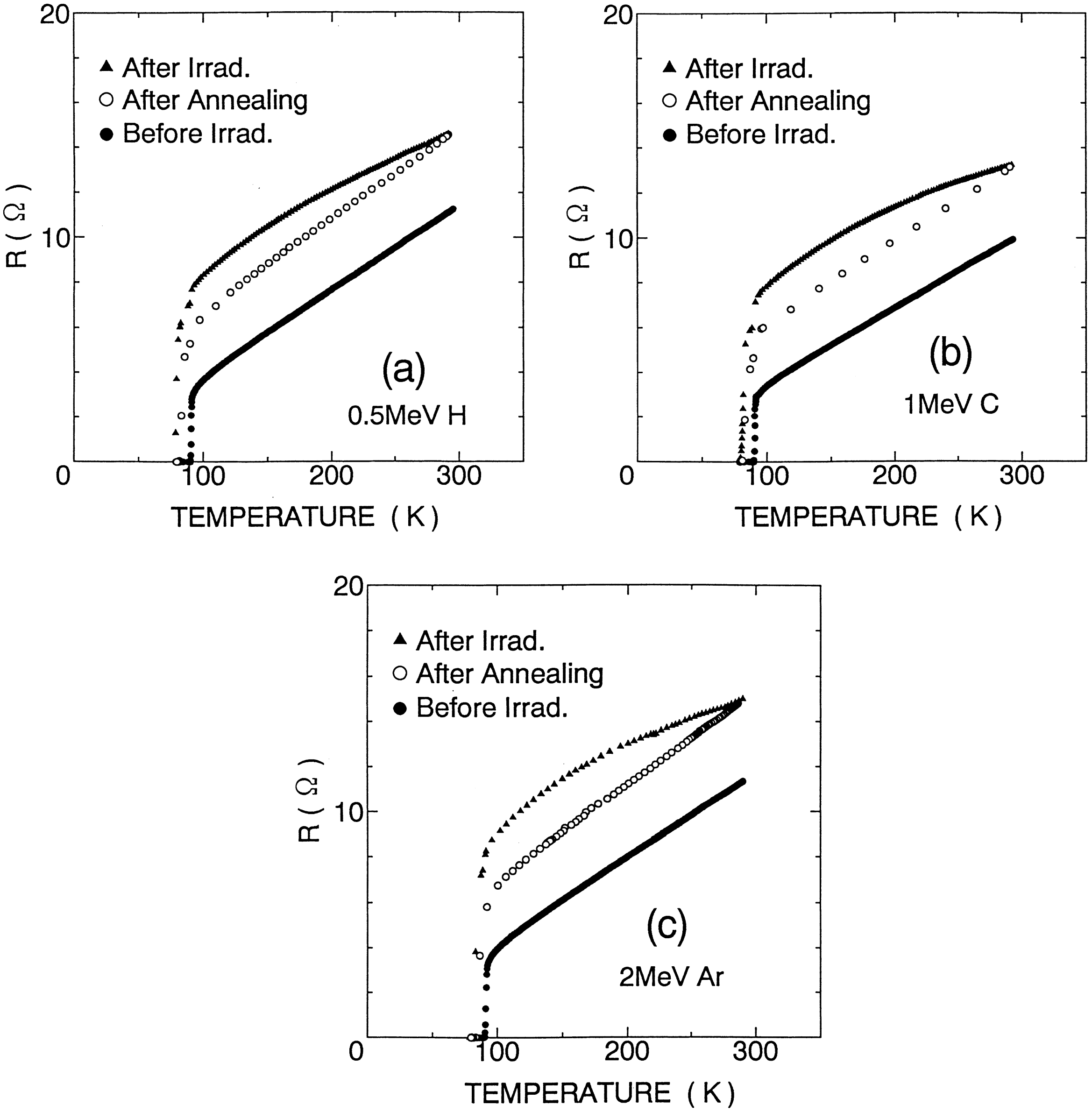

Fig. 4. (a)–(c): The resistance–temperature curves measured before ion-irradiation, when warming after ion-irradiation at 100 K, and when cooling after annealing up to 300 K. (a) The curves for 0.5 MeV H irradiation. (b) The curves for 1 MeV C. (c) The curves for 2 MeV Ar.

atomic displacements through elastic collision, when an incoming particle passes unit length in the sample. If energy transferred per collision is small ($<E_d$, E_d is a displacement threshold energy), the energy transfer does not displace atoms. This energy transfer process is called the subthreshold energy transfer. For electron irradiation, the subthreshold energy transfer is dominant, and S_n is much larger than S_d. This is the reason why S_d is better to describe defect production than S_n for electron irradiation. For ion-irradiations, the values of S_d and S_n are about the same. The figure shows that $[(\Delta R/R_0)/\Phi]_{\Phi=0}$ is proportional to S_n (or S_d) over seven orders of magnitude. This means that the energy transferred through elastic displacements determines the change in electrical resistance, reflecting the change in defect concentration. Fig. 3 shows that $-(\Delta T_c/T_{c0})/\Phi$ is also proportional to S_n (or S_d), where ΔT_c is the change in T_c due to irradiation, and T_{c0}, the value of T_c before irradiation. The linear dependence of irradiation effects on S_n is consistent with the result for radiation-induced change in c-axis lattice parameter in EBCO irradiated with 1-2 MeV ions [1]. Therefore, it is concluded that the elastic displacement dominates the damage production process in HTSC irradiated with low energy particles. The linear S_n- (or S_d-) dependence of the irradiation effects shows that the irradiation-induced resistance change and T_c change does not depend strongly on PKA energy spectrum, even though the average PKA energy is varied over three orders of magnitude. Therefore, without taking account of PKA energy, it is possible to approximately estimate the property change due to irradiation from the value of S_n (or S_d).

Several results for annealing experiments are shown in Fig. 4(a)–(c). The recovery of electrical resistance and T_c was observed for all ion-irradiations listed in Table 1. In spite of changing the average PKA energy over two orders of magnitude, almost the same recovery behavior was observed; i.e. about a half (43 ± 5%) of ΔR recovers due to the annealing, and 28 ± 6% recovery of ΔT_c is observed. These results show that the damage recovery due to 300 K annealing does not depend strongly on the PKA energy spectrum. The results of these experiments demonstrate that low temperature irradiation is necessary for exploring radiation damage in HTSC that will be used in the superconducting state.

4. Conclusion

In high-T_c superconductor $EuBa_2Cu_3O_y$ irradiated with 2 MeV electrons and 0.5–2.0 MeV ions, the normal-state resistance change and T_c depression due to irradiation are nearly proportional to S_n, indicating that the elastic displacement is a dominant damage production process. The successive annealing up to 300 K after irradiation results in significant recovery of normal-state resistance and T_c. The irradiation effects (the normal-state resistance change and T_c depression) and the defect-recovery due to successive annealing do not strongly depend on the PKA spectrum.

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