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Enhanced upper critical fields in low energy iron-irradiated single-crystalline MgB_2 thin films

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Abstract

We studied the effect of Fe ion irradiation on the upper critical field (H_{c2}) of 410 nm single-crystalline MgB_2 thin films. The irradiation energy was fixed at 140 keV when we increased the irradiation doses from 1×10^{14} ion/cm^2 to 4×10^{14} ion/cm^2. We found that H_{c2} significantly increase with increasing irradiation dose, despite the low irradiation energy. The enhancement of H_{c2} could be explained by the reduction of electron mean free path caused by defects induced from irradiation, leading to a decrease of coherence length (ξ). We also discussed the effect of irradiation on temperature-dependent resistivity in details.

Keywords: MgB2, Fe ion irradiation, upper critical field

1. INTRODUCTION

Early research found that defect plays a crucial role in the performance of superconducting properties. The effects of defect concentration on superconductivity have been widely investigated using various methods (e.g. doping and irradiation). In case of MgB_2 thin film, Carbon (C) doping is one of the most effective ways, and C-doped MgB_2 thin films with an excellent performance of H_{c2} have been reported [1]. Various kinds of irradiation were also carried out on MgB_2 thin films to study the change of H_{c2}. The obtained results significantly depended on MgB_2 samples and also the particles using for irradiation [2]. However, the typical irradiation energy is usually up to order of MeV in all study. In this study, we investigated the effect of low energy Fe ion irradiation on single-crystalline MgB_2 thin films. The perfect quality of pristine MgB_2 film is a prerequisite for variation of defect concentrations on samples. Despite low irradiation energy of 140 keV, H_{c2} shows a significant increase with the increasing irradiation doses. These results imply an effective method to develop the performance of superconducting properties in MgB_2.

2. EXPERIMENTAL

The 410 nm Single-crystalline MgB_2 thin films were fabricated by a hybrid physical-chemical vapour deposition (HPCVD) system, which is known to be one of the best methods to deposit high-quality MgB_2 thin films. The detailed fabrication process of the HPCVD system has been described elsewhere [3]. The susceptor-contained Mg pieces and we heated Al_2O_3 (000*l*) (10 mm × 10 mm) to 700 ℃ in 200 Torr of 100 sccm H_2 gas flow rate. Then, B_2H_6 (5% in H_2) gas was flowed into quartz tube chamber to start deposition of MgB_2 thin films. Finally, we cooled these MgB_2 films to room temperature in H_2 carrier gas. A clean environment and pure sources of Mg and B are essential for the growth of high-quality MgB_2 thin films. We confirmed the high-quality of the thin films in our previous study [4]. We carried out the Fe irradiation process in Korea Multi-purpose Accelerator Complex (KOMAC). The fixed energy at 140 keV with various doses of 1×10^{14}, 2×10^{14} and 4×10^{14} ions/cm^2 were used to induce the different defects density and consequently the flux pinning strength on the films. The mean projected ranges (δ) of Fe ions were estimated using the Monte Carlo simulation program SRIM [5]. We investigated crystal structure and epitaxial growth of MgB_2 thin films by X-ray diffraction (XRD). The electrical transport was measured using a physical property measurement system (PPMS 9T, Quantum Design).

3. RESULTS AND DISCUSSIONS

Figure 1 shows the temperature-dependent resistivity (R-T curve) of 410 nm thick single-crystalline MgB_2 thin film. The low residual resistivity (defined as the resistivity value just above T_c) ($\rho_0 = 1.2\ \mu\Omega$ cm) indicates high purity of the film with long electron mean free path (l) [2]. High critical temperature ($T_{(c,onset)}$ = 39.5 K) and very sharp superconducting transition (ΔT_c = 0.5 K) reflecting the film has a clean and homogenous phase [6]. The top-inset of figure 1 shows the cross-sectional image was observed with a scanning electron microscope (SEM), which is very dense without any grain boundaries. The bottom-inset shows the

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X-ray diffraction (XRD) pattern of MgB_2 thin film. The high *c*-axis orientation without any impurity peaks and the narrow full-width at half-maximum (FWHM (0002) ~ 0.15°) reflects a clean film with good crystallinity [7]. More details about the study of single-crystalline quality MgB_2 thin films can be found in our previous report [4].

Figure 2 (a) shows the comparatively R-T curves of pristine and Fe ion irradiated MgB_2 films. The resistivity increases at all temperatures, when the T_c decreases systematically from 39.5 K in pristine film to 36.9 K in largest dose irradiated-film. Figure 2 (b) shows the residual resistivity ratio (RRR = ρ_{300K}/ρ_0) of the films before and after Fe irradiations. RRR values were systematically decreased from 5.5 in pristine film to 1.73 in 4×10^{14} ion/cm^2 irradiated film. This is widespread behavior of MgB_2 observed under the various kinds of irradiation [2, 8].

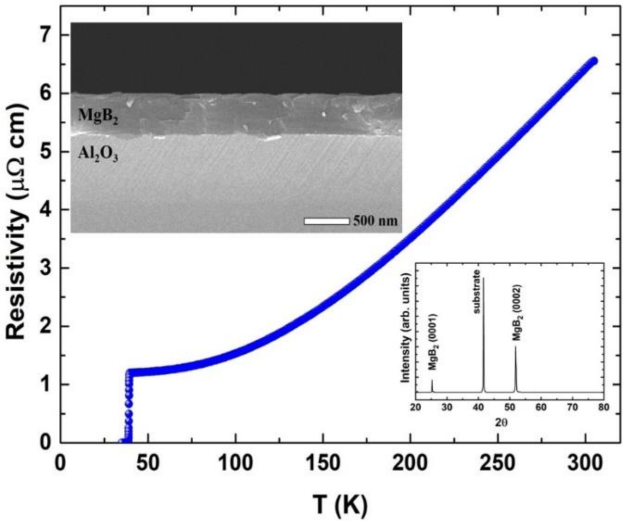

Fig. 1. The temperature-dependent resistivity (R-T curve) of 410 nm pristine single-crystalline MgB_2 thin film. The top-inset shows the cross-sectional SEM image of MgB_2 thin film when the bottom-inset shows its XRD pattern.

We widely accepted within the two-gap model for MgB_2 that active suppression of T_c to 11 K mainly comes from the interband impurity scattering. On the other hand, below 11 K when the two-gap merged to a single-gap, the intraband scattering plays a central role in determining of T_c [2, 9]. Therefore, with the irradiation level in this study, the reduction of T_c is mainly caused by irradiation-induced the interband scattering. The significant increase of ρ_0 indicating defects caused by Fe irradiation increases the scattering rate and consequently, reducing the electron mean free path [7-9]. Interestingly, despite the significant change of T_c and ρ_0, the value $\Delta\rho = \rho_{300K} - \rho_0$ shows a small change. In principle, $\Delta\rho$ is mostly due to phonon scattering; this result implies that the Fe irradiation increased the intragrain scattering without reducing the connected cross-section [2]. We will discuss details about the role of Fe ions in inducing defects below.

Figure 3 (a), (b) and (c) show the R-T curves in various fields of pristine, 1×10^{14} ion/cm^2 irradiated film and 4×10^{14} ion/cm^2 irradiated film, respectively. Figure 3 (d) shows the comparatively upper critical fields (H_{c2}) for all samples. The H_{c2} values were determined from $T_{(c,onset)}$ of R-T curves in fields. The solid lines are extrapolated function for pristine and 4×10^{14} ion/cm^2 irradiated film. Increasing irradiation level significantly increased the H_{c2} and obtained highest value at dose of 4×10^{14} ion/cm^2. The enhancement of H_{c2} in this study is smaller than that of other irradiation methods on MgB_2 such as neutrons, α-particles and so on [2]. However, irradiation energy in this study is minimal compared to typically irradiation energy (usually up to order of MeV). In a type-II superconductor, H_{c2} is a thermodynamic property which we can calculate using: $H_{c2} = \Phi_0 / (2\pi\xi^2)$, where Φ_0 is superconducting magnetic flux quantisation and ξ is coherence length [11]. The Fe ion irradiation-induced the defects in films, which reduce the electron mean free path and consequently, the coherence length, producing an increase in H_{c2} [2, 8].

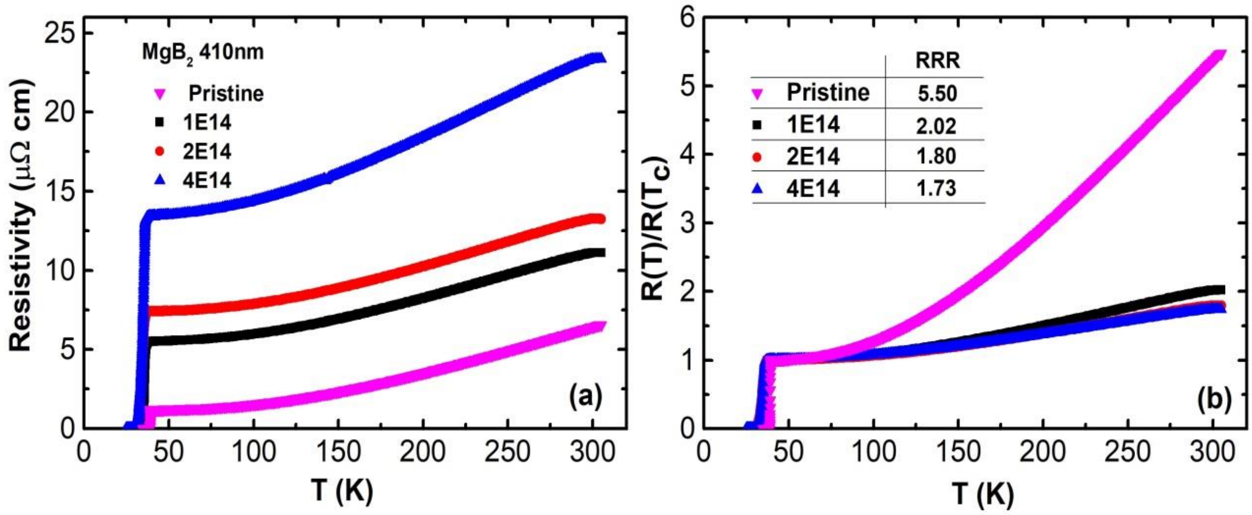

Fig. 2. (a) R-T curves of MgB_2 thin films before and after multiple doses of irradiation. (b) R-T curves normalised at T_c for comparison of residual resistivity ratio (RRR).

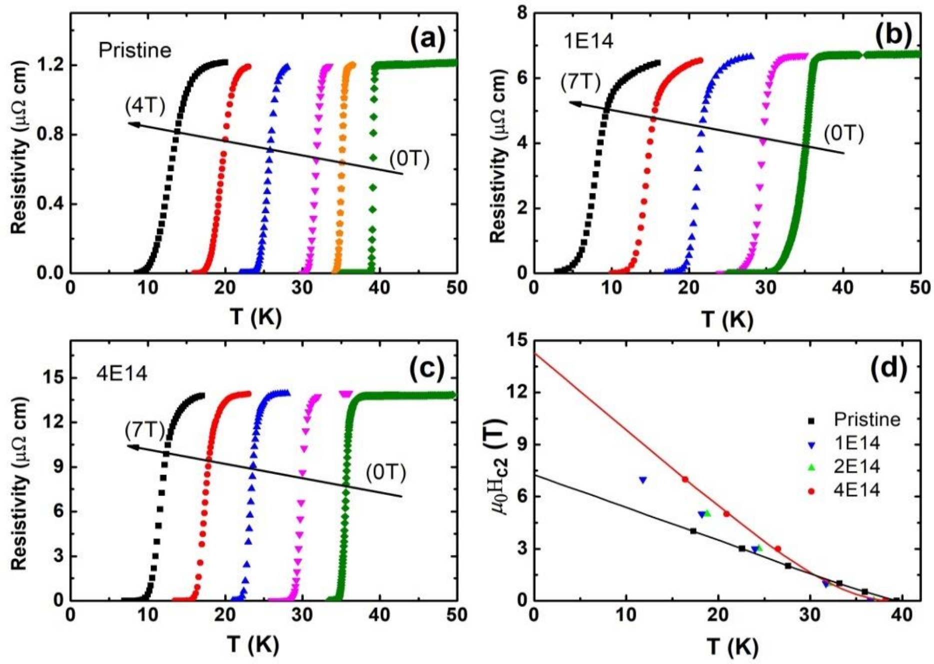

Fig. 3. (a), (b) and (c) The magnified near T_c of R-T curves in various magnetic fields of the pristine, 1×10^{14} ion/cm^2 irradiated film and 4×10^{14} ion/cm^2 irradiated film, respectively. (d) The temperature-dependent H_{c2} of pristine and irradiated samples.

Lastly, we are going to discuss the role of Fe ion irradiation in inducing defects on films. When the Fe ion penetrates the film, it leaves a track from sample's surface and collides with atom in film to produce the displacement. This process can be observed using the transport of ion in matter (TRIM) program [5]. The defects induced by Fe including ion track, point defect (Fe ion) and displacements. Figure 4 shows distribution of displacements in irradiated films using (TRIM). At fixed energy of 140 keV, one Fe ion can induce around 1.4 displacements at average depth. Therefore, the total displacements will increase systematically with the increasing irradiation dose. This ensures a precise change of defects concentration on samples. However, the increasing of H_{c2} is monotonical with irradiation dose, since it also depends on other factors like superconducting band structure and pairing interaction. The details about the study on the effect of irradiation on H_{c2} can be found in [2, 8].

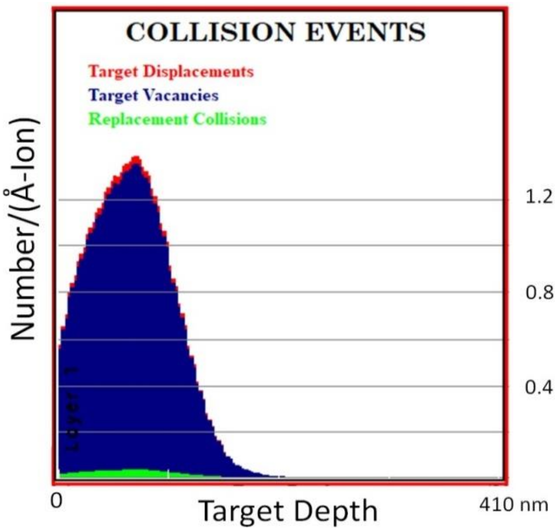

Fig. 4. The displacements induced by Fe ion irradiation in MgB_2. The data estimated using the TRIM program.

4. CONCLUISION

In conclusion, we have substantially enhanced the H_{c2} in single-crystalline in MgB_2 thin films by Fe ion irradiation at low energy of 140 keV and various doses. The defects induced by Fe ion irradiation (including ion tracks, point defects and displacements) reduce the electron mean free path in the film, leading to an increase of H_{c2}. We can expect a better performance of H_{c2}, which could be obtained at higher irradiation energy since it provides a higher ion mean projected ranges into samples and decreases the electron mean free path.

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