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Effects of α-particle beam irradiation on superconducting properties of thin film MgB_2 superconductors

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Abstract

Superconducting properties of thin film MgB2 superconductors irradiated with 45 MeV α-particle beam were studied. After the irradiation, enhancement of the critical current density and pinning force was observed, scaling close to strong pinning formula. Double logarithmic plots of the maximum pinning force density with irreversible magnetic field show a power law behavior close to carbon-doped MgB2 film or polycrystals. Variation of normalized pinning force density in the reduced magnetic field suggests scaling formulas for strong pinning mechanism like planar defects. We also observed a rapid decay of critical current density as the vortex lattice constant decreases, due to the strong interaction between vortices and increasing magnetic field.

Keywords : Superconductivity, Vortex pinning, Ion beam irradiation

1. INTRODUCTION

Since its discovery as a new superconductor in 2001 [1], MgB_2 has been of great interest in scientific community. Its relatively high level of a critical temperature and a critical field, and a simple crystal structure with no weak link make it very interesting for both theoretical and technological perspective [2-5].

For application, it is of prime importance to have high critical current (J_c), which depends on the pinning centers inside the superconductor. Higher critical current density of MgB_2 is required due to the fact that MgB_2 superconducting tapes and wires are already on the industrial production line [6]. Understanding the vortex pinning mechanism is crucial for that purpose. Further, a multitude of approaches have been developed to enhance the critical current density J_c of superconductors: doping [7-9], adding nanoparticles [10, 11] or a buffer layer [12], irradiation of particle beams [13, 14], reduction of grain size [15, 16].

One of the promising approaches to enhance pinning properties is the introduction of defects by means of particle irradiation. There were a variety of particle beams used, such as proton [17], electrons [18], neutrons [19], and heavy ions such as helium [20], silver [21-23], silicon and gold [24], lead [25], and uranium [26], with mixed results. Heavy ion irradiation enhances J_c significantly with possible degradation of T_c, by creating columnar defects in the sample. It has been shown that columnar defects are very strong pinning centers [27-30].

In this paper, we report the results of α-particle beam irradiation on the single crystalline MgB_2 thin films. We show the irradiation effect on pinning properties and analyze the underlying physics.

2. EXPERIMENTAL PROCEDURE

Thin film MgB_2 samples were prepared on Al_2O_3 (0001) substrates by a hybrid physical-chemical vapor deposition (HPCVD) method [31-35].

The samples were irradiated by an α-particle beam at 45 MeV and 100 nA from MC-50 cyclotron in Korea Institute of Radiological & Medical Sciences (KIRAMS) at room temperature. Several samples cut from the same film were irradiated along their thickness (500 nm) with different irradiation doses from 10^{11} to 10^{14} particles/cm^2.

After irradiation, the samples were brought under the magnetization measurements using Magnetic Property Measurement System (MPMS). All the measurements were performed with the applied field parallel to the beam direction. The critical current density was calculated from the M-H curves using Bean's critical state model ($J_c = 30\Delta M/r$), where ΔM is the height of M-H loop at a magnetic field H, and r is the “hydraulic radius”

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corresponding to the area of sample surface. The pinning force density F_p was calculated from the relation $F_p = J_c \times \mu_0 H$. All the samples show a diamagnetic transition in the zero field cooling (ZFC) measurements. The critical temperatures T_c at the onset of transition are listed in Table I.

3. RESULTS AND DISCUSSION

We show the irradiation effect on pinning properties and analyze the underlying physics.

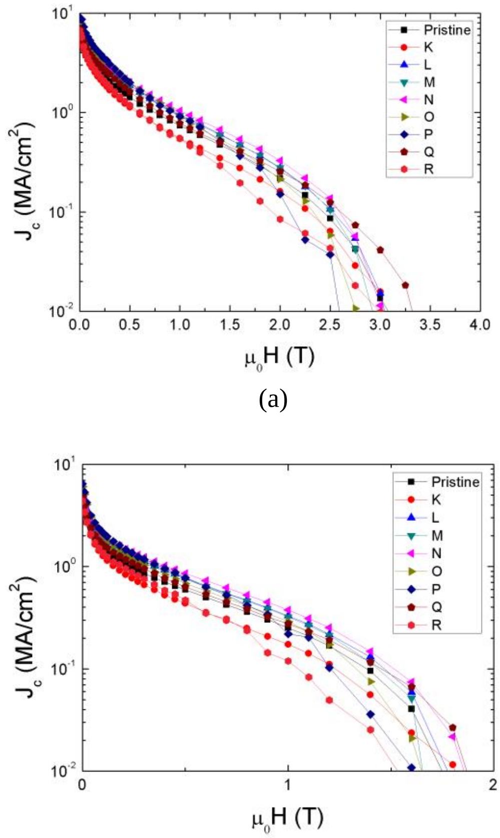
TABLE I
IRRADIATION DOSES OF α PARTICLES AND MEASURED CRITICAL PROPERTIES FOR VARIOUS MgB_2 SAMPLES.

Sample	**Irradiation dose (p/cm^2)**	**$J_{c,max}$ (T=5K) (MA/cm^2)**	**$J_{c,max}$ (T=20K) (MA/cm^2)**	**T_c (K)**
Pristine	0	6.47	4.1	37.6
K	5×10^{11}	5.18	3.59	37.6
L	1×10^{12}	7.95	5.55	37.8
M	5×10^{12}	7.56	4.98	37.8
N	1.15×10^{13}	8.74	5.75	37.8
O	5.8×10^{13}	9.02	6.08	37.8
P	7×10^{13}	9.06	6.44	37.8
Q	1.16×10^{14}	6.99	4.76	37.8
R	5.82×10^{14}	6.74	4.38	37.8

Table I lists the irradiation doses of α-particles along with the maximum critical currents at T = 5 K and 20 K, and critical temperatures for samples K to R plus unirradiated, pristine sample. For samples K to R, the irradiation dose increases from 5×10^{11} to 5.82×10^{14}. Therefore, extremely large number of defects were created inside the samples by irradiation. The maximum values of J_c's occurring in self-field (H = 0) are generally higher than that of pristine sample, except for the sample K. $J_{c,max}$ increases as the irradiation dose increases, for samples L to P. A further increase of the irradiation dose results in a decrease of J_c presumably due to a decrease in the superconducting volume fraction. Strangely enough, the sample R, bombarded with the enormous amount of particles 5.82×10^{14} p/cm^2, has $J_{c,max} = 6.74$ MA/cm^2 at T = 5 K and $J_{c,max} = 4.38$ MA/cm^2 at T = 20 K. These values are even higher than the values of $J_{c,max}$ of sample K, which has received the least dose of irradiation.

Fig. 1 shows the measured critical current density of J_c for the various samples. The amount of irradiation are summarized in Table I. The J_c value of a pristine sample was approximately 0.6 MA/cm^2 at 20 K and 1 T, which is considerably high compared to the reported value of bulk samples [36]. For the same temperature and field, it was reported that J_c is about 1 MA/cm^2 in MgB_2 film on polytype SiC substrates [37], and 0.5 MA/cm^2 from a 150 nm bridge in an MgB_2 film on SiC substrate [38].

In Fig. 1 (a) at T = 5 K, the sample P (navy diamond) shows the maximum level of J_c at a self-field. However, the J_c of the sample falls at the fastest rate as the applied field H increases. When $\mu_0 H > 2.5$ T, $J_{c,P}$ is the lowest except for the critical current of sample R. On the other hand, for sample Q (brown pentagon) the J_c starts at the lower level, persists up until the highest level of the magnetic field, $\mu_0 H$.

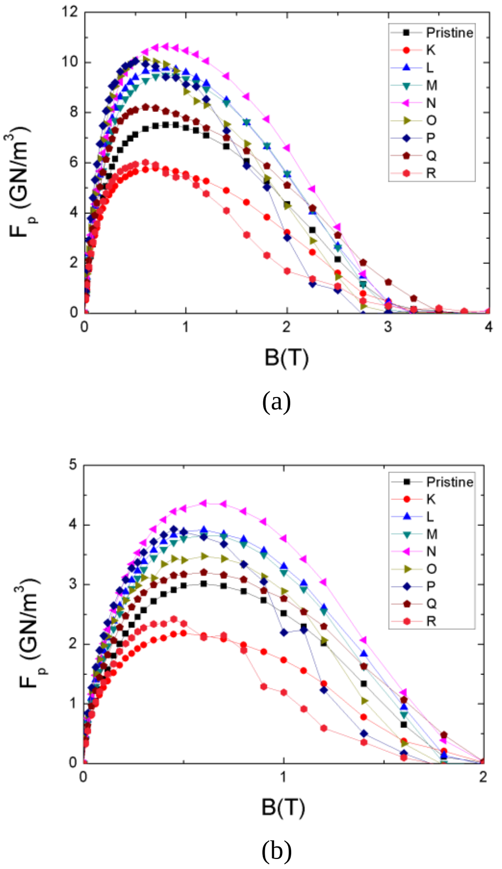


(a)

(b)

Fig. 1. Critical current density as a function of applied field for the films irradiated various doses. (a) T = 5 K, (b) T = 20 K.

For all the measured samples, the J_c was found to decay monotonically with magnetic field. For pristine sample, the rapid decrease of J_c at high magnetic field is attributed to the absence of pinning centers. As magnetic field gets higher, the J_c's of the samples diminish in the order as P - O - M - R - (Pristine, K, L, N) - Q at T = 5 K (Fig. 1 (a)). Here the J_c's of the 4 samples (Pristine, K, L, N) diminish almost in the same way. At T = 20 K, the order becomes R - P - O - M - Pristine - L - K - N – Q (Fig. 1 (b)). This suggests that there are no effective pinning centers inside the samples with their J_c's diminishing faster than pristine sample (M, O, P, R). The samples are likely to have been damaged due to the high dose of α-particle beam. Such degradation of superconductivity of sample is already manifest in sample R. The reason of the high J_c in self-field in sample R might be that the damaged crystal structure works as grains in self-field, but eventually it is not so effective as pinning centers. The other samples (K, L, N, Q) might have effective pinning centers, although the samples K, L, N do not perform much better than pristine sample at T = 5 K.



(a)

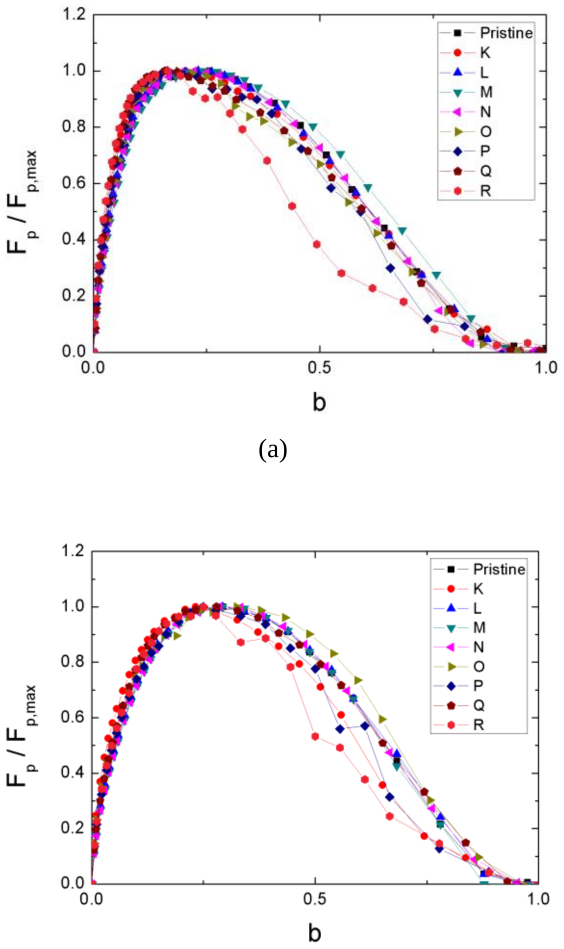
(b)

Fig. 2. Pinning force density as a function of applied field for various irradiation doses. (a) T = 5 K, (b) T = 20 K.

Fig. 2 shows the flux pinning densities (F_p) as functions of the magnetic field, calculated from the $J_c(H)$ data of Fig. 1 at 5 and 20 K. The F_p is enhanced as the irradiation dose increase in the low magnetic field, but becomes about the same magnitude in the high magnetic field. As the irradiation dose becomes larger, the density of defects increases and more vortices can be pinned at the defects. However, the pinning force is not strong enough that the critical current density diminishes in the high magnetic fields around 2 T.

TABLE II
IRREVERSIBLE FIELDS AND MAXIMUM PINNING FORCE DENSITIES FOR VARIOUS MgB_2 SAMPLES.

Sample	**B* (T=5K) (T)**	**$F_{p,max}$ (T=5K) (GN/m^3)**	**B* (T=20K) (T)**	**$F_{p,max}$ (T=20) (GN/m^3)**
Pristine	3.5	7.51	2.05	3.01
K	3.45	5.78	2.15	2.19
L	3.45	9.77	2.05	3.92
M	3.3	9.49	2.05	3.83
N	3.6	10.63	2.1	4.36
O	3.2	10.1	1.85	3.48
P	3.05	10.06	1.8	3.93
Q	3.8	8.22	2.15	3.21
R	3.65	6.02	1.8	2.42



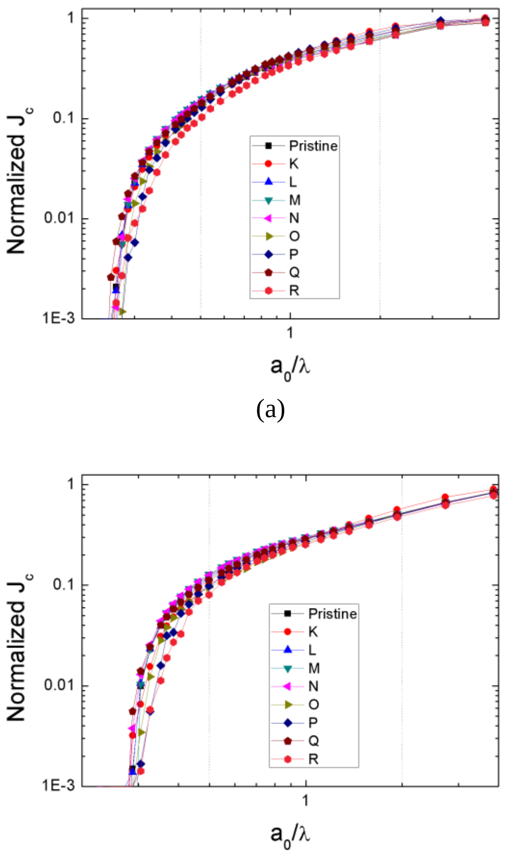
(a)

(b)

Fig. 3. Normalized pinning force density as a function of irreversible field for various irradiation doses. (a) T = 5 K, (b) T = 20 K.

From the Kramer plot $J_c^{1/2} B^{1/4} \propto (B^*-B)$ [3,39–41], we estimate the irreversible field B* by a linear fitting in the region of high magnetic field. The values of B* are listed in Table II along with the maximum values of the flux pinning force density in each case. Double logarithmic plots of $F_{p,max}$ -B* show that $F_{p,max}$ roughly scales with B* according to the power law $F_{p,max} \propto (B^*)^{1.7}$ at both temperatures T = 5 K and 20 K, which is close to the behavior of carbon-doped MgB_2 films or polycrystals [8, 39].

The pinning force densities F_p are normalized by the maximum pinning force density $F_{p,max}$ for each sample and plotted against the reduced magnetic field b = B/B*, which are shown in Fig. 3. These curves generally fit to the curve $b^{0.55}(1 - b)^{1.8}$ at T = 5 K, $b^{0.75}(1 - b)^{1.8}$ at T = 20 K. These relations are close to the scaling formula for a strong pinning mechanism, such as planar defects [42, 43]. It is difficult to describe the physical mechanism of the scaling model for flux pinning precisely, but the data suggest a strong intrinsic pinning where the boron layers in MgB_2 are playing an important role [28].



(a)

(b)

Fig. 4. Normalized critical current density as a function of vortex lattice constant (a_0) nondimensionalized with penetration depth (λ) for various irradiation doses. (a) T = 5 K, (b) T = 20 K.

Fig. 4 shows normalized critical current density as a function of inter-vortex distance a_0/λ for various irradiation doses. The J_c's are normalized to the $J_{c,max}$ for each sample, and the vortex lattice constant a_0 is estimated by using the relation $a_0 \approx (\varphi_0/B)^{1/2}$, where φ_0 is the flux quantum and B is magnetic field caused by trapped vortices in the sample. Here, we used $\lambda(0)$ = 100 nm and the relation $\lambda(T) = \lambda(0)/[1-(T/T_c)^2]^{0.5}$ to obtain the $\lambda(T)$ at the temperatures 5 and 20 K [6,44,45]. The dependence of the penetration depth λ on magnetic field, due to the interband coupling, has been reported [46,47] but ignored in this study.

The size of the vortex–vortex interaction energy for finite films is mainly decided by the inter-vortex distance a_0/λ, and the film thickness. If the film is not too thick and the inter-vortex distance is large enough, the vortex–vortex interaction energy will be much larger than that in the bulk sample, and become almost saturated in the region of $a_0 > 3\lambda$ [48]. Rapid increase in the interaction energy for $a_0 < 2\lambda$ in the MgB_2 thin films is inferred in Fig. 4. The J_c's decrease all along, because the inter-vortex interaction is strong and the pinning is weak in our samples. Furthermore, for $a_0/\lambda < 0.5$, below the first dashed line, the J_c's show an exponential decay as the interaction between vortices becomes stronger. The suppression of superconductivity in high magnetic field might also have influenced on it. The linear region between $a_0/\lambda \approx 0.5$-2 (between the two dashed lines) are related to collective pinning [49,50]. In Fig. 4, the curves of the normalized J_c's overlap fairly well for $a_0 > \lambda$ for all samples. However, when the vortex lattice constant become smaller than the penetration depth, the rates of decrease in the normalized J_c's become higher for higher irradiation dose due to the increasing inter-vortex interactions.

4. CONCLUSION AND SUMMARY

We present the studies of the high-energy irradiation effect on the superconducting properties of single crystalline MgB_2 thin film samples. We found the irradiation generally improves both the critical current density and pinning force density. It was found that $F_{p,max} \propto (B^*)^{1.7}$ at both T = 5 K and 20 K, which is the behavior close to carbon-doped MgB_2 films or polycrystals. Variation of normalized pinning force density $F_p/F_{p,max}$ in the reduced magnetic field b = B/B* roughly fits to the curve $b^{0.55}(1 - b)^{1.8}$ at T = 5 K, $b^{0.75}(1 - b)^{1.8}$ at T = 20 K, suggesting scaling formulas for strong pinning mechanism like planar defects. Exponential decay of critical current is observed as the vortex lattice constant decreases, due to the strong interaction between vortices. In the future the optimal energy and irradiation dose will be sought for further enhancement of pinning in the MgB_2 film.

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