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The effect of 200 MeV Ag ion irradiation on the temperature and field dependence of critical current density (J_C) of high quality MgB_2 thin films is studied. Substantial increase in J_C is observed over a certain field range for the film irradiated at a dose of 10^{12} ions/cm^2. Our analysis suggests that columnar defects are not formed under irradiation conditions used in these studies, which correspond to an electronic energy loss of about 16 keV/nm. Defects clusters are likely to be responsible for the observed improvement in J_C. *© 2004 American Institute of Physics.*
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The discovery of superconductivity at 39 K in MgB_2 has renewed the interest in the area of intermetallic superconductors.[1–4] It is known that J_C of a superconductor can be enhanced by creating vortex pinning centers.[5] One way to produce such pinning centers is high-energy heavy ion irradiation to generate columnar defects along the ion trajectories. Columnar defects have been shown to enhance J_C in YBCO, $Bi_2Sr_2CaCu_2O_{8+\delta}$, and other high T_C superconductors.[6] However, only a marginal increase in J_C has been reported by high-energy heavy ion irradiation in MgB_2.[7–10]

In this letter, we report the results of 200 MeV Ag ion irradiation (corresponding to an electronic energy loss, $S_e = 16$ keV/nm) of high quality epitaxial thin films of MgB_2. Our analysis shows that the threshold electronic energy loss (S_{et}) for creating columnar defects in MgB_2 is much higher than that compared to the high T_C films. As a result columnar defects are not formed in our films. However, substantial increase in the J_C (in specific field range) is observed for the sample subjected to high irradiation dose, presumably because of the pinning caused by agglomerated defects.

The films used for these studies were grown on 4H–SiC (0001) by a hybrid physical–chemical vapor deposition technique.[11] The films were patterned in the form of microbridges (20 μm$\times$2 mm and 30 μm$\times$2 mm) for the J_C measurements. A standard four-probe technique with a dc current source was used for transport measurements. The irradiations were performed at room temperature with 200 MeV ^{107}Ag ion beam from a 15UD pelletron accelerator at the Nuclear Science Center, New Delhi, at doses of 3×10^{11} (sample ID: C_{11}) and 10^{12} (sample ID: C_{12}) ions/cm^2. The approximate range of the ions in MgB_2 is about 18 μm, much larger than the film thickness (150 nm).

Figure 1 shows the temperature dependence of resistivity (ρ) for the unirradiated and irradiated films. These data were

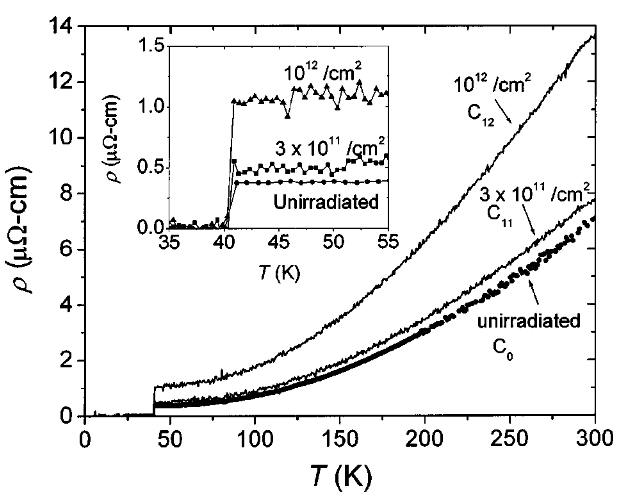

FIG. 1. The $\rho-T$ curves for the unirradiated and irradiated samples. The inset shows same curves on expanded scale.

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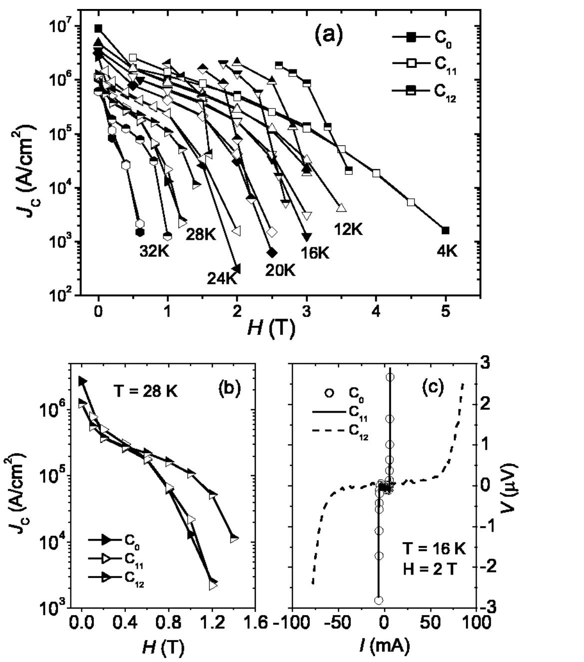

FIG. 2. (a) J_C vs H curves at different temperatures for unirradiated and irradiated samples. The data for samples C_0, C_{11}, and C_{12} are shown by filled, open, and half-filled symbols, respectively. (b) The same data for the case of $T=28$ K. (c) $I-V$ curves for samples C_0, C_{11}, and C_{12} at $T=28$ K and $H=1$ T.

measured with a constant current of 0.1 μA. A rather low value of normal state ρ, high residual resistance ratio (RRR $=19.2$), and $T_C=40$ K of the unirradiated film indicate the high quality of the film. No change in T_C (inset of Fig. 1) was observed for both the irradiated films. The ρ was found to increase only slightly for sample C_{11}, suggesting that after irradiation hardly any damage is induced/sustained in sample C_{11}. However, for sample C_{12}, a moderate level of irradiation-induced damage is evident from an almost two-fold increase in ρ as well as a drop in RRR by about 30%.

Figure 2(a) shows J_C as a function of H at different T for irradiated and unirradiated films. The J_C values were obtained from current (I) versus voltage (V) measurements (10 μV/cm criterion). After irradiation at a dose of 3×10^{11} ions/cm^2 (sample C_{11}), the J_C and its dependence on H and T were similar to that of unirradiated sample (except for a small increase in J_C at higher H). However, after irradiation with 10^{12} ions/cm^2 (sample C_{12}), substantial changes were observed in the J_C values as well as its T and H dependence. At zero and low H, the J_C is slightly reduced after irradiation. At higher H (up to a certain field H^*), it is larger after irradiation. This is explicitly shown in Fig. 2(b), where data for $T=28$ K is plotted. As an example, the $I-V$ curves from which the J_C values are determined are shown in Fig. 2(c) for a particular case of $T=28$ K and $H=2$ T. The substantial difference in the $I-V$ curves of samples C_{12} and C_0 is clearly visible. This improvement in J_C of sample C_{12} continues up to H^*, above which it drops below the value for the unirradiated sample [Fig. 2(a), curves at low T]. The qualitative features of the field dependence of J_C remain the same even with the use of different criteria (e.g., 1 μV/cm) to determine J_C. In short, in a specific range of H, about an order of magnitude increase in J_C is observed after irradiation with 200 MeV Ag ions at a dose of 10^{12} ions/cm^2.

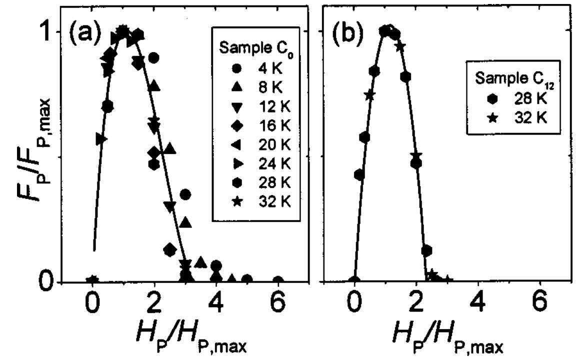

FIG. 3. Normalized pinning force as a function of normalized field for the samples C_0 (a) and C_{12} (b). The lines are fit to the data.

It has been shown[12] earlier that the pinning force density ($F_P=J_C\times H$) vs H curves measured at all temperatures can be scaled into a single curve when plotted on the reduced scale, $F_P/F_{P\,\max}(=f)$ vs $H_P/H_{P\,\max}(=h)$. Here $F_{P\,\max}$ is the maximum value of F_P and $H_{P\,\max}$ is the corresponding field. The functional form of this universal curve depends on the pinning mechanism. Such scaling behaviors are seen in our measurements with $f=1.9h^{0.9}\,(1-0.3h)^{1.8}$ for unirradiated sample C_0 [see Fig. 3(a)], $f=1.99\text{h}^{0.7}\,(1-0.3h)^{1.8}$ for sample C_{11}, and $f=1.8h(1-0.43h)^{1.0}$ for sample C_{12} [see Fig. 3(b)]. This indicates that sample C_{11} has a similar pinning mechanism as for sample C_0, whereas in sample C_{12} the dominant pinning centers created by irradiation are different.

In order to observe the defect structure on the film surface, the film morphology was studied by atomic force microscopy. Earlier, using the same microscope, we had clearly observed[13] the morphological deformations caused by columnar defects formed in $La_{0.7}Ca_{0.3}MnO_3$ films. However, no such signatures are observed in either of the samples C_{11} and C_{12}. Similarly, no indications of columnar defects were observed in the scanning electron microscopy. These observations strongly suggest that columnar defects are not formed in MgB_2 at the ion beam energy used here. This would explain our J_C data for the sample C_{11}.

In the electronic energy loss regime, when S_e is above some threshold value (S_{et}), columnar defects can be formed.[14] By using the stopping and range of ions in matter (SRIM) simulation program, we found that the dominant loss in our films is the electronic energy loss, which is ~16 keV/nm throughout the film thickness. This value is close to S_{et} for high T_C oxide superconductors and oxide insulators (4–25 keV/nm).[13–15] However, given the intermetallic nature, the threshold value for MgB_2 may be much higher than that of oxides. For Fe, only point defects are formed for S_e up to 70 keV/nm.[16] In Ti for S_e ~39 keV/nm, the damage was in the form of isolated regions where high density of dislocation loops was found.[17] No substantial damage was observed in a number of metals such as Cu, Ag, and W even after subjecting to a very high $S_e\sim100$ keV/nm.[17] In $NiZr_2$, columnar defects are found above $S_e\sim48$ keV/nm.[17] In Ni_3B, following the irradiation with high S_e, the columnar defects were formed, but they were unstable at room temperature and disappeared in a few months.[17]

Based on S_{et} values in metals in metallic alloys, it seems reasonable that no columnar defects are expected to form in our films. Due to the lack of a theoretical model to describe the columnar defect formation in intermetallic compounds or metals, it is not possible to estimate the value of S_{et} for MgB_2. At S_e lower than S_{et} either point defect clusters or spherical/elongated discontinuous regions of modified material are formed depending upon S_e value relative to S_{et}. Dammak and Dunlop observed that discrete regions with high density of dislocation loops of various shapes could be formed in metallic targets.[18] Moreover, point defect agglomerates can also be formed.[19] Either of these defect configurations is possible in our case.

In the framework of formation of small defects it is understandable that the J_C is not changed for sample C_{11} (low dose); however, with a substantial increase in irradiation dose, changes in the J_C are observed (sample C_{12}). At lower dose, the defect density is low and no strong pinning site density is offered and only a small decrease in J_C is seen arising from reduced superconducting fraction. With an increase in dose, and hence an increase in defect density, the defects can combine and form extended defects capable of interacting with and pinning the vortices strongly, thereby changing the J_C. Such an improvement in J_C (in the high field regime) was also observed recently in MgB_2 powders irradiated with high-energy protons and neutrons.[20] It was suggested that the point defects might form loops capable of pinning the vortices.

It would be useful to mention here that as shown in Fig 2(a), there is no enhancement of J_C for sample C_{12} above the field H^*. Indeed, above H^*, it drops below that of unirradiated film. Such a behavior has been observed when the point defects were created in high T_C superconductors either by electron irradiation or by oxygen deficiency.[21] Generally, columnar defects do not produce this type of behavior.

We now comment on why no substantial improvement in J_C was observed in MgB_2 irradiated with heavy ions by different groups. Note that the studies done so far have all used the conditions where S_e is not much higher than what we used here. Chikumoto *et al.*[7] used 5.8 GeV Pb ions corresponding to S_e in the range $\sim$18–20 keV/nm. Okayasu *et al.*[8] used 3.54 GeV Xe ions, corresponding to S_e $\sim$10 keV/nm. For 1.2 GeV U irradiation by Olsson *et al.*,[10] the value of S_e was $\sim$25 keV/nm. As in our case, the columnar defects are not likely to form in their samples and small defects are possibly created. Since the maximum irradiation doses studied in these other studies are low (in the range 1×10^{11}–2×10^{11} ions/cm^2), the density of pinning centers is too small to observe significant changes in J_C.

In conclusion, significant enhancement in critical current density, in a specific magnetic field range, is observed for MgB_2 films irradiated with 200 MeV ^{107}Ag ions (electronic energy loss $\sim$16 keV/nm) at a dose of 10^{12} ions/cm^2. No columnar defects are observed in any of the films. Formation of defect clusters in high concentration is suggested to be responsible for the observed improvement in J_C.

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