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Heavy-Ion Damage to Magnesium Diboride Films: Electrical Transport-Current Characterization

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ABSTRACT

The use of magnesium diboride in superconducting magnets, transmission lines, or other large-scale applications depends on the transport-current characteristics of this material in magnetic field, and how they compare to the properties of conventional and high-temperature superconductors. Thin films of boron grown on sapphire substrates during electron-beam evaporation were exposed to Mg vapor to produce 0.5-μm thick layers of the metallic compound MgB_2. Four-terminal measurements of their voltage-current relations, E(J), were carried out before and after exposure to B_ϕ=1-T and higher doses of 1-Gev U ions. These doses lowered critical temperatures T_c≈39 K less than 0.1 degree, raised the normal-state resistivity, and reduced the loss-free critical current density, J_c. Higher doses added little. The reduction of current densities was greater in the presence of applied magnetic field greater than 0.1 T.

INTRODUCTION

The relatively new superconducting material MgB_2 [1] shows characteristics that give it encouraging prospects for many practical future applications. This compound is intrinsically stable and not sensitive to environmental exposures as are some high-temperature superconducting compounds such as $YBa_2Cu_3O_x$. Early studies [2] indicated that, unlike the higher temperature superconductors $YBa_2Cu_3O_x$ and $Bi_2Sr_2Ca_2Cu_3O_x$, MgB_2 grain boundaries permit excellent intergranular electrical current flow. These features are common to both bulk ceramic material and to thin films. On the other hand, the naturally strong electrical anisotropy limits bulk, intergranular current flow.

Like classical low temperature superconductors, crystalline defects can interact with mixed-state vortices, pinning them and reducing their lossy motion while they are under a driving force arising from electrical transport current. Such defects can be introduced in a controlled way by exposing the material to ionizing radiation. Our films were irradiated by 1-Gev U ions at Argonne National Laboratory. One expects such radiation to produce badly damaged or amorphous tracks through the crystalline film. For the high-T_c compounds such badly damaged regions locally reduce the superconducting order parameter. Low temperature superconductors cannot change their order parameters over such short ranges and have no such local reduction. With a low-temperature coherence length of 3-6 nm, MgB_2 is expected to behave similarly to the high-T_c materials. Consistent with an earlier proton irradiation study, [3] we found damage to reduce loss-free critical currents at significant magnetic field.

FILM GROWTH

Thin films have been grown by several techniques.[4-9] The films of this report were produced by evaporating boron, depositing it amorphously on sapphire substrates, and heating that film in a magnesium atmosphere. This technique is discussed in more detail elsewhere. [9,10] In the first step amorphous boron films of 500-600 nm thicknesses were deposited on sapphire substrates. The boron atmosphere was generated by electron-beam heating of the source in a vacuum chamber with a base pressure of 10^{-6} Torr. Mg was introduced by exposing the B films to Mg vapor inside a crimped Ta tube sitting in a sealed quartz furnace chamber. The film substrates were sandwiched between cold-pressed MgB_2 pellets sitting near some Mg wire. Film growth occurred while the assembly was heated to 890 °C for one hour. For transport current measurements, the resulting black film was etched into a narrow stripe with substrate-wide end patches. Current contacts were made by pressing indium pads between the wide film ends and square Cu blocks. Additional film was grown upon a sapphire substrate with maximum dimension less that 6 mm, small enough to fit into a SQUID magnetometer.

SEM images, such as that of Fig. 1, clearly show many film grains. These grains appear of random orientation, but x-ray analysis indicates some degree of c-axis but random in-plane texture. [10]

ELECTRICAL CHARACTERIZATION

Four-terminal electrical transport-current measurements of 0.1-0.4-mm wide film strips and magnetization measurements of films on 40-mm^2 plates are discussed below. We note that the critical current densities deduced from both types of study agree reasonably well. Additional information is available in the detailed current voltage characteristics. At relatively high temperature and high magnetic field we observed linear electrical potential with current flow at very low currents below the critical values. In the

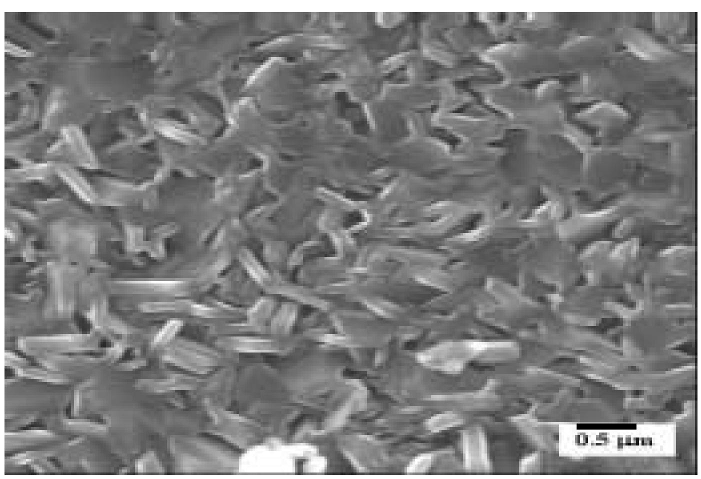

Fig. 1. SEM micrograph for MgB_2 film on Al_2O_3 substrate showing its granular microstructure.

intermediate regime a nonlinear power relation dominates. We define an irreversibility condition as where the potential as a function of current density, *E(J)* is proportional to J^2. Under conditions just below this irreversibility line the function *E(J)* rises very sharply from the sub-critical regime (E≅0) with a high-power-law relation $E(J) \propto J^n$, n~10-100. Finally, very high current flow brings the potential to approach $E=\rho_n J$, where ρ_n is the normal-state resistivity.

CRITICAL TEMPERATURES

The critical temperatures, T_c, of two samples are shown in Figure 2 measured by different techniques. Magnetization of the film grown on a substrate of less than 6-mm size was measured in the SQUID magnetometer with an applied filed of 4 Oe. Magnetic hysteresis of this sample in much higher applied fields is discussed below. The resistance of a film strip shows a sharp transition at the high-temperature end of the magnetic transition. The reader will note that an ion beam dose of 5×10^{10} ions/cm^2 (B_ϕ=1 T) increased electrical resistivity but made very little change in the critical temperature, T_c, of the superconducting state. However, we caution the reader that our resistance observations are substantially less certain than the observed data scatter. Various

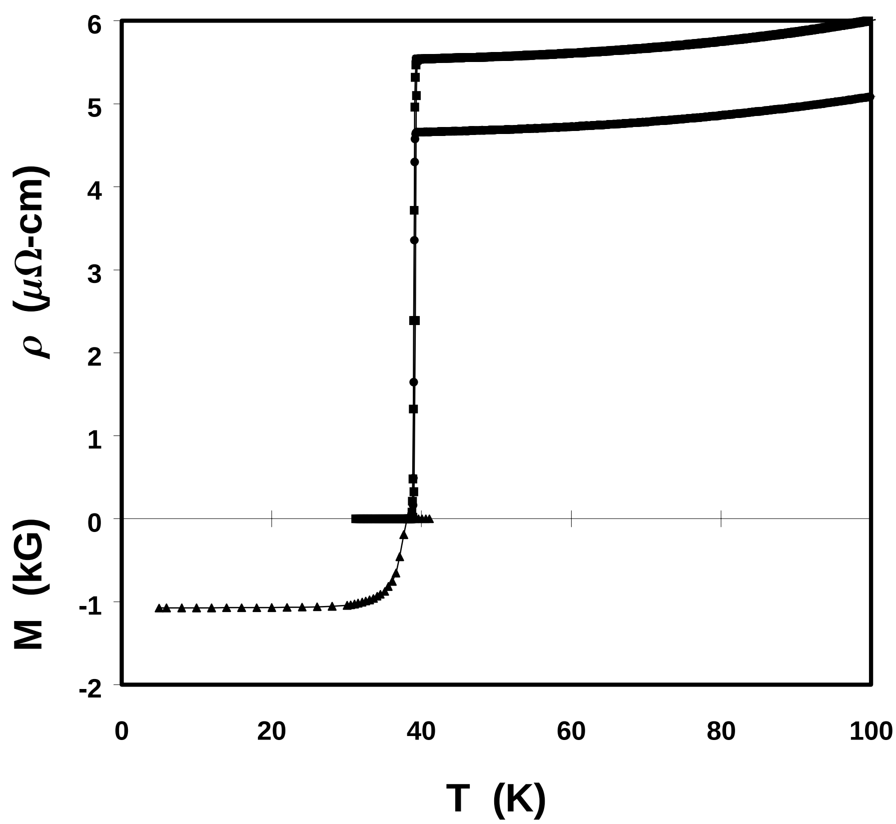

Fig. 2 Magnetization (▲) and transport-current resistive transitions (1-T dose ■, unirradiated ●) are shown for MgB_2 films.

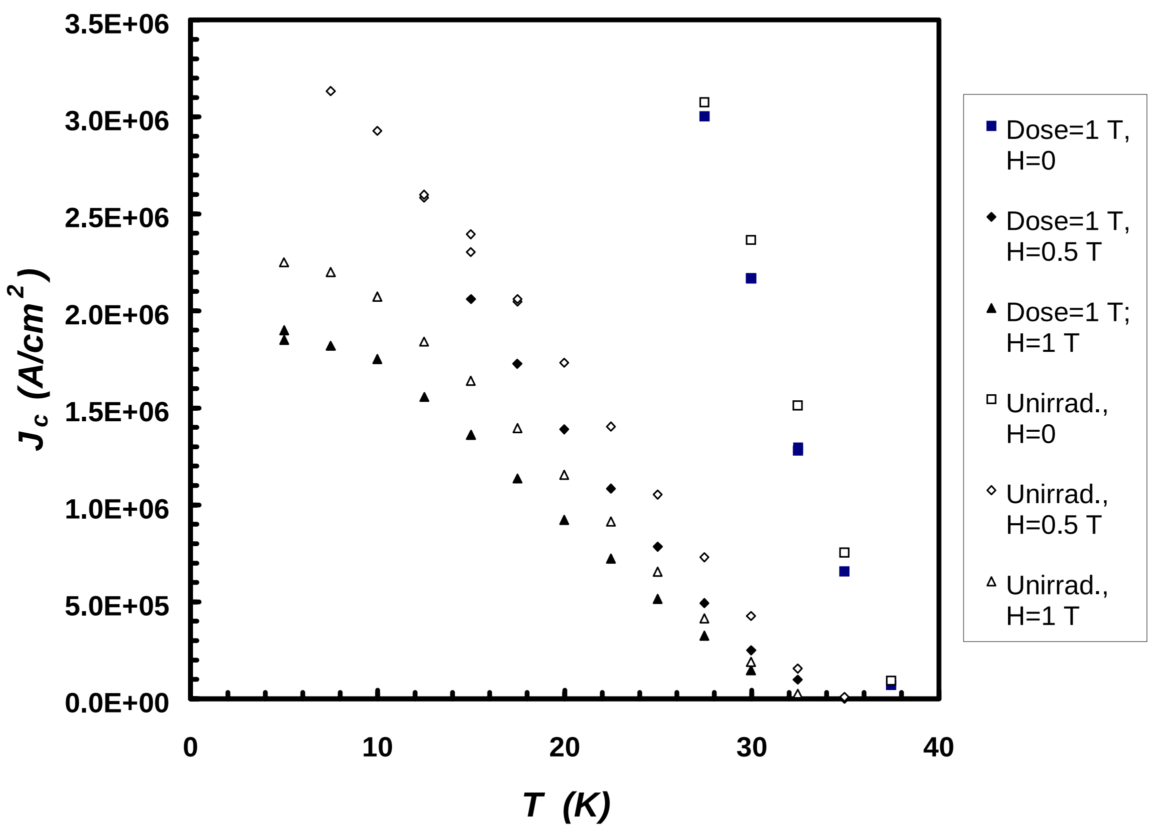

Fig. 3 Transport critical current density of MgB_2 film before ands after irradiation to a dose of 5×10^{10} ions/cm^2 (B_ϕ=1 T).

measurements gave resistance scales that varied by about 20%; likely arising from differing current paths between changing voltage-contact positions.

CRITICAL CURRENT DENSITY

We report observed transport critical current densities (J_c) of the film exposed to a 1-T dose of 1-GeV U ions. In self-field the radiation changed J_c very little, but with modest magnetic field applied (B>0.1 T), the result was a current-carrying capacity reduced below the pre-irradiation value. Other samples with heavier doses showed comparable effects. The film exposed to B_ϕ=4 T showed $J_c(T)$ curves that crossed the data for an unirradiated sample at a temperature of about 15 K. We speculate that this reduction of critical current density arises because of the loss of some local magnetic field alignment perpendicular to grain c axes in the presence of macroscopic applied field perpendicular to the film surface and predominately parallel to c. It has been widely observed in studies of high-T_c superconductors that **H**⊥c permits vortex pinning between Cu-O planes and permits very high loss-free current flow. Bulk transport current is naturally inclined to take percolative paths that make the self-field locally parallel to the ab planes. Heavy ion damage in those planar superconductors both increases J_c for **H**//c and decreases J_c for **H**⊥c. [11] One expects radiation damage to improve local current flow for all c-oriented grains; however the presence of many grains with c 45° from the film surface is evident in the (101) peak, which is approximately 5% of the (002) peak strength in Fig. 2 of Ref. 10. The presence of these and other differently oriented grains contributes to flux pinning, but also leads to complex current flow paths. The vortex lines must consist of both pancake vortices in the c planes linked by Josephson vortex lengths. Assuming the disordered tracks of heavy ion damage reduces the local order parameter implies pinning of the planar vortices and easy motion of the intrinsically pinned Josephson lengths. Although MgB_2 is less anisotropic than the high-T_c materials, [12,13] this observation suggests a comparable image of mixed magnetic flux lines.

CONCLUSIONS

The polycrystalline MgB_2 films with excellent inter-granular contact carry quite large currents. However, some subtle features suggest that the current flow in the crystalline c direction is weak. In particular the relatively small portion of non-c-oriented grains make heavy-ion irradiation reduce the sample current-carrying capacity in the presence of applied magnetic field. This conclusion appears to contradict previous observations of relatively weak anisotropy. Both the intrinsic anisotropy and the damage effect of heavy ion irradiation need further study.

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