Electron scattering dependence of dendritic magnetic instability in superconducting MgB_2 films

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Magnetic instability in both ultrapure and carbon-doped MgB_2 films is investigated by magneto-optical imaging, transport, and bulk magnetization measurements. In the carbon-doped MgB_2 thin films, familiar dendritic flux-jump patterns were observed at low temperature as reported in previous experiments. In the ultrapure MgB_2 thin film, however, a remarkably stable flux penetration was observed, clearly showing the classic behavior of the critical state model. Such different behavior indicates that the electron scattering ultimately controls the magnetic stability of the MgB_2 films. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1827931]

Potential application of superconducting MgB_2 in power transmission cables, magnets, motors must take the magnetic stability of the conductor into account. A critical issue is stability against possible flux jumps. This is an avalanche process where flux motion dissipates heat and leads to a local temperature rise which reduces local pinning and facilitates further flux motion.[1,2] Unprotected flux jumps can sometimes result in a thermal runaway and destroy superconducting equipment. Strong flux instabilities in thin films and bulk MgB_2 at low temperatures have been reported.[3–6] Using magneto-optical imaging (MOI) techniques, Johansen *et al.* revealed that below 10 K the penetration of magnetic flux in pulsed-laser-deposited (PLD) MgB_2 films was dominated by dendritic structures abruptly formed in response to an applied field.[3] Though dendritic magnetic instability is believed to be of thermomagnetic origin, the phenomenon is still poorly understood. Recently, Johansen *et al.*[3] and Aranson *et al.*[7] numerically simulated dendritic flux jump in type II superconductors based on the thermal feedback mechanism. However, these simulations are unable to relate the occurrence of flux jump quantitatively to the parameters specific to a particular superconductor, such as its critical temperature T_c, upper critical field H_{c2}, normal state resistivity ρ_n, and critical current density J_c, etc. Furthermore, the central issue of what controls the magnetic stability, particularly in MgB_2, remains unsolved.

The goal of the present work is to explore suppression of the magnetic instability in MgB_2 by varying materials properties, and to determine the key factor responsible for the dendritic flux jumps in MgB_2 films. Experiments focused on high quality MgB_2 thin films made by hybrid physical-chemical vapor deposition (HPCVD).[8] It has been shown previously that the HPCVD process is very successful in producing ultrapure MgB_2 films with very low resistivity and clean-limit behavior ("ultra-pure"), being much cleaner than even pure films made by PLD or other route.[9] In addition, films with a broad range of "dirty-limit properties" could also be obtained through carbon doping via HPCVD process.[10] Magnetic behaviors of these films were studied by a combination of MOI, transport, and bulk magnetization measurements. These results were then compared to our earlier assessments of pure MgB_2 films made by PLD.[5] Our studies showed that dendritic flux jumps can be completely eliminated by keeping ρ_n sufficiently low, such as in the ultrapure MgB_2 thin films made by HPCVD.

Two types of MgB_2 film (ultrapure and C-doped) were grown on *c*-cut SiC single crystalline substrates using the *in situ* HPCVD process described previously.[8] The ultrapure films are clean and *epitaxial* with the *c*-axis perpendicular to the surface, while the C-doped films are uniaxially oriented with the *c*-axis perpendicular to the surface, similar to most of the PLD films reported so far. Films sized 5×5 mm^2 of ultrapure MgB_2 (330 nm thick) and 0.12 formula carbon doped MgB_2 (200 nm thick) were selected for MOI study. T_c are 41.2 and 38.4 K for the ultrapure and the C-doped samples, respectively. Flux motion in these MgB_2 thin films was directly recorded using the high resolution MOI station described elsewhere.[5] Bulk magnetization was measured on the *same* films in a Quantum Design MPMS SQUID magnetometer with the applied field $H_a\perp$ film surface.

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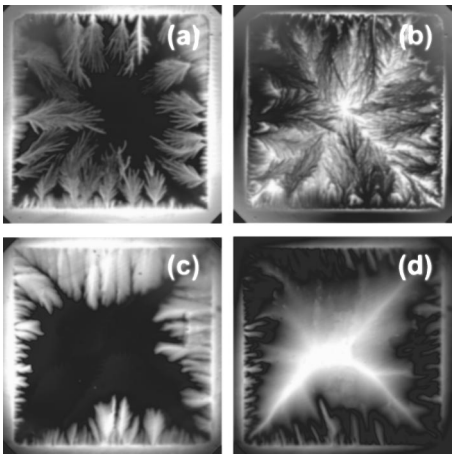

FIG. 1. Magneto-optical images showing flux penetration patterns in the zero-field-cooled C-doped and ultrapure MgB_2 films (5×5 mm^2) at 4.2 K: (a) dendritic flux penetration into the C-doped film at $\mu_0H_a=8$ mT; (b) remanent state of the C-doped film showing the exit of the dendritic flux after μ_0H_a reduced from 0.1 T to zero; (c) stable and gradual flux penetration into the ultrapure film at $\mu_0H_a=20$ mT. Note: at $\mu_0H_a<10$ mT, nearly perfect shielding (no flux entry) was observed; (d) remanent state of the ultrapure film showing regular roof-top flux trapping pattern after μ_0H_a reduced from 0.1 T to zero.

Figure 1 shows the MO images. Striking differences in the flux penetration patterns are immediately apparent between C-doped [(a) and (b)] and ultrapure MgB_2 films [(c) and (d)]. These images were taken at 4.2 K during the initial magnetization (a) and (c) after zero-field cooling and in the remanent states (b) and (d). Figure 1(a) shows vigorous dendritic flux penetration into the C-doped film at external field $\mu_0H_a=8$ mT. The dendrites nucleate randomly near the film edge and propagate into the films immediately. Figure 1(b) shows the remanent state of the C-doped film after μ_0H_a was reduced from 0.1 T to zero, where the dark dendrites show the sudden exit of flux. In general, the behavior of the dendritic flux motion in these C-doped films is essentially the same as that observed previously in pure MgB_2 films made by PLD.[3,5] Similarly, at $T>10$ K, MOI did not reveal any flux jumps in the C-doped films. In a striking contrast, dendritic flux jumps are completely absent in the ultrapure MgB_2 films. Instead, a regular and gradual flux penetration was observed, as shown in Fig. 1(c) taken at $\mu_0H_a=20$ mT and in Fig. 1(d) taken after μ_0H_a was reduced from 0.1 T to zero, being consistent with the prediction of the critical state model. The MO images of Figs. 1(c) and 1(d) are not indicative of completely homogenous flux penetration, as can be seen in some other superconducting systems.

The magnetic behavior of the C-doped and the ultrapure MgB_2 films was further explored by bulk magnetization measurements. Figure 2 shows that the initial magnetization of the C-doped film contains small flux jumps, as indicated by pronounced noise illustrated in the inset to Fig. 2. Such behavior was observed at $1.8\text{ K}\leqslant T\leqslant 9.5$ K for μ_0H_a up to 0.15 T. At $T\geqslant 10$ K, both initial and full hysteresis measurements gave smooth magnetization curves for the C-doped film. In contrast, smooth magnetization curves were always observed at all temperatures, as low as 1.8 K, for the ultrapure film. These observations are in excellent agreement with those flux profiles found in the MOI studies above.

To determine the key factors responsible for the disappearance of the dendritic flux jumps in the ultrapure MgB_2 films, we analyze various parameters relevant to the thermomagnetic instability. We first examine $J_c(T)$. In general, the higher the value of J_c is, the steeper the slope of the flux gradient in the critical state is, and hence the higher is the tendency for a breakdown of a critical state with respect to hot spot formation. In addition, higher $|dJ_c/dT|$ gives faster propagation of this breakdown. Figure 3 shows the T dependence of J_c obtained for the C-doped and the ultrapure films from both transport measurements of similarly processed films in self field,[11] and magnetization measurements in remnant field of the actual films viewed by MOI (the standard Bean model is applied to magnetic hysteresis). The large error bar in J_c for the C-doped film at 4.2 K is due to slight differences in C-concentration among the films. In fact, the ultrapure film has higher J_c and $|dJ_c/dT|$ than the C-doped film. This rules out the possibility that J_c is responsible for the absence of dendritic flux jumps in the ultrapure MgB_2 films.

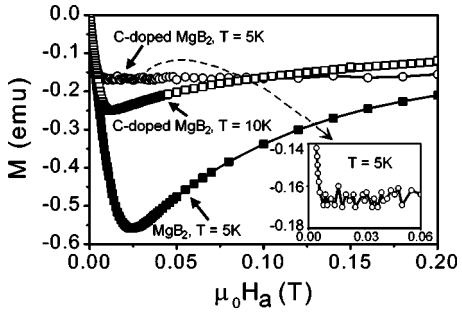

FIG. 2. Initial magnetization of the C-doped and ultrapure MgB_2 films. The inset is an expanded view of the magnetization curve for the C-doped film at 5 K, showing pronounced noise due to flux jumps. A regular magnetization behavior was observed for the ultrapure MgB_2 film at all temperatures from 1.8 K to T_c, as well as for the C-doped film at $T\geqslant 10$ K.

Next, we examine the conditions required for local flux jumps, which depend on the ratio τ of the flux (t_m) and thermal (t_t) diffusion time constants.[1,2,7] The dimensionless parameter τ is given by $\tau=t_m/t_t=D_t/D_m=\mu_0\kappa/C\rho_f$, where the magnetic diffusivity $D_m=\rho_f/\mu_0$, thermal diffusivity $D_t=\kappa/C$, μ_0 is the permeability of vacuum; and κ, C, and ρ_f are the superconductor's thermal conductivity, heat capacity, and flux flow resistivity, respectively. Under local adiabatic conditions, where $\tau\ll 1(t_m\ll t_t)$, the magnetic flux diffusion is considerably faster than that of heat, and there is not enough time to redistribute and remove the heat released due to flux motion. Under these conditions, dendritic flux jumps occur. Such conditions applied to earlier experiments on thin

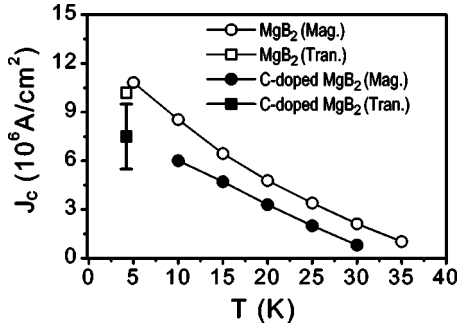

FIG. 3. Temperature dependence of J_c for the C-doped and ultrapure MgB_2 films determined by the transport (Tran.) and magnetization (Mag.) methods.

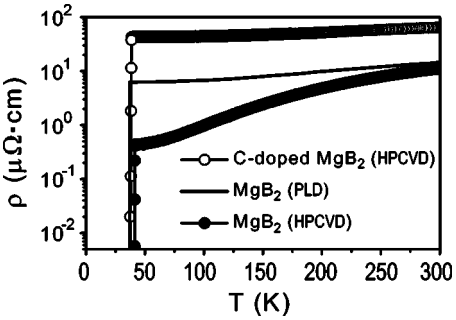

FIG. 4. Temperature dependence of resistivity of the C-doped and ultrapure MgB_2 films plotted along with the pure MgB_2 film made by PLD (Refs. 5 and 16).

films of Nb (Ref.12) and MgB_2 as discussed earlier.[3,5] Although it is not feasible for us to measure the thermal conductivity and the heat capacity of these MgB_2 films directly, other works on the C-doped MgB_2 samples suggest that these parameters should not be too different from those of pure MgB_2.[13] It becomes clear that the key parameter that changes the local adiabatic condition is the flux flow resistivity ρ_f. For simplicity, ρ_f is approximated by $\rho_f = \rho_n H_a / H_{c2}$.[14] It is clear that ρ_f must be greatly reduced in order to slow down the flux diffusion. This can be accomplished by either a drastic reduction of ρ_n or a large increase of H_{c2}. In one-band superconductors these trends oppose each other, H_{c2} being proportional to ρ_n, and thus it is not possible to separately alter ρ_n and H_{c2} easily.[14] However, in two-band superconductors it is possible to embody strong electron scattering and high H_{c2} at low temperature in one dirty band while keeping low ρ_n in the other clean band.[15]

Figure 4 shows the T dependence of resistivity for the ultrapure and C-doped MgB_2 films at zero field, plotted along with the result for the PLD film reported earlier.[5,16] T_c is similar for all three films ($\sim$38–41 K), while the difference in ρ_n at T_c is huge ($\sim$0.4 $\mu\Omega$ cm for the ultrapure and $\sim$40 $\mu\Omega$ cm for the C-doped film, respectively, while for the earlier PLD film, ρ_n at T_c is $\sim$7 $\mu\Omega$ cm). This dramatic change in resistivity (over two orders of magnitude) is not compensated for by threefold changes in H_{c2}. $\mu_0 H_{c2}$ for the C-doped film was found to be $\sim$25 T for $H//c$ at 4.2 K, based on the C-doping, as compared to 7 T in the ultrapure MgB_2 films.[10] Taking $H_a = 0.1$ T as an example, ρ_f for the ultrapure MgB_2 film is $\sim$0.006 $\mu\Omega$ cm, versus 0.16 $\mu\Omega$ cm in our carbon doped sample. For the earlier pure MgB_2 film made by PLD,[5,16] ρ_f is $\sim$0.1 $\mu\Omega$ cm, where $H_{c2} \sim 7$ T at 4.2 K was used. In fact, our C-doped film and earlier PLD films have comparable ρ_f at low temperatures. Thus, it is not surprising to observe similar dendritic flux jumps in those films. In comparison, ρ_f in the ultrapure MgB_2 films is about two orders of magnitude lower. This drastically reduced ρ_f in the ultrapure MgB_2 film slows flux diffusion considerably, and hence prevents dendritic flux jumps.

In summary, we report the absence of dendritic flux jumps in the ultrapure MgB_2 films at temperatures as low as 1.8 K. Similar dendritic flux jump behavior observed in C-doped MgB_2 films and earlier pure MgB_2 films made by PLD is likely due to their comparable values of flux flow resistivity. It is shown that the magnetic stability in MgB_2 films is closely related to their normal state resistivity. The onset of dendritic instabilities in dirty-limit MgB_2 films perhaps manifests another unique feature of electron scattering in the two-band superconductors.

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