

Dendritic magnetic avalanches in carbon-free MgB₂ thin films with and without a deposited Au layer

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From magneto optic images (MOI), the dendritic magnetic avalanche is known to appear dominantly for thin films of the newly discovered MgB₂. To clarify the origin of this phenomenon, we studied in detail the MOI of carbon-free MgB₂ thin films with and without a deposited gold layer. The MOI indicated that carbon contamination was not the main source of the avalanche. The MOI clearly showed that the deposition of metallic gold on top of a MgB₂ thin film improved its thermal stability and suppressed the sudden appearance of the dendritic flux avalanche. This is consistent with the previous observation of flux noise in the magnetization. © 2005 American Institute of Physics. [DOI: 10.1063/1.2084323]

The binary metallic MgB₂ superconductor with $T_c = 39$ K is a very interesting material for basic science and applications. The relatively high upper critical field H_{c2} (20–30 T, 49 T) Refs. 1 and 2 of MgB₂ and its extremely high critical current density J_c ($\sim 10^7$ A/cm²),³ especially in thin films, suggest that MgB₂ could be a much more important superconducting material than conventional metallic superconductors. However, the critical current was found to be seriously limited by a phenomenon called the vortex avalanche (flux jumps or magnetic flux noise). In particular, this phenomenon prevails at low temperatures ($T < 15$ K) and low magnetic fields ($H \leq 1000$ Oe).^{4,5} The dendritic flux patterns formed in the course of an avalanche were studied in detail by using magneto optic imaging (MOI).⁴ Even though the details were somewhat different, abrupt flux dynamics with dendritic penetration had been observed earlier in other superconductors such as Nb films⁶ and YBCO films, where a laser pulse is needed to trigger the instability.⁷

The dendritic flux penetration can be explained by a thermomagnetic instability due to the heat generated by vortex motion. Aranson *et al.*⁸ and Rakhmanov *et al.*⁹ carried out a linear analysis and found a numerical solution to the thermal diffusion and Maxwell equations, predicting that an instability might result in very nonuniform dendritic-like temperature and flux distributions.

Experimentally, Choi *et al.* reported that the flux jumps in MgB₂ films could be cured by the superconductors being thermally stabilized after having been coated with a metallic Au film.¹⁰ They observed, for a gold coating, a dramatic reduction in the flux noise in the magnetic hysteresis ($M-H$) loop and an enhancement of J_c up to 1.22×10^7 A/cm² at $H=0$ Oe and $T=5$ K.¹⁰ This strongly sug-

gested that thermal stabilization greatly suppressed the vortex avalanche.

Recently, Ye *et al.*¹¹ reported MOI results and $M-H$ curves for two kinds of MgB₂ thin film samples: one without serious carbon contamination and one with 12% carbon contamination (C_{0.12}MgB₂, called C-MgB₂ in this paper). Both were prepared by using the hybrid chemical-physical vapor deposition (HPCVD). Since dendrites were seen only in C-MgB₂, they concluded that the avalanches mainly involved electron scattering due to carbon contamination, and were not the result of a thermal instability.

To clarify the origin of the avalanche behavior, we synthesized carbon-free c -axis oriented MgB₂ thin films with and without a gold coating and performed MOI, and magnetization measurements. In this work, we showed that ultra clean, carbon-free MgB₂ thin films indeed displayed dendritic flux avalanches; moreover, we found that the avalanches disappeared with the addition of a gold coating, all of which support the thermal instability scenario and not electron scattering due to carbon doping.

The MgB₂ thin films in this study were fabricated by using a two step method.¹² Briefly, an amorphous boron thin film was deposited on a Al₂O₃ (1 $\bar{1}$ 0 2) substrate at room temperature by using pulsed laser deposition. The base pressure was 10^{-8} Torr. The B film was put into a Nb tube with high-purity Mg (99.9%) and heat treated. To eliminate possible contamination with oxygen, water, and carbon, we never allowed the samples to be exposed to air until the final thin film had been produced. Post-annealing was done in a high-purity Ar (99.999%) atmosphere.

The carbon contents in these samples were confirmed to be below the resolution limits of wavelength dispersive spec-

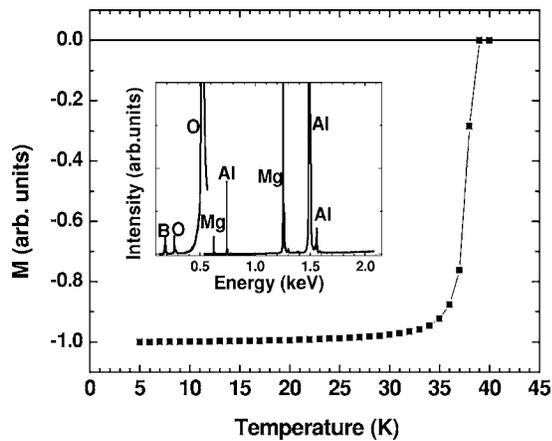


FIG. 1. Zero-field-cooled magnetization at 4 Oe vs temperature ($5 \leq T \leq 42$ K) of a bare MgB_2 thin film. The inset is a wavelength dispersive spectrum of an arbitrary surface of a MgB_2 thin film and was obtained using EPMA.

troscopy (WDS, 0.01%) and energy dispersive spectroscopy (EDS, 1%) by using electron probe micro analysis (EPMA). These values were far below the 12% for C- MgB_2 prepared by Ye *et al.*

Rectangular samples with dimensions of 2×3 mm² and with thickness of 500 nm were chosen for the magnetic measurements. The *c*-axis orientation of the MgB_2 film was confirmed using scanning electron microscopy (SEM).¹³ The magnetization (M - T and M - H curves) was measured by using a SQUID magnetometer (Quantum Design, MPM-SXL) for $H \parallel c$ axis. In this experiment, we measured the M - H loop (at $T=5$ K) and the MOI (at $T=3.8$ K) of MgB_2 thin films coated with Au films of different thicknesses. The gold deposition caused no observable deterioration in the superconductivity of the samples.¹⁰ MOI was performed using a film of in-plane magnetization ferrite garnet as the Faraday-active sensor measuring the field distribution over the surface of the MgB_2 sample. The details of the MOI setup can be found elsewhere.¹⁴

Figure 1 shows the temperature dependent low-field magnetic susceptibility for a bare MgB_2 thin film, which has a sharp transition with onset at $T_c=39$ K. The superconducting transition for the MgB_2 film coated with a thick Au layer was the same as that shown in Fig. 1, implying that the gold deposition did not adversely affect the superconducting properties. For the elemental analysis, we measured wavelength dispersive spectra for many different surfaces by using EPMA (inset in Fig. 1). The inset shows that, within the resolution limit, carbon was not present in the MgB_2 films. We could only detect B, Mg, O, and Al, where the signals from O and Al are from the Al_2O_3 substrate.

Figure 2(a) shows MOI of the flux penetration in a carbon-free MgB_2 thin film with the magnetic field perpendicular to the film at $H=34$ mT and $T=3.8$ K. One can see that the flux penetrates the film in a typical dendritic fashion. It should be emphasized that the exact dendrite pattern varies widely between experiments repeated under the same external conditions; hence, the structure is not a fingerprint of defect regions in the superconductor. Also, the extremely abrupt formation of each flux dendrite, faster than we could capture with our image recording system, demonstrates a characteristic feature of an instability, presumably one of thermo-magnetic origin.

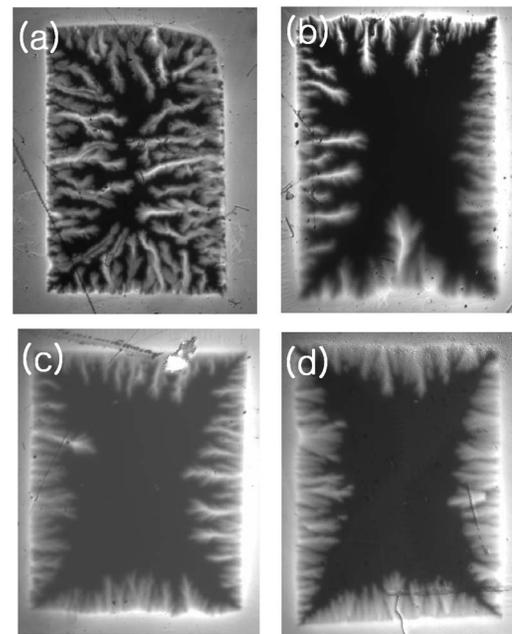


FIG. 2. Magneto optical (MO) images of flux penetrations into the virgin states of MgB_2 thin films at 3.8 K for gold thicknesses of (a) 0, (b) 0.2, (c) 0.9, and (d) 2.55 μm . The images were taken at an applied field of 34 mT.

For films made by using HPCVD, the dendrites appear only in C-contaminated MgB_2 thin films, which is quite different from our observation. The main conclusion of Ye *et al.* for films prepared using HPCVD was that magnetic flux jumping was mostly due to electron scattering by carbon impurity, but that cannot be correct because flux jumping still was presented in our carbon-free MgB_2 thin films.

To clarify this issue, we prepared MgB_2 films with Au coatings of three different thicknesses: 0.2, 0.9, and 2.55 μm . The MO images obtained at 3.8 K for these three films are shown in Figs. 2(b)–2(d), respectively. It is evident that with increasing Au thickness, the dendritic character of the flux penetration gradually disappears. We notice, however, that even with the thickest Au layer, the flux penetration pattern is far from being ideally smooth. The reason for this is the presence of small defects being spread over the films area and along the edge, and distorting the penetration by creating well-known parabolic or fan-like flux patterns.^{15,16} These patterns are very easily distinguished from the dendritic structures by their vastly different dynamics. All the

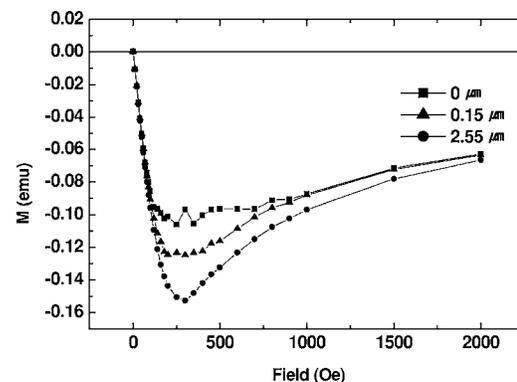


FIG. 3. Initial magnetization hysteresis (M - H) loop for 0-, 0.15-, and 2.55- μm -thick Au films on MgB_2 thin films at 5 K in the field range of $0 \leq H \leq 2000$ Oe.

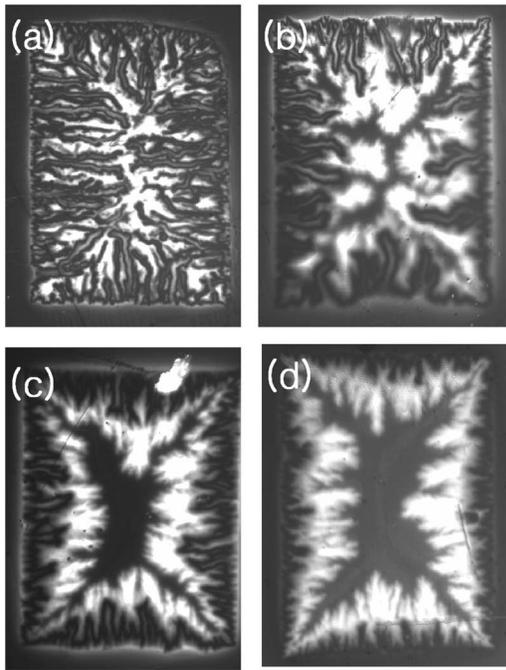


FIG. 4. Remanent state after a maximum applied field of 60 mT for MgB_2 thin films at 3.8 K with gold thicknesses of (a) 0, (b) 0.2, (c) 0.9, and (d) 2.55 μm .

irregular flux patterns seen in Fig. 2(d) evolve slowly when the applied field is ramped at a slow rate. The dendrites seen in Fig. 2(a) develop nearly instantaneously and apparently independently of the field sweep rate. The images in Figs. 2(b) and 2(c), where the Au layer is below 1 μm , show a cross-over behavior where the widths of the dendrites become increasingly wider and more diffuse.

The visual MOI results are quite consistent with the magnetization results. Shown in Fig. 3 are the virgin branches of the $M-H$ loops for a bare thin film, a film with a 0.15- μm -thick Au coating, and a film with a 2.55- μm -thick Au coating. Even with a thin 0.15- μm -thick Au layer, the maximum magnetization is substantially increased because the jumps in magnetization (M) are greatly reduced. In the case of film with the 2.55- μm -thick Au, the magnetization had the highest value, and the jumps in M almost disappeared. Also, generally, we did not observe any magnetic flux noise in the $M-H$ loops of some MgB_2 thin films that had been contaminated with excess metallic Mg during fabrication. Notice that the magnetization deviates among the three films only in the field interval $50 \text{ Oe} \leq H \leq 2000 \text{ Oe}$. This is consistent with the previous observation that both a lower and upper threshold field exist for the formation of flux dendrites.^{4,5} Hence, both at very low fields and for $H > 2 \text{ kOe}$, the Au coating has little or no effect.

Figures 4(a)–4(d) show MO images in the remanent state of MgB_2 thin films at $T=3.8 \text{ K}$ with four different gold thicknesses after first applying a large field that gave a white background in the images up to the point where maximum penetration occurred. In Fig. 4(a) one sees a typical image of a bare MgB_2 thin film containing many dendrites of two polarities. The dendrites with a dark rim enter the film while the field is decreasing and contain flux of opposite polarity. The cores of these dendrites look gray and correspond to moderate densities of antflux. Thus, the dark rim represents an annihilation zone where the flux density is exactly zero. In

Figs. 4(b) and 4(c), the number of dendrites is smaller than in Fig. 4(a), while in Fig. 4(d) the dendrites are completely absent. This means that a gold layer suppresses the dendritic instability for decreasing applied field.

Suppression of dendritic avalanches by a gold layer, and the clear sensitivity of dendritic avalanches to the thickness of the gold layer suggests a thermal origin for the instability. Indeed, the gold layer increases the effective conductivity of the MgB_2+Au sandwich by a value proportional to the gold thickness. Higher conductivity is known to improve the stability of a superconductor with respect to thermal avalanches.^{8,9} The gold conductivity at 4 K is comparable to the flux-flow conductivity of MgB_2 . Hence, a noticeable decline in the number of avalanches is expected when the gold layer becomes approximately as thick as the MgB_2 film. This is exactly what we found experimentally.

In summary, magnetization measurements, as well as visualizations of flux distributions by using MOI, demonstrate that the dendritic flux instability also exists in ultra clean carbon-free c -axis oriented MgB_2 films. Our results show that the instability cannot be caused by electron scattering due to carbon doping as argued in Ref. 11, and fully support for a thermal origin for dendritic avalanches. Deposition of gold on top of the MgB_2 film completely suppresses the instability if the gold layer is thicker than 2.5 μm . The present work further proves that coating with a thin metallic layer can enhance the critical current density of MgB_2 films at $T < 15 \text{ K}$, and for $H < 1 \text{ kOe}$.

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