Width-dependent upper threshold field for flux noise in MgB_2 strips

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The authors measured magnetization hysteresis curves and used magneto-optical imaging to visualize the flux distributions in superconducting MgB_2 films in order to study dendritic flux avalanches. The flux avalanches are found to disappear above some upper threshold field that is typically ~1 kOe, but strongly depends on the film width. If the film is made wider, this threshold field first increases and then tends to saturate. This behavior is quantitatively explained using a thermomagnetic model for the dendritic avalanches and taking into account the field dependence of J_c. The results demonstrate that patterning superconducting films into narrow strips substantially increases the range of magnetic fields for which they can be used for applications. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2760141]

Magnetic flux jumps in the form of dendritic avalanches in superconducting films have attracted much attention,[1–5] but the physical picture of their nucleation and propagation is not yet fully understood. However, the most pronounced dendritic avalanches have been observed in thin films of MgB_2.[6–9] They represent a critical deficiency of magnesium diboride, which is otherwise very promising for many applications.[10–12]

The dendritic avalanches occur at temperatures below a certain fraction of T_c (reported to be around 0.65 for Nb and 0.25 for MgB_2, this is called the threshold temperature) And at low fields ($H \leqslant 1$ kOe). In the presence of dendritic avalanches, the global sample properties, such as the magnetization or the apparent critical current density J_c, become very noisy while their average values are drastically reduced.[8,13] This creates a major problem for any applications and makes suppression of dendritic jumps an important practical goal.

It is well accepted that dendritic flux penetration is related to a thermomagnetic instability driven by heat generated by moving vortices. Theoretical models[14,15] predict that such an instability can, indeed, lead to propagation of elongated and branching flux dendrites. More support for the thermomagnetic mechanism comes from experiments in which the dendritic instability was suppressed and hence the high J_c recovered by improving the thermal conditions.[6,7,16]

Another method to get rid of the magnetization noise is to pattern films in narrow strips. Recent magneto-optical (MO) studies[9] demonstrated that the threshold field for the *onset* of dendritic avalanches is larger for narrower strips. Even more importance for applications is the *upper* threshold field above which the avalanche activity terminates, revealed by magnetization[13] and MO studies.[17] Whether the upper threshold field can be affected by varying the film geometry has so far remained an open question. In this work, we studied a set of specially designed long rectangular MgB_2 thin film strips having different widths. The upper threshold fields for the MgB_2 films were usually beyond the field range where MO indicator had good sensitivity ($\lesssim 800$ Oe). To cover a much broader range of fields, we supplemented MO imaging with measurements of the magnetic hysteresis $M(H)$ curves, which provided a very accurate global magnetic characterization. We demonstrate that the upper threshold field is reduced by decreasing the film width and that these results are in quantitative agreement with the thermomagnetic model of the dendritic instability.

The 400-nm-thick, c-axis-oriented and carbon-free MgB_2 thin films were fabricated using a two-step process.[18] The longer side of the rectangular samples prepared by photolithography was 3 mm for all strips, but the widths ranged from 0.2 to 1.6 mm. The magnetization [$M(T)$ and $M(H)$ curves] was measured by using a superconducting quantum interference device magnetometer (Quantum Design, MPMSXL) for $H \| c$ axis. The films showed a sharp $T_c = 39$ K. MO images were taken using a ferrite garnet film of 5 μm in thickness as a magnetic field sensor and were recorded by using a 12 bits, 1.4 Mpixel charge coupled device camera.[19] In these experiments, the applied magnetic field was strong enough for the vortices penetrating into the narrowest strip.

Figure 1 shows MO images of flux penetration in MgB_2 films of three different widths, 1.6, 0.4, and 0.2 mm, for $T = 4$ and 10 K, and $H \| c = 18$ mT. At 4 K, we see numerous dendritic avalanches in the 1.6 mm wide film, but almost no avalanches in the 0.2 mm wide film. In general, as the width decreases, the number of dendritic structures, the number of their branches, and the length of each branch are all drastically reduced. Comparing the two panels, one can trace the temperature dependence of the flux patterns: a large treelike structure is formed in one single burst of flux explosion at 10 K while many small structures appear instead at a lower temperature of 4 K. We, thus, conclude that the lower threshold field (when the first dendrite appears) increases but the threshold temperature decreases when the films are made narrower. This improved stability is consistent with the thermomagnetic model.[9]

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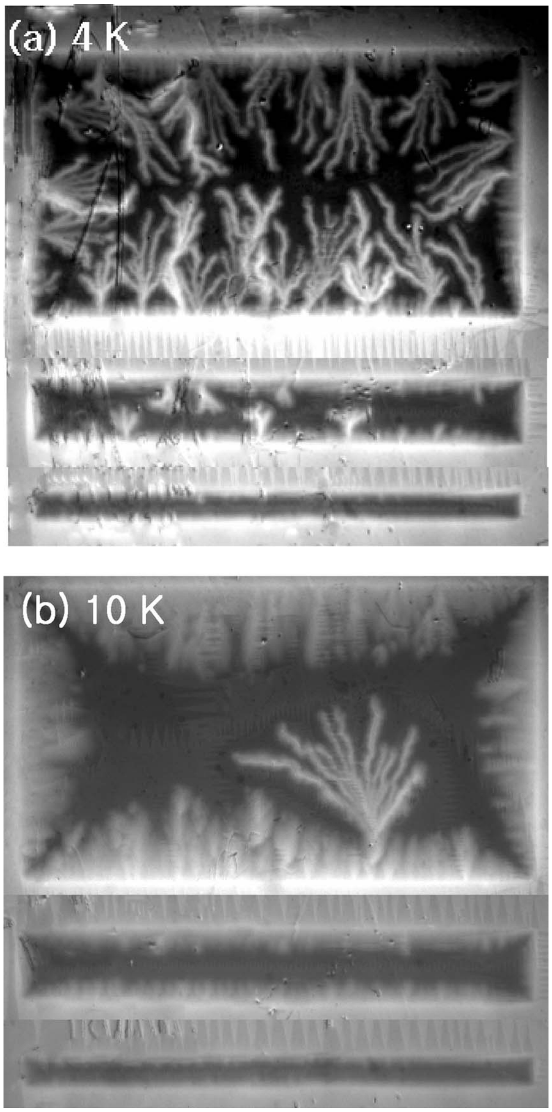

FIG. 1. Magneto-optical images of flux penetration into the virgin state of MgB_2 thin films with widths of 1.6, 0.4, and 0.2 mm at $T=4$ (a) and 10 K (b). Numerous dendritic structures were formed by abrupt flux avalanches. The applied field is 18 mT.

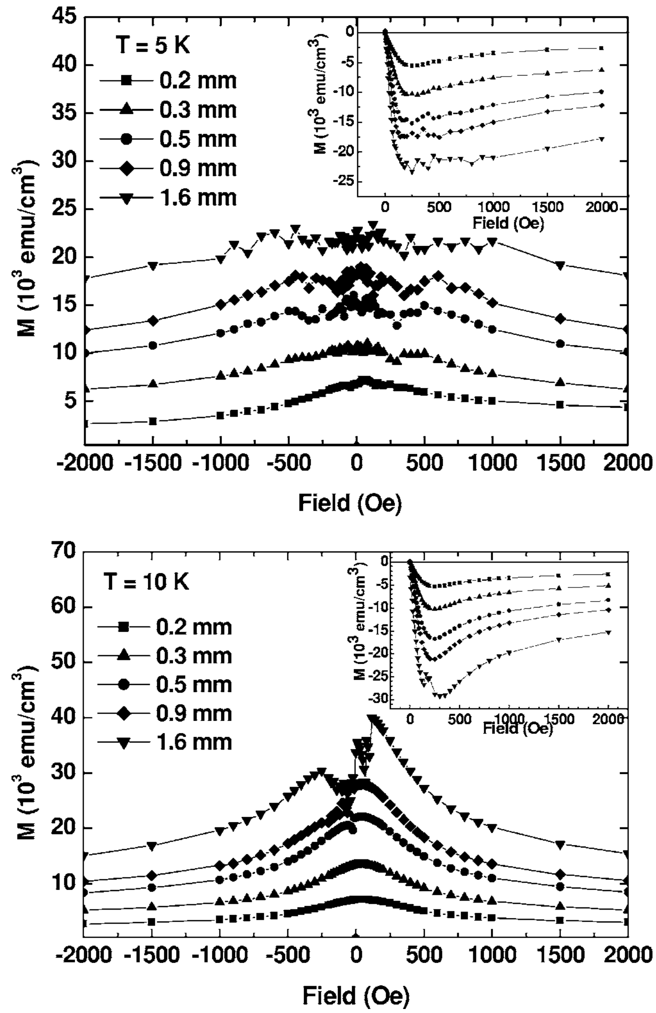

FIG. 2. Magnetization hysteresis loops $M(H)$ for MgB_2 films with different widths at 5 (a) and 10 K (b). The noisy region around $H=0$ is a result of dendritic flux avalanches. Inset: the virgin branches of the loops.

Figure 2 shows $M(H)$ curves for five MgB_2 films of different widths at (a) 5 K and (b) 10 K. The data are obtained by first applying a field of 5 T and decreasing it down to negative values. The curves show a noticeable noise in a range of magnetic fields around zero, which is a signature of dendritic avalanches. We, thus, can define two upper threshold fields: one field when the noise starts at the decreasing-field branch, and the other one when it stops during the subsequent field increase. The noise is most pronounced for the 1.6 mm wide strip, for which both upper threshold fields are ≈ 1 kOe, which is consistent with previous results.[13] The insets of Figs. 2(a) and 2(b) show the virgin curves. They start with a smooth region, but after some *lower* threshold field is exceeded the noise sets in. Comparing panels (a) and (b) of Fig. 2, we see that at 10 K, the avalanches occur less frequently and in a narrower range of fields than at 5 K. However, the magnitude of the magnetization jump becomes larger. Indeed, the MO image of Fig. 1(b) demonstrates that avalanches at 10 K tend to develop into big treelike structures. A similar dendritic tree must be responsible for the big jump in the virgin M-H curve for the 1.6 mm wide film shown in the inset of Fig. 2(b).

Two conclusions can be drawn from Fig. 2. First, the flux noise is suppressed as the film width is decreased. This is most clearly seen in the virgin curves where the noise shows up only for wide films while there is just one tiny bump on the curves for the two narrowest films. The observed suppression of dendritic avalanches in narrow films is consistent with earlier observations made by MO imaging in a more restricted field range.[9] A similar tendency is now also seen on the major M-H loops, where the noisy region is considerably larger for wider films.

The second conclusion is a stronger avalanche activity occurs on the decreasing field branch than on the virgin curve, as can be seen by comparing the main plot and the inset. In particular, the major loops for the 0.3 and the 0.2 mm wide films are quite noisy at 5 K while there is essentially no noise on the corresponding virgin curves. These observations possibly imply that flux-antiflux annihilation during the field descent facilitates the nucleation of avalanches.[2,5]

Figure 3 shows the upper threshold field averaged between the descending- and the ascending-field branches at 5 and 10 K as functions of the film width. The field values were extracted from the derivative dM/dH vs H curves. The flux noise extends to a broader range of fields for lower temperatures and for wider films. Moreover, the latter ten-

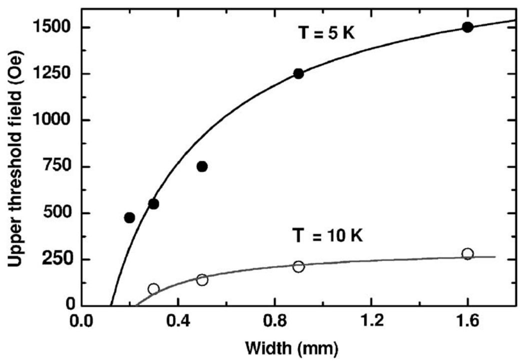

FIG. 3. Upper threshold field for dendritic avalanches vs film width extracted from the experimental data of Fig. 2 (symbols) and from the theoretical fit using the model of Ref. 15.

dency becomes less pronounced as the width increases. This behavior can be quantitatively explained using the results of the thermomagnetic model.[15] The model predicts the threshold flux penetration depth, ℓ^*, at which a dendritic instability should develop in a superconducting strip:

$$\ell^* = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{J_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{ndJ_c E}}\right)^{-1}. \quad (1)$$

Here, d is the film thickness, $T^* \equiv -(\partial \ln J_c/\partial T)^{-1}$, κ is the thermal conductivity, E is the electric field generated by vortex motion, and h_0 is the heat transfer coefficient to the substrate. The parameter n characterizes the nonlinearity of the current-voltage curve of the superconductor, $n = \partial \ln E/\partial \ln J \gg 1$. The critical current density J_c is strongly field dependent as one immediately sees from the measured $M(H)$ curves. Using the 10 K curves of Fig. 2 (and excluding their noisy regions), we find a good fit for this dependence by combining the Kim and the exponential models, $J_c(H) = [8.5e^{-|H|/H_1} + 11/(1+|H|/H_2)] \times 10^{10}\ \mathrm{A/cm^2}$, with $H_1 = 400$ Oe, and $H_2 = 3200$ Oe, and a slightly higher $J_c(H)$ for 5 K. One should now substitute this $J_c(H)$ into the equation for ℓ^*. The instability cannot happen if $\ell^* > w$ (w is the film half width), which defines the upper threshold field as a function of w. The experimental data of Fig. 3 were fitted using the above formulas with two free parameters, $\kappa T^*/E = 25$ A (10 K) or 45 A (5 K) and $h_0 T^*/nE = 27\,700$ A/m (10 K) or 15 700 A/m (5 K). The fits reproduce very well the increase of the threshold field with the width, as well as the saturation at large width. Remarkably, the absence of avalanches in the 0.2 mm wide film at 10 K is also consistent with the theoretical curve, which crosses the x axis at $2w > 0.2$ mm. The upper threshold field for dendritic avalanches in NbN films can be explained and quantitatively described by incorporating a $J_c(H)$ dependence into the thermomagnetic model of Ref. 15.[17]

To compare data for different widths, it is more informative to look at the apparent critical current density, $J_c \approx M/w$, rather than at the magnetization itself because J_c must be width independent. A quite accurate value for J_c in the absence of flux noise can be obtained from the $M(H)$ curves for the 0.2 mm wide strip, where the dendritic avalanches are essentially absent. Table I shows the avalanche-induced suppression, ΔJ_c, of the critical current density for four other strip width. The suppression, ΔJ_c, at 5 K can be quite substantial—of the order of J_c itself—in agreement with earlier MO results.[8]

TABLE I. Avalanche-induced reduction of J_c.

$2w$ (mm)	0.3	0.5	0.9	1.6
ΔJ_c (5 K) ($\times 10^{10}$ A/m^2)	1.7	2.1	2.1	2.5
ΔJ_c (10 K) ($\times 10^{10}$ A/m^2)	0.015	0.025	0.1	0.6

In summary, dendritic flux avalanches suppress the critical current density of superconducting MgB_2 films and lead to a pronounced noise in their magnetization. We explored the upper threshold field above which the avalanches disappear and its dependence on the film width, and we provide a quantitative explanation of the observed behavior. We find that using narrower films allows one to confine the destructive effect of avalanches to a smaller range of magnetic fields and to make it smaller in magnitude. This information can be important when designing various superconducting devices.

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[1] M. R. Wertheimer and J. de G. Gilchrist, J. Phys. Chem. Solids **28**, 2509 (1967).
[2] C. A. Duran, P. L. Gammel, R. E. Miller, and D. J. Bishop, Phys. Rev. B **52**, 75 (1995).
[3] I. A. Rudnev, S. V. Antonenko, D. V. Shantsev, T. H. Johansen, and A. E. Primenko, Cryogenics **43**, 663 (2003).
[4] S. C. Wimbush, B. Holzapfel, and Ch. Jooss, J. Appl. Phys. **96**, 3589 (2004).
[5] I. A. Rudnev, D. V. Shantsev, T. H. Johansen, and A. E. Primenko, Appl. Phys. Lett. **87**, 042502 (2005).
[6] M. Baziljevich, A. V. Bobyl, D. V. Shantsev, T. H. Johansen, and S. I. Lee, Physica C **369**, 93 (2002).
[7] Eun-Mi Choi, Hyun-Sook Lee, Hyun Jung Kim, Byeongwon Kang, Sung-Ik Lee, A. A. F. Olsen, D. V. Shantsev, and T. H. Johansen, Appl. Phys. Lett. **87**, 152501 (2005).
[8] T. H. Johansen, M. Baziljevich, D. V. Shantsev, P. E. Goa, Y. M. Galperin, W. N. Kang, H. J. Kim, E. M. Choi, M.-S. Kim, and S. I. Lee, Europhys. Lett. **59**, 599 (2002).
[9] D. V. Denisov, D. V. Shantsev, Y. M. Galperin, Eun-Mi Choi, Hyun-Sook Lee, Sung-Ik Lee, P. E. Goa, A. A. F. Olsen, and T. H. Johansen, Phys. Rev. Lett. **97**, 077002 (2006).
[10] M. H. Jung, M. Jaime, A. H. Lacerda, G. S. Boebinger, W. N. Kang, Hyeong-Jin Kim, Eun-Mi Choi, and Sung-Ik Lee, Chem. Phys. Lett. **343**, 447 (2001).
[11] Hyeong-Jin Kim, W. N. Kang, Eun-Mi Choi, Mun-Seog Kim, Kijoon H. P. Kim, and Sung-Ik Lee, Phys. Rev. Lett. **87**, 087002 (2001).
[12] W. N. Kang, C. U. Jung, Kijoon H. P. Kim, Min-Seok Park, S. Y. Lee, Hyeong-Jin Kim, Eun-Mi Choi, Kyung Hee Kim, Mun-Seog Kim, and Sung-Ik Lee, Appl. Phys. Lett. **79**, 982 (2001).
[13] Z. W. Zhao, S. L. Li, Y. M. Ni, H. P. Yang, Z. Y. Liu, H. H. Wen, W. N. Kang, H. J. Kim, E. M. Choi, and S. I. Lee, Phys. Rev. B **65**, 064512 (2002).
[14] I. Aranson, A. Gurevich, M. Welling, R. Wijngaarden, V. Vlasko-Vlasov, V. Vinokur, and U. Welp, Phys. Rev. Lett. **94**, 037002 (2005).
[15] D. V. Denisov, A. L. Rakhmanov, D. V. Shantsev, Y. M. Galperin, and T. H. Johansen, Phys. Rev. B **73**, 014512 (2006).
[16] Eun-Mi Choi, Hyun-Sook Lee, Heon-Jung Kim, Sung-Ik Lee, Hyeong-Jin Kim, and W. N. Kang, Appl. Phys. Lett. **84**, 82 (2004).
[17] V. V. Yurchenko D. V. Shantsev, T. H. Johansen, M. R. Nevala, I. J. Maasilta, K. Senapati, and R. C. Budhani, e-print arXiv:cond-mat/0702683.
[18] W. N. Kang, Hyeong-Jin Kim, Eun-Mi Choi, C. U. Jung, and Sung-Ik Lee, Science **292**, 1521 (2001).
[19] T. H. Johansen, M. Baziljevich, H. Bratsberg, Y. Galperin, P. E. Lindelof, Y. Shen, and P. Vase, Phys. Rev. B **54**, 16264 (1996).