Current-induced dendritic magnetic instability in superconducting MgB_2 films

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Magneto-optical imaging reveals that in superconducting films of MgB_2 a pulse of transport current creates avalanche-like flux dynamics where highly branching dendritic patterns are formed. The instability is triggered when the current exceeds a threshold value, and the superconductor, shaped as a long strip, is initially in the critical state. The instability exists up to 19 K, which is a much wider temperature range than in previous experiments, where dendrites were formed by a slowly varying magnetic field. The instability is believed to be of thermomagnetic origin indicating that thermal stabilization may become crucial in applications of MgB_2. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1485304]

Following the discovery[1] of superconductivity below 39 K in polycrystalline MgB_2 a tremendous effort is now being invested to produce high-quality films for basic studies and for potential industrial use. Of primary importance for technological applications is the magnitude and stability of the critical current density J_c, or more generally, the static and dynamical behavior of the magnetic vortices. Whereas J_c as high as 10^7 A/cm^2 have already been reported for MgB_2 thin films[2,3] it has also been shown that this promising value and the technological potential may be challenged by a surprising complexity in the flux dynamics. Magneto-optical (MO) imaging recently revealed[3,4] that below 10 K the flux penetration in MgB_2 films is dominated by large dendritic structures abruptly entering the film, thus dramatically contrasting the smooth and regular flux dynamics normally found in type-II superconductors. This observation is consistent with the large fluctuations reported in the magnetization for various MgB_2 samples.[5–8] The abrupt drops appearing in the magnetization curve, much like at flux jumps[9,10] only in very large numbers, give an effective 50% suppression of the apparent J_c.[3]

Abrupt flux dynamics with dendritic penetration patterns has been observed earlier also in films of Nb[11–13] and YBCO.[14,15] In all the previous studies the dendrites or magnetization noise have been the result of a gradual increase or decrease of the applied magnetic field (or a short laser pulse perturbing the remanent state).[14,15] It is therefore still an open question—one of vital importance for many practical applications—whether flux dendrites will be formed also in response to a transport current. In this work it is shown that in MgB_2 thin films, a pulse of transport current indeed can trigger the dendritic instability, and we use MO imaging to reveal details of this behavior.

A film of MgB_2 was fabricated on $(1\bar{1}02)$ Al_2O_3 substrate using pulsed laser deposition. An amorphous B film was first deposited, and then sintered at high temperature in a Mg atmosphere.[2] The film had transition at 39 K with width 0.7 K, and a high degree of c-axis alignment perpendicular to the film plane. The film thickness was 300 nm, and its lateral dimensions were 3×10 mm^2. The strip was at both ends equipped with a contact pad of size 3×1.5 mm^2 fabricated by sputtering of Au through a mask. Copper wires were attached to the pads using silver paste. The MO imaging was performed with the sample mounted on the cold finger in an Oxford Microstat–He optical cryostat. The MO sensing element, a plate of in-plane magnetization ferrite garnet film, was placed on the MgB_2 film covering the area between the contacts. The pulses of transport current with a rise time of 0.1 μs and duration of 3 μs were sent through the MgB_2 film using a power transistor controlled by a pulse generator. The MO images were recorded immediately after the pulse, the camera exposure time being 250 ms. The time development of the $I-V$ characteristics during the pulse measured by a two-point scheme was monitored via a TDS-420 oscilloscope.

First, MO images were taken of the MgB_2 film after zero-field-cooling (ZFC) to 3.5 K and applying a perpendicular magnetic field. Results of this reference experiment (with no transport current) are shown in Fig. 1. In the images both for increasing (a) and decreasing field (b) one clearly sees that the flux penetration picture is dominated by dendritic patterns. The dendrites are formed instantaneously in response to a slowly varying applied field. Like in the thicker MgB_2 film studied in Ref. 3, also this sample has a threshold temperature of 10 K, above which the flux penetration pro-

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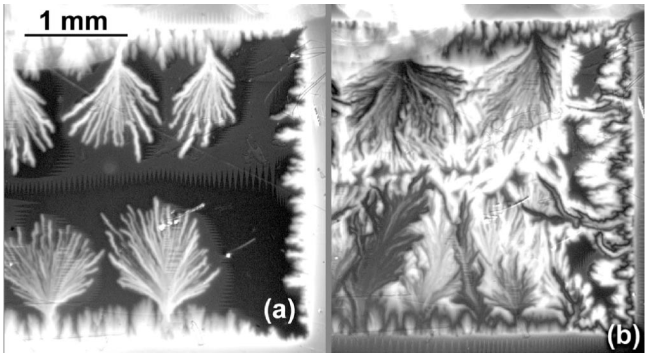

FIG. 1. Magneto-optical images of the flux distribution in a rectangular strip of MgB_2 thin film at 3.5 K. The image brightness represents the magnitude of the local flux density. (a) Several branching dendritic flux structures have been created by a 10 mT field applied to the ZFC film. (b) Remanent state after a maximum applied field of 70 mT. Dark dendrites containing antiflux are formed on top of the bright dendrites created while the field was increased. Both images were taken before current contacts were attached to the film.

ceeds in a conventional way with a gradual advancement of flux front.

Shown in Figs. 2(a) and 2(b) are flux distributions recorded at 12.5 K, as the applied field cycled from 0 to 70 mT, and back to the remanent state. Evidently, no dendrites were formed, and the final state image, (b), shows all the characteristics of a critical remanent state, where the field is maximum at the so-called discontinuity lines.[18] They are seen as the most bright lines in the image, one in the center of the strip and two pointing towards the corners. At these lines the current, which flows in rectangular loops, as indicated by the white arrows, changes its direction discontinuously. Even without dendrites the flux distribution is not smooth, especially near the edges, see also Fig. 1(a), indicating nonuniformity of the film.

With the sample prepared in the remanent state, (b), a pulse of transport current was applied. As a result, dendritic flux structures of the type seen in (c) and (d) were formed. In (c) and (d) the current pulse was passed through the strip in opposite directions, as indicated by black arrows. Interestingly, one observes that the dendrites always develop from the side of the film where the transport current adds up with the remanent state persistent current. Furthermore, the dendrites tend to expand to the middle of the film, in agreement with numerical simulations.[19] This contrasts the virgin penetration seen in Fig. 1(a), where the dendrites develop more freely into the Meissner state region.

Similar experiments performed at different temperatures showed that a current pulse will trigger flux dendrites up to 19 K, but never above. This threshold temperature is approximately twice that of dendrite formation induced by a slowly changing ($\sim$0.01 T/s) applied field. The difference in threshold temperature can be qualitatively explained by the sensitivity of thermomagnetic instability to the field (or current) ramp rate that determines magnitude of the electric field in the sample.[10,9] The dendrite pattern was insensitive to a change in the pulse duration in the range 1.5–15 μs if the rise time was kept constant. This also suggests that all dendrites are formed during the rise time.

In another series of experiments the height of the current pulse, I, was varied. By applying the pulse to the same remanent state, Fig. 2(b), we found that dendrites occur only when I exceeds a certain magnitude. In the present case, the threshold current equals 7.0 A at $T=12.5$ K, and depends only weakly on temperature. We also observe that the more I exceeds the threshold, the larger the dendritic structure be-

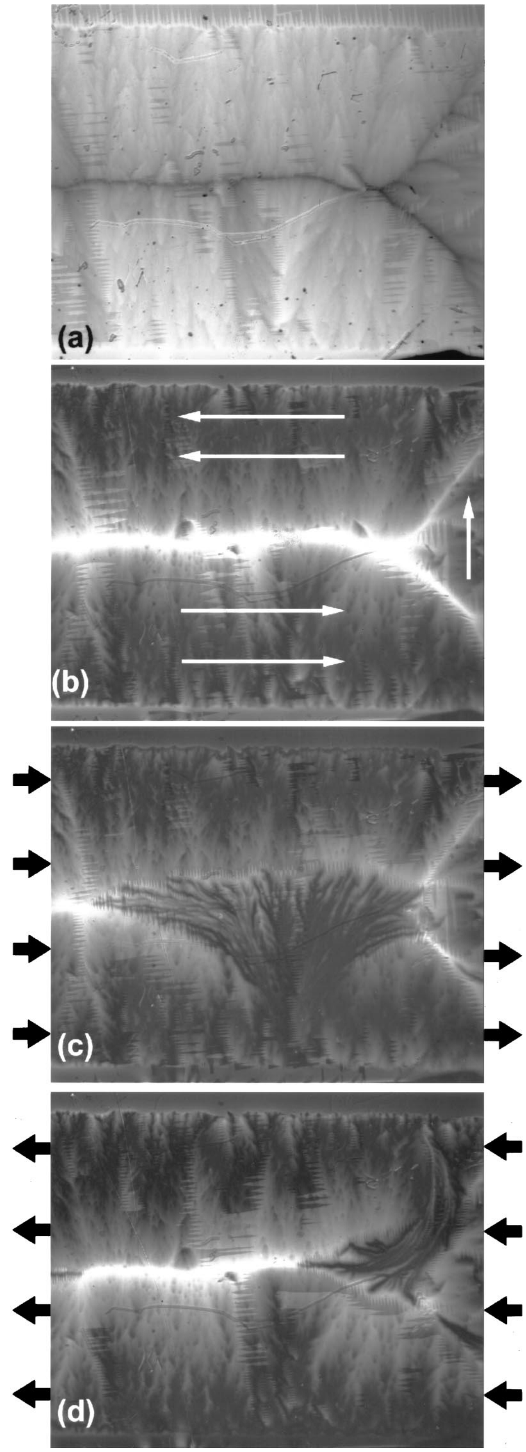

FIG. 2. MO images of the MgB_2 film at 12.5 K. (a) Applying a field of 34 mT after ZFC. (b) Remanent state after having raised the field to a maximum of 70 mT. White arrows indicate the direction of the shielding currents in the rectangular film. (c), (d) After applying a 8.5 A current pulse to the remanent state, (b), with opposite current directions, see black arrows. The pulse creates dendritic flux structures, which always develop from the edge where the transport and shielding currents add up constructively. The pulse also leads to marginal flux exit seen as slight darkening of the opposite edge; this effect is discussed in more detail in other theoretical (see Ref. 16) and experimental (see Ref. 17) works. Zigzag lines are caused by domain walls in the MO film and should be ignored.

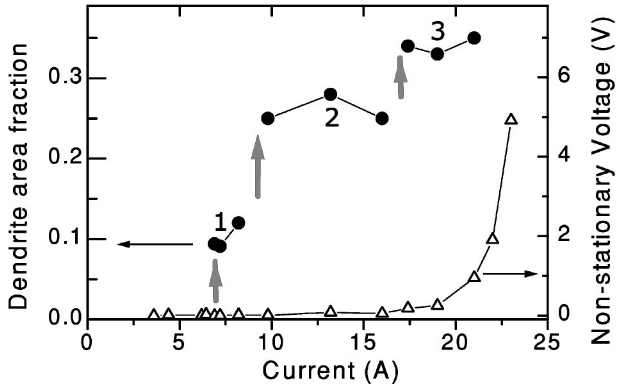

FIG. 3. The area covered by the current-induced dendrites (solid circles) at $T=12.5$ K. The vertical arrows indicate at which currents the number of dendrites increases by one. Open triangles show an increase in the voltage from 1.0 to 2.7 μs after the pulse start.

comes in size. Eventually, for sufficiently large I two dendrites are formed during the pulse. The full scenario is illustrated in Fig. 3, which shows by solid circles the area covered by the dendrite(s). The vertical arrows indicate at which I the number of dendrites is incremented from zero (below 7 A) to three (at 17 A). For very large currents heating near the contact pads affects the results. It was detected for $I>15$ A by the appearance of a nonstationary voltage across the sample which increased during the pulse, see Fig. 3. In addition, flux-free areas around the contacts were seen in the MO images.

Current-induced dendrites were formed not only by starting from the critical remanent state, but also from critical states like the one in Fig. 2(a). The dendrites develop then from the opposite side of the strip since the flow of screening currents is here reversed compared to the remanent state. Hence, all these results show consistently that the dendritic instability is triggered when the transport and the critical-state shielding current flow in the same direction. All attempts to create dendrites by passing a current pulse through a virgin ZFC film failed for I up to 30 A, even at the lowest temperature of 3.5 K.

It is believed that the dendritic avalanche behavior results from a thermomagnetic instability in the superconductor. Vortex dynamics simulations[3,19] and experiments on MgB_2 films under different thermal conditions[20] suggest that the instability stems from the local heating produced by flux motion. The heating will facilitate flux motion nearby, which in turn can lead to a large-scale avalanche invasion of depinned flux lines. The same mechanism is responsible for flux jumps found in the tesla range of the magnetization loop of bulk materials.[10] The present investigation is the first one to demonstrate that the dendritic type of the thermomagnetic instability can be triggered by a transport current. Moreover, films of MgB_2 are found more susceptible for the current-induced instability than for instability induced by varying the applied field. This shows that careful design of thermal stabilization may become essential in order to make viable devices out of MgB_2 films.

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