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RAPID COMMUNICATION

Mapping flux avalanches in MgB_2 films—equivalence between magneto-optical imaging and magnetic measurements

F Colauto[1], E M Choi[2], J Y Lee[2], S I Lee[2], V V Yurchenko[3], T H Johansen[3] and W A Ortiz[1]

[1] Departamento de Física, Universidade Federal de São Carlos, C.P. 676, 13565-905 São Carlos, SP, Brazil
[2] National Creative Research Initiative Center for Superconductivity, Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
[3] Department of Physics, University of Oslo, POB 1048 Blindern, 0316 Oslo, Norway

E-mail: fcolauto@df.ufscar.br

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Abstract
Vortex avalanches are known to occur in MgB_2 films within a certain range of temperatures and magnetic fields. These events, resulting from a thermomagnetic instability, were first revealed by real-time magneto-optical imaging, which exposed dendritic paths of abrupt flux propagation. This very powerful technique has, however, a practical limitation, since sensors that are currently available cannot be used at high magnetic fields. This letter shows that results obtained using dc magnetometry are in good correspondence with those furnished by magneto-optical imaging, demonstrating that the two techniques can be efficiently used as complementary tools to map vortex avalanches in superconducting films.

(Some figures in this article are in colour only in the electronic version)

Immediately after superconductivity was reported in MgB_2 [1], its vast potential for applications was recognized. Significantly high critical temperatures, $T_c \sim 40$ K, and upper critical fields, H_{c2}, which might exceed many dozens of Tesla for films in the dirty limit, as well as large, non weak-link limited, critical currents [2], are appealing features which qualify magnesium diboride for a wide range of applications, from digital electronics [3] to large-scale devices [2].

At temperatures below 10 K, a slow increase of the magnetic field applied perpendicular to the plane of MgB_2 films might trigger vortex avalanches, in the form of narrow dendrites [4]. The electric field that is induced locally by the moving vortices leads to Joule heating, and thereby a reduction in flux pinning and the corresponding critical current density, J_c. This facilitates even further flux motion, leading eventually to thermomagnetic runaway [4, 5]. This spectacular form of flux penetration takes place above a certain magnetic field, i.e. the lower threshold field. The phenomenon was first detected in experiments employing magneto-optical imaging (MOI) techniques, which provided direct visual observations of the magnetic field profile on the sample surface. Without MOI, it would be barely possible to recognize the dendritic patterns of flux penetration occurring in MgB_2 films. As a matter of fact, Lorentz microscopy could be another technique with a similar capability, although it requires films thin enough to allow for electron transmission [6].

The MOI technique relies on the Faraday effect, present in Bi-doped ferrite garnet films with in-plane magnetization, which serve as magnetic field sensors. The Bi:YIG indicator employed on the experiments reported here has a saturation

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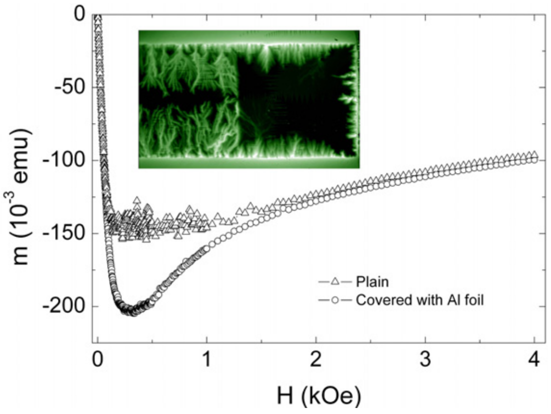

Figure 1. $m(H)$ taken at $T = 4$ K for a plain MgB_2 film (fluctuating) and for the same sample covered with a piece of aluminum foil (smooth). Inset: MOI taken at 4 K and 120 Oe of a similar MgB_2 film half-covered with Al foil.

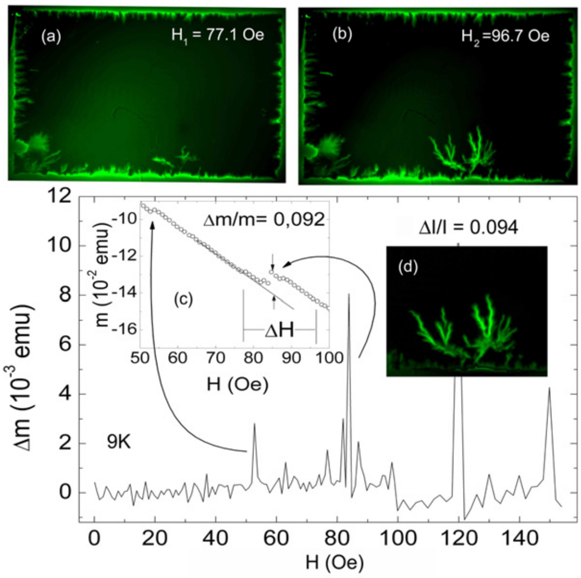

Figure 2. Main graph shows difference between successive values of the magnetic moment measured at 9 K. Images (a) and (b) were taken at the fields indicated, corresponding to the same ΔH shown at the original $m(H)$ curve, inset (c). Inset (d) is the difference in intensities, (b) minus (a).

field of around 800 Oe [7]. This imposes a practical limitation when one intends to use this technique to study events occurring at higher fields. For example, studies of the dendritic instability in MgB_2 show that different regimes exist [4], depending on the temperature and applied field. In particular, the avalanches are found to vanish above a certain temperature-dependent upper threshold magnetic field, implying that the thermomagnetic instability is restrained to a limited region in the high-temperature (HT) phase diagram. The scientific interest related to mapping this region in the HT plane is apparent, most obviously to ensure the absence of instabilities when designing practical applications.

While the lower threshold field has been thoroughly investigated, and mechanisms responsible for the appearance of the avalanches elucidated [5, 8], the understanding of the upper threshold field is even more challenging. However, a recent MOI study of NbN films shed some light on the phenomenon [9] and related the upper threshold field to the magnetic field dependence of the critical current density. Due to the much higher critical current and its weaker field dependence, the instability in MgB_2 extends over a much broader field range than in NbN. Therefore, MOI cannot be applied to fully determine the upper boundary of the 'dendritic phase', and alternative techniques have to be employed. In this letter we demonstrate that dc magnetometry (DCM) produces results that are quantitatively equivalent to those obtained by MOI, in the range of fields and temperatures where both techniques are applicable. This qualifies DCM as a convenient tool for delimitation of the thermomagnetic instability zone on the phase diagram.

To demonstrate the parity between MOI and DCM, we used both techniques to determine the lower threshold field, where the applied fields are below the saturation limits of the MOI garnet indicator. The MOI setup used in this work is described in [10], whereas dc magnetic measurements were conducted using two magnetometers by Quantum Design: a Physical Property Measurement System (PPMS) and a Magnetic Property Measurement System (MPMS).

In figure 1, one can see, in the MOI image of an MgB_2 film carried out at 4 K, that flux avalanches have resulted in dendritic patterns rooted along the edges of the rectangular sample. In the magnetic moment versus field (m–H) curve of a similar sample, also measured at 4 K, the avalanches are evidenced by the jumps in $m(H)$ [11]. The field dependence of m was measured at different temperatures, and confirmed the occurrence of fluctuations in the temperature interval up to 10 K, as reported previously [4]. To confirm even further the equivalence of the two techniques, DCM was performed on the same film now covered with a foil of aluminum. As shown previously with MOI [12, 13], the presence of a metallic layer on the MgB_2 film suppresses the instability. The smooth $m(H)$ curve in figure 1, also taken at $T = 4$ K, shows that the avalanches are indeed suppressed when this technique is applied.

Figure 2 shows an example of the similarity of both measurements, taken at 9 K. Ramping up the field slowly ($\sim$10 Oe s^{-1}), we took successive magneto-optical images. Shown at the top of the figure, images (a) and (b) represent the field distribution captured by the MOI experiment just before and immediately after the second dendrite appeared. Analogously, we increased the field at similar rates while measuring the magnetic moment of the sample. The main graph shows the subtraction of successive points, taken at 9 K, while increasing the magnetic field. The subtraction is performed simply to eliminate an inclined background, thus emphasizing the jumps in $m(H)$, which appear now in the form of peaks. The magnetic field difference between both images, ΔH, is exactly the same shown in inset (c), which shows the original data, before subtraction, in the region where the second major jump in $m(H)$ takes place. Inset (d) is obtained by subtracting image (a) from (b), and the relative increase in intensity which it represents, $\Delta I/I = 0.094$, is impressively correlated to the corresponding relative jump $\Delta m/m = 0.092$. It is worth mentioning that the first jump is

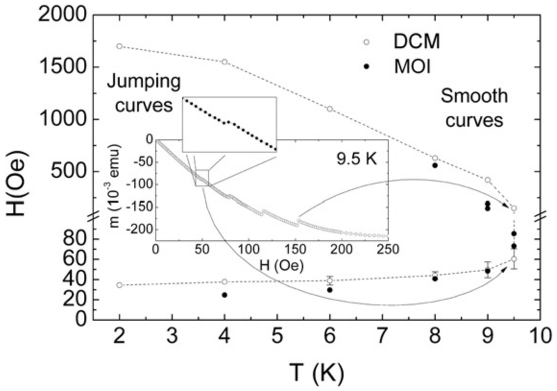

Figure 3. Limits of the instability region as determined by MOI and DCM measurements. Notice a break on the vertical scale, inserted for clarity. Insets illustrate the field interval where fluctuations appear.

also closely correlated to the first avalanche: both take place at $H \sim 51$ Oe, and the corresponding ratios are $\Delta I/I = 0.0287$ and $\Delta m/m = 0.0291$. Although not presented here, similar results were collected at other temperatures in the range 4–9.5 K.

Noticeable is the fact that, although the values of the field for the first and second jumps on the $m(H)$ curve coincide to a high accuracy with the lower fields measured with MOI, the exact value of the lower fields may be slightly different, which stems from the stochastic nature of the process. On the other hand, the results obtained with the two techniques may vary for yet another reason. As follows from the model [5], the onset of the avalanches depends, among other, on the coefficient of the heat transfer from the sample to the substrate, which may be different if different techniques are used: in the MOI setup the sample is placed on a cold-finger, while in DCM experiments the sample is 'suspended' in the sample chamber, being in contact with a heat exchange gas. Nevertheless, both methods give quite consistent and reliable estimates within a reasonable error range.

The set of experimental data derived from the observation of the flux avalanches with MOI, along with those collected from deviations of the magnetic moment from its otherwise smooth behavior, are compiled in figure 3. Experiments were routinely reproduced several times. Symbol sizes constitute a rough, overestimated, upper limit to the experimental error, except when indicated by vertical bars. A break was inserted on the field axis, so that one can observe the complete region of interest at a glance. For the whole temperature interval, the lower frontier could be determined in both experiments. Similarly, the upper border could also be identified and compared for temperatures in the 8–9.5 K range. In view of its consistency and reproducibility, we repute this set of data as compelling evidence that one can reliably take the observed features appearing on the magnetic moment curves as clear indicators of the occurrence of vortex avalanches, as if one were seeing them with the aid of MOI.

In summary, we have successfully mapped the flux avalanches in MgB_2 films using MOI and DCM as complementary techniques. On the one hand, seeing the very impressive images of MOI, one testifies that the fluctuating magnetic moment is due to the dendritic vortex avalanches penetrating the superconducting film. On the other hand, the widely available technique of dc magnetometry is shown to capture the most important features of the process, so that the simultaneous access to both allowed us to complete the task of mapping the region of the thermomagnetic instability on the phase diagram. In view of the consistent correspondence of both experimental approaches, we conclude that, in spite of its lack of images to facilitate observations, DCM can be used as an efficient alternative to complement MOI experiments, particularly in the range of fields unavailable for the latter technique.

Acknowledgments

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